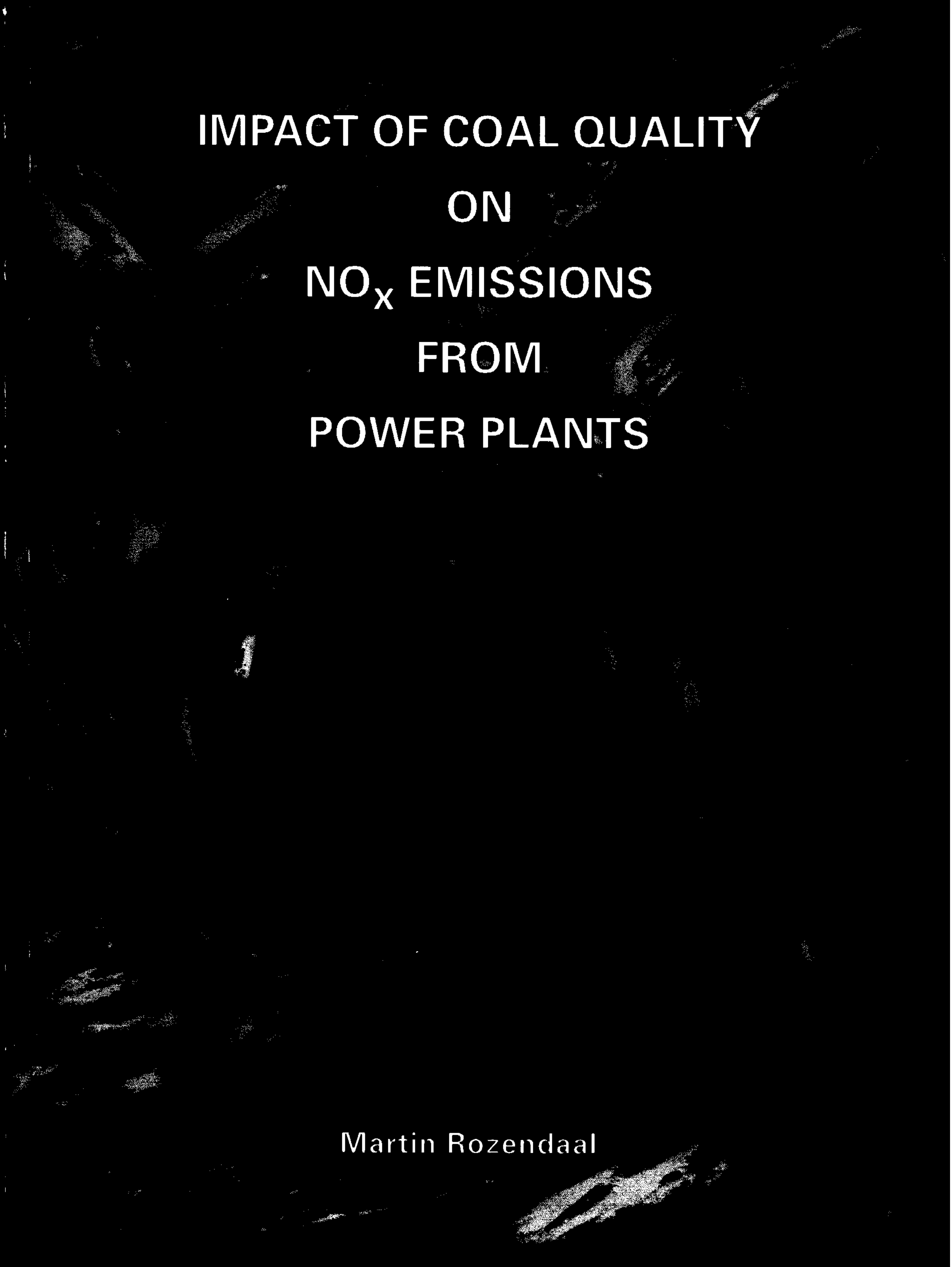

IMPACT OF COAL QUALITY ON NO_x EMISSIONS FROM POWER PLANTS

Martin Rozendaal

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Proefschrift

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aan de Technische Universiteit Delft,
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in het openbaar te verdedigen ten overstaan van een commissie,
door het College voor Promoties aangewezen,

op dinsdag 30 november 1999 te 10.30 uur
door

Cornelis Martin ROZENDAAL

werktuigkundig ingenieur
geboren te Rotterdam

Dit proefschrift is goedgekeurd door de promotor:

Prof. Dr.-Ing. K.R.G. Hein

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voor Trudy
voor Sanne en Daan

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CONTENTS

Chapter 1 GENERAL INTRODUCTION

1.1 BACKGROUND

About 40 per cent of the electricity supply in the Netherlands is generated with conventional coal-fired power plants. This corresponds to the combustion of about 9 million tonnes of coal per year. Since no commercially recoverable quantities of coal can be found in the Netherlands, coal is imported from countries all over the world. Coal resources are widely distributed, but the larger part is found in the Northern Hemisphere.

Coal is formed by a slow decomposition of vegetation through two distinct processes: diagenesis and metamorphosis (Krevelen, 1981). The first process is the result of bacterial changes in the vegetable debris before it gets deeply buried in the earth's crust. The second occurs after the material has been buried and involves slow chemical changes taking place under the influence of heat and pressure. The resultant product is coal that is composed of complex organic polymers consisting of large polycyclic aromatic clusters of several fused rings strung together by assorted hydrocarbon chains of varying lengths and other heteroatom (O, N, S) linkages. The organic fraction in coal is a heterogeneous mixture of macerals (the organic counterpart of the minerals in coal), and primarily consists of carbon, hydrogen, oxygen, nitrogen and sulphur. Besides the organic constituents coal also contains mineral impurities. Aluminosilicate clay minerals are the most abundant mineral species in coal.

The nature of the vegetation, the specific conditions under which the coal is formed, the mineral matter content and the age eventually determine the type of coal, the characteristics and, hence, the suitability for specific applications. Due to the heterogeneous nature of coal many different qualities are available and traded on the world coal market. Technical restrictions imposed by the design and operation of power plants determine the type of coal that can be burned and the range in which coal characteristics may vary, without jeopardising plant performance.

Due to legislative regulations regarding pollutant control for large-scale industrial fuel conversion processes, new technologies have been developed, such as coal gasification and (pressurised) fluidised bed combustion. However, because of the technological improvements, pulverised coal combustion will remain the main coal-based technology for electricity production in the near future. Pulverised coal-fired boilers may be classified in dry-bottom and wet-bottom boilers. In wet-bottom boilers 50 to 85 per cent of the total ash is removed as a continuous stream of molten slag. In dry-bottom boilers approximately 90 per cent of the total ash is removed as fine ash particles (fly ash) with the flue gas stream. Pulverised coal-fired boilers may further be classified by the arrangement of the burners in the boiler walls into front-wall, opposed-wall, tangential- and down-shot fired boilers. This thesis focuses on the type of boilers used in the Dutch utility sector; opposed-wall and tangential-fired boilers. **Table 1.1** lists the pulverised coal-fired boilers in the Netherlands, including some general features.

Table 1.1 Coal-fired power plants in the Netherlands[1)]

	Gelderland unit 13	Hemweg unit 8	Amer unit 8	Amer unit 9	Borssele unit 12	Maasvlakte unit 1 and 2
Load (MW_e)	602	630	645	600	403	518 (per unit)
Commissioned	1980	1994	1980	1993	1987[2)]	1987/1988[3)]
Burner arrangement	Opposed-wall	Opposed-wall	Tangential	Tangential	Tangential	Tangential
low NO_x measures[4)]	low NO_x burners SCR	low NO_x burners OFA	OFA SCR	low NO_x burners OFA FGR	OFA	OFA

[1)] All units are equipped with dry-bottom boilers.

[2)] This unit was originally designed for gas/oil combustion. In 1987 this unit was retrofitted to coal combustion.

[3)] These units were originally designed for gas/oil combustion. In 1987 (unit 2) and 1988 these units were retrofitted to coal combustion.

[4)] Environmental measures regarding NO_x reduction are discussed in chapter 3.

Raw coal that is delivered to the power stations is ground in pulverisers. Subsequently, the pulverised coal is pneumatically transported to the burners. The burners initiate combustion and control the mixing of coal with air and, hence, control flame stability. During combustion the organic material of the coal reacts to gaseous combustion products. The mineral matter in coal is converted into ash. The major part of the ash leaves the combustion chamber with the flue gases as fly ash, passing the superheater and reheater sections of the boiler. The fly ash may cause operational problems such as slagging, fouling and erosion of heat transfer surfaces. Slagging of the furnace walls or radiant superheaters occurs by molten ash droplets, causing a reduced heat transfer and creating corrosive conditions. The molten ash coagulates in the cooler regions of the combustion chamber and may cause fouling and erosion of heat transfer surfaces further downstream in the boiler.

During coal combustion environmentally hazardous species, such as sulphur dioxide (SO_2) and nitrogen oxides (NO_x), are formed. Emissions from these species are controlled by various means to meet the emission limits imposed by national and regional authorities. In modern power plants flue gas desulphurisation units have been installed to reduce the SO_2 emissions. NO_x emissions can be controlled during combustion by in-furnace reduction measures or by post-combustion control technologies removing the nitrogen oxides from the flue gases. The formation of NO_x mainly depends on overall and local oxygen availability, combustion temperature and coal properties. Therefore, by means of a proper design of the combustion equipment, the oxygen availability and temperature can be controlled to obtain conditions that are less favourable for NO_x formation.

Coal quality plays an important role in many combustion-related aspects and a poor quality may disturb a reliable, efficient and environmentally sound electricity production. Various coal classification systems (see chapter 2) have been developed in order to qualify the behaviour of the coal when it is heated or burned. These classification systems are widely applied, but the usefulness is limited when coals of the same rank are compared. The complexity of current installations and the increased concern about the environmental impact of coal combustion demand a better understanding of the impact of coal quality on power plant performance.

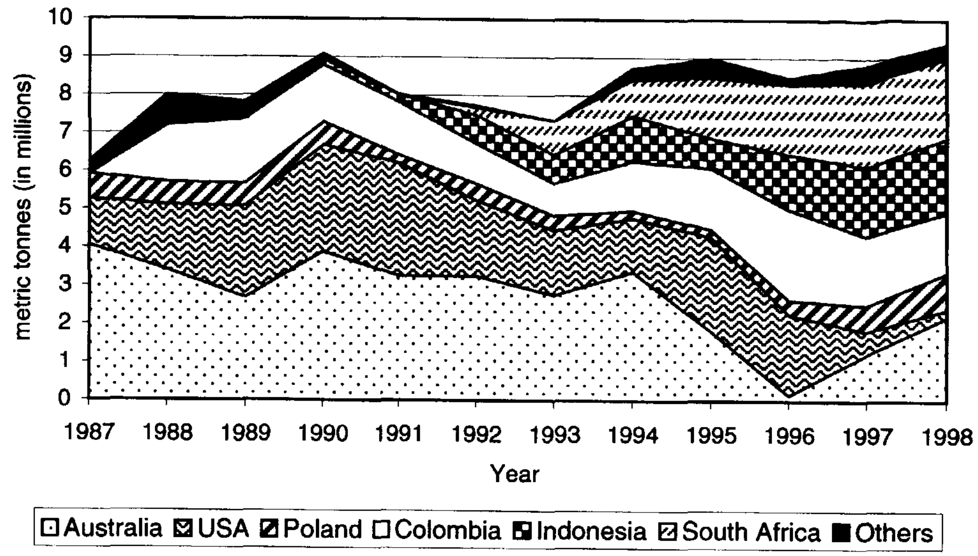


Figure 1.1 Origin of coals delivered to power stations in the Netherlands in the last decade (GKE, 1999)

Figure 1.1 illustrates the origin of the coals burned in the power stations in the Netherlands in the last decade (GKE, 1999). The origin of the coals fluctuates over the years. The decision to purchase a specific type of coal depends on many factors, such as the price, the transportation costs, the quality of the coal and the security of supply. The quality of coal is determined by the fuel characteristics (chemical composition and physical and mechanical properties) and is related to the layout and operating conditions of the power plant. Prior to purchase the impact of a certain coal on plant performance is assessed or predicted, based on experiences and/or evaluation tools. It is common for countries without indigenous coal resources to import coals for economic reasons from various sources. In the Netherlands an improved fuel quality control is achieved by blending coals. The main advantage of coal blending is the possibility to burn a larger diversity of coals, which results in lower fuel costs.However, due to the heterogeneous nature of coal, the prediction of the impact of coal quality on power plant performance is inherently complex. It becomes even more complicated when coal blends are burned since unexpected interactions may occur during preparation and combustion.

1.2 SCOPE OF THE THESIS

As pointed out above, power plant performance is affected by coal quality. Apart from an efficient and reliable operation, major concerns in this respect are the NO_x emissions and the quality of the fly ash. Power plants have to meet the emission limits imposed by national and regional authorities, and it is expected that in the future the stringent emission limits will be tightened even more. The nitrogen chemistry in pulverised coal flames is very complex and is affected by the operational conditions, boiler design and coal characteristics. Many research activities in a laboratory environment are being employed to obtain a better understanding of the influence of combustion conditions and coal characteristics on NO_x formation and reduction mechanisms. However, because of the complex reactions involved no simple and universal model is currently available to predict the NO_x emissions from full-scale boilers on the basis of the elemental composition of coal or other standardised coal analyses. Furthermore, because of the extensive impact of local combustion conditions it is difficult to extrapolate the results of laboratory experiments to full-scale applications.

The low NO_x conditions prevailing in modern pulverised coal-fired boilers often have a negative effect on the unburned carbon content in the fly ash. The fly ash produced in the Dutch boilers has to be applied in, for instance, the cement industry and therefore certain specification requirements have to be met. For many applications the unburned carbon content in the fly ash is desired to be below 5 per cent. Apart from the economic value of fly ash, it is profitable to obtain a good burnout and, hence, low unburned carbon levels from the point of view of combustion efficiency.

The main objectives of the study presented in this thesis are to develop NO_x prediction formulas based on the characteristics of the coal, and to obtain a better understanding of the impact of coal quality and coal blending on NO_x emissions from full-scale boilers and on the burnout of coal.

To create a reference framework for the experiments, the main processes in pulverised coal combustion (chapter 2) and NO_x formation (chapter 3) are reviewed. In chapter 4 the experiences with coal blending and the impact on combustion performance are addressed. General trends on the impact of coal characteristics under low NO_x conditions have been studied using a pilot-scale facility with a capacity of 1 MW_{th} (chapter 6). However, to overcome the limitations of extrapolating laboratory results to full-scale installations, it was decided to perform elaborate experiments at three pulverised coal-fired units in the Netherlands. A description of the experimental equipment and the full-scale installations is given in chapter 5. Chapter 7 presents the applicability of standard coal characteristics for predicting NO_x emissions and burnout for two pulverised coal-fired units. The applicability of more advanced coal characteristics, other than determined with the proximate and ultimate analysis, to predict the NO_x emissions from a tangentially and an opposed wall-fired unit are discussed in chapters 8 and 9, respectively. The effect of coal blending on NO_x emissions and burnout of three pulverised coal-fired units is given in chapter 10. The extensive consideration of overall results in chapter 11 assists in the extrapolation of the results to other pulverised coal-fired boilers. The concluding remarks and recommendations are presented in chapter 12.

Chapter 2 PULVERISED COAL COMBUSTION

2.1 INTRODUCTION

The layout of a pulverised coal-fired boiler with its specific heat transfer surfaces is based on the characteristics of a design coal. Coal-fired power plants dependent on world-traded coals are often designed to burn a range of coals with varying characteristics. Coals are bought on the world coal market often from a number of distributors. Consequently, the quality of the coals delivered to the power stations may vary significantly. The fluctuations in coal quality emerge in the coal characteristics, such as the heating value, the chemical composition, the ash content and the ash composition. Power plant operation and performance can suffer from these variations in coal quality, which may result in unscheduled outages, a lower efficiency, increased maintenance, corrosion problems, an increase of emissions, and subsequently, an increase of generation costs. At present, due to the liberalisation of the European electricity market, coal-fired power stations are facing a shift from base load operation towards peak load operation. Coal quality also has an impact on the turndown ratio and ramp rate of a coal-fired boiler. To conclude, an accurate prediction and understanding of the effect of coal quality on power plant performance are essential.

This chapter briefly reviews the features of coal with respect to pulverised coal combustion. Some basic coal characterisation tests are discussed in relation to the actual conditions encountered in pulverised coal-fired boilers. In addition, some recently developed more advanced characterisation tests are presented.

2.2 COAL STRUCTURE

Coal is a very heterogeneous material formed from a diversity of source materials. Together with the differences in conditions during the coalification process, this results in the heterogeneous nature of coal and the wide variety of coal types and characteristics. Coals are characterised by various methods, such as the proximate, the ultimate and the maceral analysis. The latter one provides information on the petrographic composition of coal.

Coalification is a continuous transformation of parent plant material towards a pure carbon structure. The heterogeneous nature of the parent material forms the basis for the different physical and petrographic structures found in coal. These petrographic structures, referred to as macerals, are the smallest physically distinctive entities of coal. They have different chemical structures and are visible under an optical microscope. The macerals are classified into three main maceral groups: vitrinite, exinite and inertinite. Each group contains several macerals that differ from one another in morphology and structure (see, for instance, Stach et al., 1982). Exinite has the highest hydrogen and volatile content in the three maceral groups, whereas inertinite has the highest carbon content. Vitrinite is the most abundant maceral in coals originating from the Northern Hemisphere. Inertinite is the main component of most of the Southern Hemisphere coals. Generally, exinite and vitrinite are considered as the reactive components and inertinite as the less reactive component of coal.

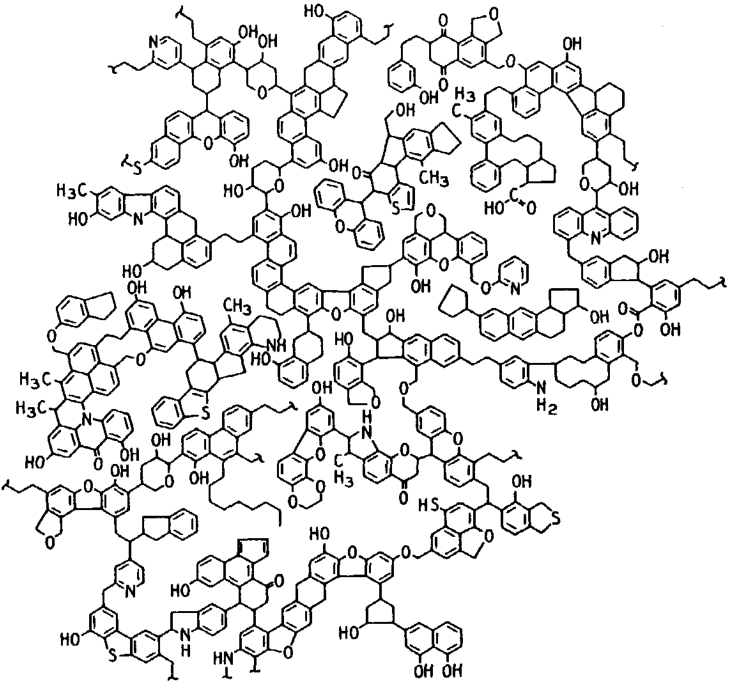


Figure 2.1 Model structure of a high-volatile coal (Shinn, 1984)

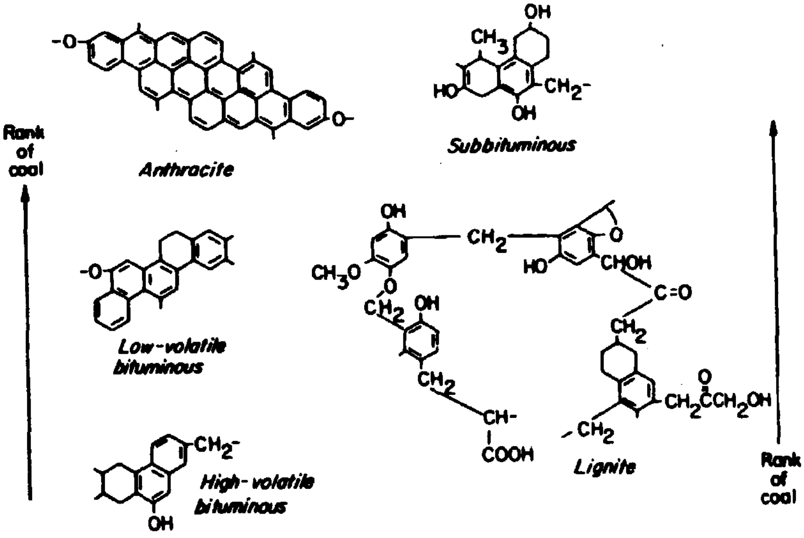


Figure 2.2 Representative chemical structures for various coal ranks (Villesvik, 1983)

The molecular structure of coal consists of aromatic and aliphatic compounds and functional groups (**figure 2.1**). The multiring aromatic components are linked together by relatively weak bonds, which are the first to break up when coal is heated. With increasing coal rank the relative contribution of aromatics increases, whereas the contribution of functional groups and aliphatics decreases (**figure 2.2**). Consequently, the carbon content increases with increasing coal rank. Lignite and sub-bituminous coals (low rank coals) contain more hydrogen and oxygen than higher rank bituminous coals and anthracite.

Coal contains a considerable amount of inert mineral matter. A small part of the mineral matter originates from the mineral matter contained in the parent material (inherent mineral matter). The largest contribution is from external sources (extraneous mineral matter), which are added during the coalification process by sedimentation and percolation of mineral waters. With the mining of the coal the adjacent rock layers also contribute to the (extraneous) mineral matter. Extraneous mineral matter forms more discrete and more readily removable inorganics. The main constituents of the mineral matter are clay minerals, silica (predominantly quartz), carbonates and sulphides (for instance pyrite). It is often assumed that mineral matter is inert during combustion. But there is a distinct difference between mineral matter and the ash produced from it by combustion, since dehydration, thermal decomposition, oxidation and partial loss of volatile inorganics such as Cl, Hg, K, Na, P, and S occur during combustion (Berkowitz, 1994).

2.3 COAL CLASSIFICATION

The volatile content and the carbon and hydrogen content are often used to classify coals. Various domestic and international coal classification schemes are used. An overview of the main classification systems is given in **figure 2.3** (Skorupska, 1993).

2.4 COAL COMPOSITION

The proximate analysis of coal is a simple and commonly applied characterisation test. This test procedure yields the following coal characteristics: total moisture, air-dried (or inherent) moisture, volatile matter, ash and fixed carbon content.

The total moisture content is measured on a coal sample (particle size < 20 mm) of 600 gram. The sample is placed in a furnace of 105 – 110 °C under reducing conditions (N_2) for 3 hours. The total moisture content is the weight difference of the sample before and after heating. Inherent moisture is measured with another sample that is first heated to a temperature of 35 °C under reducing conditions (N_2). Subsequently, the sample is crushed to particles < 200 μm. A crucible with 1 gram of sample is placed in a furnace at a temperature of 105 – 110 °C for thirty minutes. The weight difference before and after heating is the inherent moisture content.

The ash content is measured using a sample (particle size < 200 μm) of 1 gram. The sample is placed in a furnace and heated in air to a temperature of 815 °C. The resulting mass is used for the calculation of the ash content.

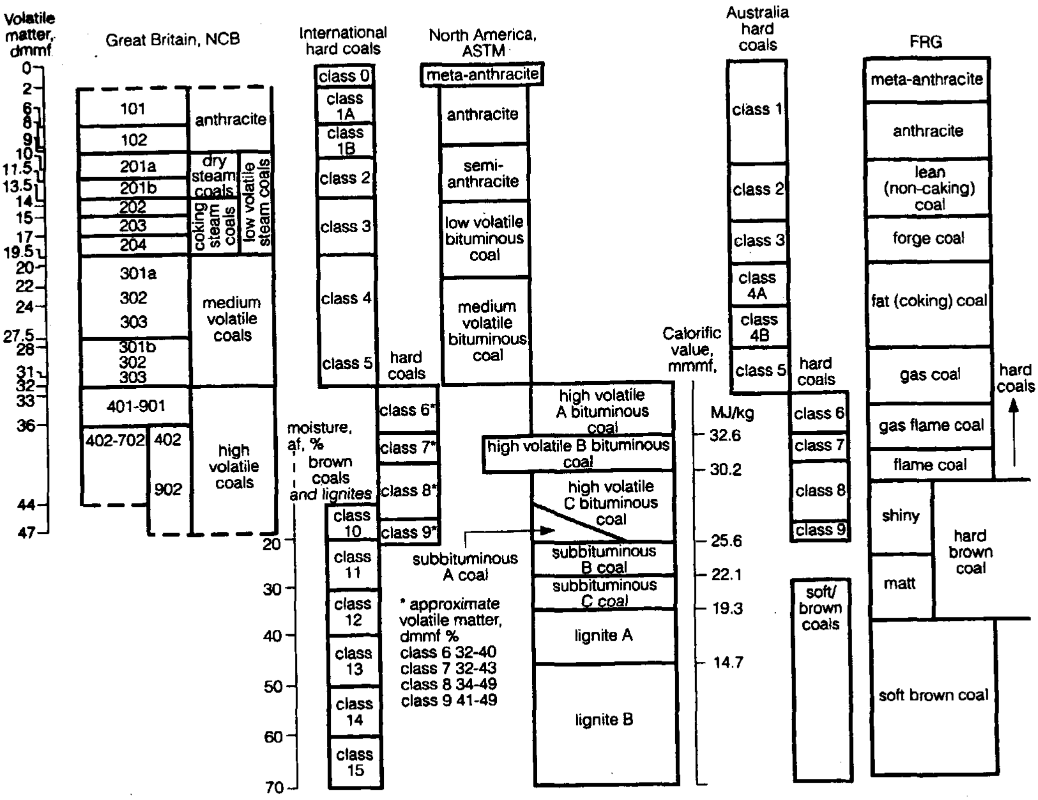


Figure 2.3 Coal classification systems (Skorupska, 1993)

The proximate volatile matter content is measured using a sample of 1 gram of coal (particle size < 200 μm), which is placed in a crucible and heated in a furnace under reducing conditions (N_2) to a temperature of 900 °C and is represented by the weight loss, corrected for inherent moisture (ISO, 1998). The fixed carbon content is measured by difference (100 minus the sum of moisture, ash and volatiles).

The volatile matter content is used as an indication for flame stability and coal reactivity. A commonly used parameter based on the proximate volatile matter content is the fuel ratio (ratio of the fixed carbon content to the volatile matter content). The volatile matter content and fuel ratio are sometimes used as an indication of the propensity of a coal to form NO_x during combustion, as will be discussed in chapter 3. In section 2.7 the applicability of the proximate volatile matter with respect to pulverised coal combustion is discussed.

The ultimate analysis determines the elemental composition (C, H, N, O, S) of the organic fraction in coal. **Table 2.1** shows some typical values of the carbon, hydrogen and oxygen content for different coal ranks, together with the volatile matter content and the calorific value.

Table 2.1 Typical coal compositions (Waterhouse, 1994)

	Carbon (%, dmmf)	Hydrogen (%, dmmf)	Oxygen (%, dmmf)	Volatile matter (%, dmmf)	Moisture (%, mmf)	Calorific value (MJ/kg, dmmf)
Lignite	62 - 73	5.9 - 4.3	30 - 20	65 - 42	70 - 31	23.7 - 29.5
Subbituminous	70 - 80	6.0 - 4.5	22 - 13	52 - 37	35 - 16	28.6 - 31.9
Bituminous						
- High-volatile	76 - 88	6.0 - 4.9	16 - 4.5	49 - 32	21 - 1	30.9 - 37.0
- Medium-volatile	84 - 91.5	5.4 - 4.5	8.5 - 2	32 - 20	4 - 1	34.2 - 37.2
- Low-volatile	90.5 - 93.5	4.8 - 3.7	3.5 - 1.5	20 - 9	1 - 2	37.2 - 36.1
Anthracite	92.5 - 96	3.9 - 2.0	2.5 - 1	9 - 4	1.5 - 3	36.6 - 34.5

The elemental composition of coal is used as a basis for combustion calculations, by which the stoichiometric air requirement, the flue gas volume and the gas composition can be calculated.

2.5 COAL COMBUSTION

Coal combustion is principally the oxidation of organic material in coal and generally comprises the following steps:

- initial heating of the particle and release of moisture
- release and combustion of volatile matter
- combustion of char.

In the initial phase of heating, the moisture is evaporated and released, followed by the release of the volatiles (pyrolysis or devolatilisation). The heating of the particle is caused by recirculating hot flue gases and by radiation from the flames and the furnace walls. The volatile components mix with the air and ignite at sufficiently high temperatures. The release of the volatiles leaves a porous char structure that is primarily composed of carbon. The combustion of the char starts after the volatiles have been burned or simultaneously with the combustion of the volatiles, as a result of oxygen diffusion to the char particle. In this process char combustion is the rate-determining step, since the volatiles burn at a much faster rate (homogeneous reaction versus the heterogeneous char oxidation reaction). After the char has been burned the mineral matter or ash remains.

2.5.1 Release and combustion of volatiles

The release of volatile matter involves complex chemical reactions and diffusion processes of volatile reaction products and depends on a number of parameters, such as coal rank, heating rate, peak temperature, residence time, particle size, pressure and the surrounding gas composition (Gavalas et al., 1982; Saxena, 1990).

Mass transfer plays a major role during pyrolysis. Gaseous products, such as CO, CO_2, H_2, H_2O, CH_4 and higher hydrocarbons (tar), generated inside a coal particle move from the inner part of the particle to the external surface. The rate of mass transfer inside the particle depends on the type of coal. In softening coals the volatile species have to move from the inside of the particle to the external surface through viscous molten coal. In a non-softening coal mass transfer proceeds through the porous structure of the coal particle.

With the release of the volatiles also nitrogen and sulphur species are released. As pyrolysis proceeds the O/C and H/C ratios in the remaining char decrease, due to the evolution of water, carbon oxides and light hydrocarbons, all of which possess O/C or H/C ratios higher than the parent coal.

Ignition of a coal particle is governed by competition between pyrolysis and surface oxidation and is influenced by particle size, volatile matter contents and heating rate (Berkowitz, 1994). Two combustion regimes are identified. One combustion regime takes place when particles are small (< 100 μm) and heating rates are below 10^3 °C/s. Under these conditions oxygen can reach the surface without being hindered by a large discharge of volatile matter. Surface oxidation can proceed as fast as or faster than pyrolysis. The particle will ignite heterogeneously, and the combustion of volatiles and char proceeds simultaneously. The second combustion regime becomes operative when the heating rate exceeds $10^3 - 10^4$ °C/s or with large particles (>> 200 μm) which heat up much slower. The rate of pyrolysis exceeds the rate of carbon oxidation at the particle surface. In this combustion regime the discharge of volatile matter impedes the diffusion of oxygen to the particle surface and ignition is homogeneous (Berkowitz, 1994). This combustion regime is valid for pulverised coal flames, since the heating rates exceed 10^4 °C/s.

The gas phase concentration of volatile species decreases with increasing distance from the coal particle. Once ignited the rate of diffusion of the volatile species from inside the coal particle to the surrounding boundary layer and the rate of diffusion of oxygen from the bulk of the gas into the boundary layer control flame development. The rate of diffusion of volatile species decreases as combustion proceeds, moving the flame towards the surface of the char. At a certain moment the temperature of the char and the oxygen concentration at the char surface is sufficient for ignition of the remaining char. The ignition of char can start before all the volatile matter has been released from the particle.

2.5.2 Combustion of char

After ignition and (partial) combustion of the volatile species evolved from the particle the remaining char starts to react with diffusing oxygen. This heterogeneous reaction includes several mechanisms:

- Diffusion of oxygen to the external surface area and into the pores of the coal particle
- Chemical reaction with the fixed carbon
- Removal of combustion products (CO and CO_2).

Oxygen diffusing to the particle surface will react with the char (heterogeneous char oxidation) according the reactions (Zelkowski, 1986):

$$C + \tfrac{1}{2} O_2 \rightarrow CO \tag{2.1}$$

$$C + O_2 \rightarrow CO_2 \tag{2.2}$$

CO is oxidised to CO_2 in the film layer surrounding the particle:

$$CO + \frac{1}{2} O_2 \rightarrow CO_2 \qquad (2.3)$$

Another approach is that the combustion products in the boundary zone impede free diffusion of oxygen towards the surface or that the oxygen is completely used for the oxidation of CO in the film layer surrounding the particle. In that case carbon reacts with CO_2 (Zelkowski, 1986):

$$C + CO_2 \rightarrow 2\,CO \qquad (2.4)$$

2.5.3 Effect of particle size and temperature

In suspension firing, coal is pulverised typically to particles of which 70 – 95% is smaller than 75 μm. This to assure complete combustion and to minimise deposits of ash and carbon on heat transfer surfaces. Char combustion is dependent on particle size and temperature.

Generally, the following rate-determining steps are identified:

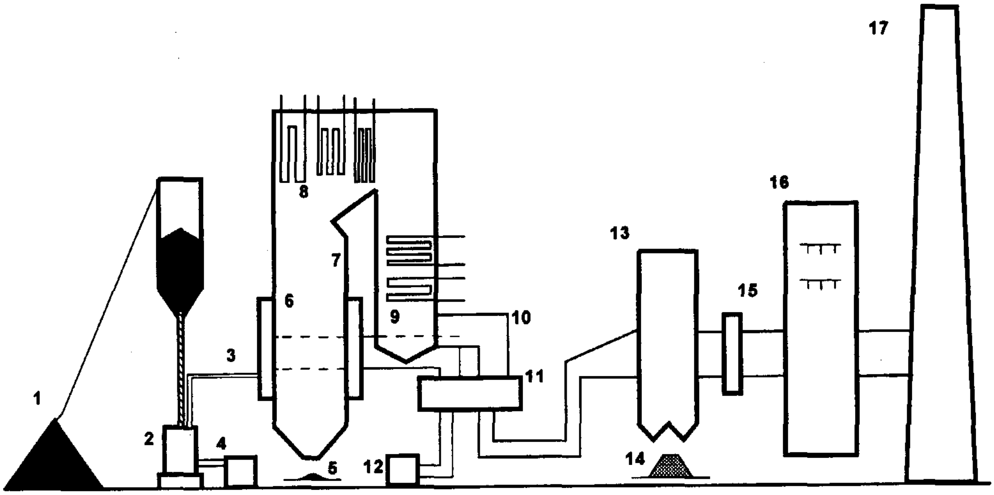
- diffusion of oxygen to the particle surface is the rate-determining step at high temperatures (> 1400 °C) or with large particles
- pore diffusion and the chemical reaction are the rate-determining steps at intermediate temperatures
- the chemical reaction is the rate-determining step at low temperatures (< 900 °C) or with small particles.

As combustion progresses the diffusion of oxygen into the pores of the particle becomes more difficult, because of the relative increase of the inert material and the longer distances from the surface to the remaining carbon. The burnout of the char will become increasingly slower which makes char burnout the slowest step in the coal particle combustion. Volatile matter evolves and burns in time-scales of the order of 10 – 50 ms in comparison of the char that will be "completely" burned in 500 to 2000 ms (Sayre et al., 1991).

2.6 PULVERISED COAL-FIRED BOILERS

Pulverised coal-fired units are used to generate steam for electricity and/or heat production. The main components of a typical coal-fired power plant include (illustrated in **figure 2.4**):

- coal handling and storage
- pulverisers
- air supply
- burners
- furnace
- flue gas fans
- ash transport systems
- emission control technologies.



1 Coal storage
2 Pulverisers
3 pc transportlines
4 Primary air fan
5 Bottom ash
6 Burners
7 Furnace wall
8 Super- and reheaters
9 Economiser
10 Flue gas duct
11 Air preheater
12 Air fan
13 Electrostatic precipitator
14 Fly ash
15 Flue gas fan
16 Flue gas desulphurisation
17 Chimney

Figure 2.4 Typical configuration of a pulverised coal-fired power plant

Contrary to fixed bed combustion, pulverised coal combustion is characterised by a pneumatic transport of pulverised coal with approximately 20% of the combustion air into a combustion chamber. The largest part of the combustion air is preheated at a higher temperature (typically to 300 °C) and enters through separate ducts, placed close to the coal carrying ducts.

Pulverised coal is injected into the furnace through the burners. The functions of a burner can be summarised as follows:

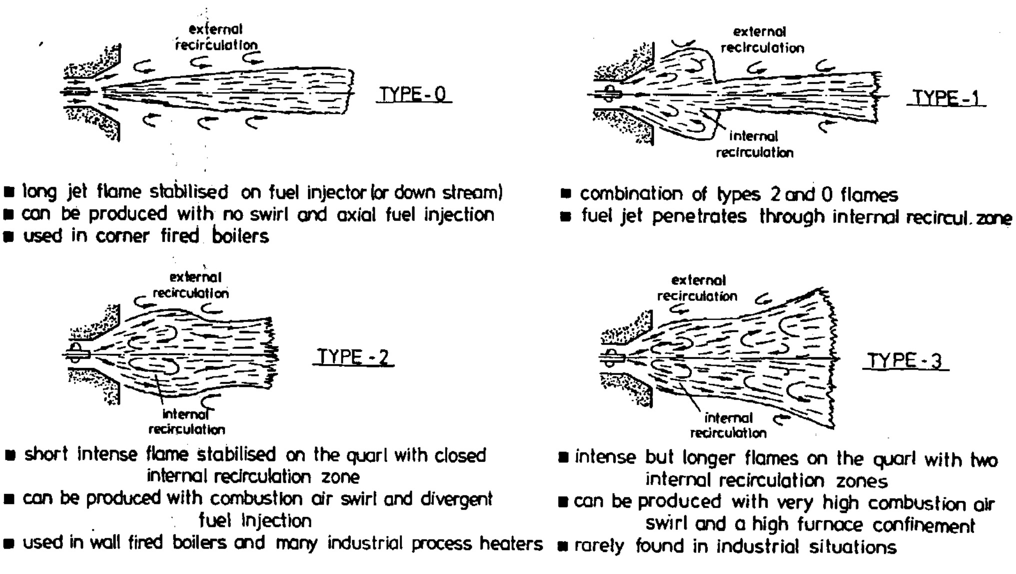
- to introduce the desired quantities of fuel and air into a furnace
- to provide stable ignition and safe operation for sufficient turndown ratios
- to induce proper mixing of fuel and air
- to allow for variations in coal quality
- to ensure low emission combustion.

The air required for the transport (and drying) of pulverised coal from the pulverisers to the burner is supplied by the primary air fans. The combustion air is supplied to the windbox by the forced draft fans.

Two burner types for pulverised coal combustion can be identified; swirl burners and jet burners. Examples of both types are shown in **figures 3.6 and 3.7**. In a simple swirl burner part of the combustion air (secondary air) is introduced into the furnace with a swirl. The secondary air surrounds the primary air/pulverised coal mixture that is introduced into the furnace through the centre of the burner. If the swirl of the combustion air is high enough recirculation of hot combustion gases in the centre of the flame occurs. Ignition takes place where the hot combustion gases have heated the primary air/pulverised coal mixture to sufficient high temperatures.

In a jet burner the pulverised coal with transport air (primary air) is introduced with the secondary air in parallel flows. Mixing of the hot combustion gases occurs from outside the primary air fuel jet. Jet burners are generally situated in the corners of tangential-fired boilers. The pulverised coal is injected towards the tangent of an imaginary circle in the centre of the furnace, whereby in the centre of the furnace a rotating fireball is created. The ignition of the pulverised coal typically takes place at some distance (20 - 100 cm) from the burner nozzle. Although, depending on the design of the burner nozzle, coal characteristics and temperature the flame can also be attached to the burner nozzle.

Generally, the design of both burner types is quite different. The secondary air ducts and the ducts for the primary air/pulverised coal mixture in jet burners are situated above each other in a burner box. The mixing of the combustion air (or secondary air) with the primary air/pulverised coal primary air flow is achieved by the large velocity difference between both flows. Typically, the primary air enters the furnace with a velocity of 20 m/s, whereas the velocity of the secondary air can be higher than 40 m/s. In swirl burners the secondary air ducts surrounds the primary air/pulverised coal ducts that are placed in the centre of the burner. In many swirl burners the flame is stabilised in the quarl of the burner, using a flame holder or flame stabilising ring. At the periphery of the primary air/pulverised coal duct an indented ring is often used to create small eddies where pulverised coal and secondary air are intensively mixed.



- long jet flame stabilised on fuel injector (or down stream)
- can be produced with no swirl and axial fuel injection
- used in corner fired boilers

- combination of types 2 and 0 flames
- fuel jet penetrates through internal recircul. zone

- short intense flame stabilised on the quarl with closed internal recirculation zone
- can be produced with combustion air swirl and divergent fuel injection
- used in wall fired boilers and many industrial process heaters

- intense but longer flames on the quarl with two internal recirculation zones
- can be produced with very high combustion air swirl and a high furnace confinement
- rarely found in industrial situations

Figure 2.5 IFRF flame classification system (Morgan et al., 1989)

Figure 2.5 illustrates the different types of flames characterised by the International Flame Research Foundation (IFRF). The type-0 flame represents the jet burner with the parallel flow of pulverised coal and combustion air. The other flame types are swirl-stabilised flames.

The induced draft fans withdraw the flue gases from the furnace and balance the furnace pressure. The flue gases respectively pass the super- and reheaters, the low temperature superheater and the economiser releasing part of their heat. When leaving the boiler, the flue gases flow through the air heaters to preheat the combustion air. Sometimes a flue gas treatment unit is installed before the air heater to lower the NO_x emissions. The main technology applied is selective catalytic reduction (SCR), in which the NO_x emissions are reduced through injection of ammonia in the presence of a catalyst. After the air heater, the flue gases flow through fly ash collectors (electrostatic precipitators) which remove the fly ash from the flue gases.

The amount of fly ash depends on the ash content of coal. Generally, 85 - 95% of the mineral matter in coal leaves the furnace as fly ash. The remaining part leaves the furnace as bottom ash through the hopper in the bottom of the furnace. After the fly ash collectors, the flue gases flow through the FGD installations where SO_2 is removed.

2.7 VOLATILE YIELDS AT ELEVATED TEMPERATURES

2.7.1 Pulverised coal-fired conditions

The volatile matter content of coal is often used as a measure to characterise the ease of ignition and, hence, flame stability. Coals with a very low volatile content such as anthracite are much more difficult to ignite than high-volatile coals. In order to maintain stable combustion with low-volatile coals the temperature of the primary air/pulverised coal mixture is increased and/or the fineness of the pulverised coal increased. The volatile matter is also used to characterise the reactivity of coal and char burnout. Pulveriser safety problems may arise with high-volatile coals due to the increased risk of fire caused by spontaneous combustion. The volatile matter content is also related to the propensity of coal to form NO_x.

Although the volatile matter content of coal measured with the proximate analysis is widely accepted and used for coal purchase, the applicability to present pulverised coal combustion is doubtful. The applicability of coal characterisation tests, in general, is criticised (Ham et al., 1993; Skorupska, 1993). In a review by Skorupska (1993) it was concluded that most of the coal characterisation tests have many shortcomings and do not adequately reflect the process conditions during pulverised coal combustion. Zelkowski et al. (1998) pleaded for the use of parameters determined with practice-orientated characterisation tests in combination with the traditional tests to compare the combustion behaviour of world-traded coals with a reference coal. (In chapter 4 some of the general coal characterisation tests are described in view of the applicability of these tests for the combustion of coal blends).

Table 2.2 lists the differences between typical pulverised coal combustion conditions and the conditions used for the measurement of the volatile matter in the proximate analysis

Table 2.2 Conditions during proximate analysis (volatile matter) and typical pc-firing conditions

	Combustion mode	Particle size (μm)	Heating rate (°C/s)	Final temperature (°C)	Residence time (s)
proximate volatile matter	fixed bed	< 200	100	900	420
typical pc-firing conditions	suspension	< 200	$10^4 - 10^6$	1300 – 1700	< 1

To measure the volatile matter yield at more practical conditions special analysis equipment has been developed (Carpenter et al., 1993), such as a drop tube furnace (DTF) and a heated wire grid reactor (HWG). A description of these experimental techniques is given in chapter 5. The volatile matter yield determined at higher temperatures and/or heating rates compared to the conditions with the proximate analysis is sometimes referred to as the high temperature volatile matter (HTVM).

2.7.2 Illustrative examples

The devolatilisation behaviour of a number of coals has been characterised by Knill et al. (1990) using an isothermal plug flow reactor. Eight bituminous coals were selected (volatile matter ranged from 19 - 40 wt.-%, daf). The particle size distribution was concentrated in the fraction between 75 and 90 μm. Volatile matter yield was measured after treatment at 1000, 1200 and 1400 °C. The composition of the gas was 0% O_2, 6% CO_2 and 10 - 16% H_2O (simulating the reducing gas which would be around a devolatilising coal particle). The ash-tracer method (see chapter 5) was used to determine the total volatile yield. The ratio of the volatile yield at elevated temperatures and the proximate volatile yield is defined as the yield factor:

$$\text{yield factor} = \frac{V}{VM} \quad (= \text{R factor}) \tag{2.5}$$

with: V the volatile yield at elevated temperatures or at a rapid heating rate (wt.-%, daf)
VM the volatile matter measured with the proximate analysis (wt.-%, daf) (ISO, 1998)

The yield factor obtained by Knill et al. (1990) was in the order of 1.1 to 1.8 and was independent of the temperature during devolatilisation. The yield did not increase above 1000 °C. The coal with a yield factor of 1.8 had an ash content of only 3%. A small error in the ash determination leads to large differences in the calculated volatile yield (see chapter 5). In another study by IFRF with seven high volatile bituminous coals the yield factor varied from 1.6 to 1.7 (Knill et al., 1989). Low rank coals have been found to devolatilise for much longer periods of time than higher rank coals, as illustrated in **figure 2.6** (Carpenter et al., 1993). The results presented in this figure were taken from Sayre et al. (1991).

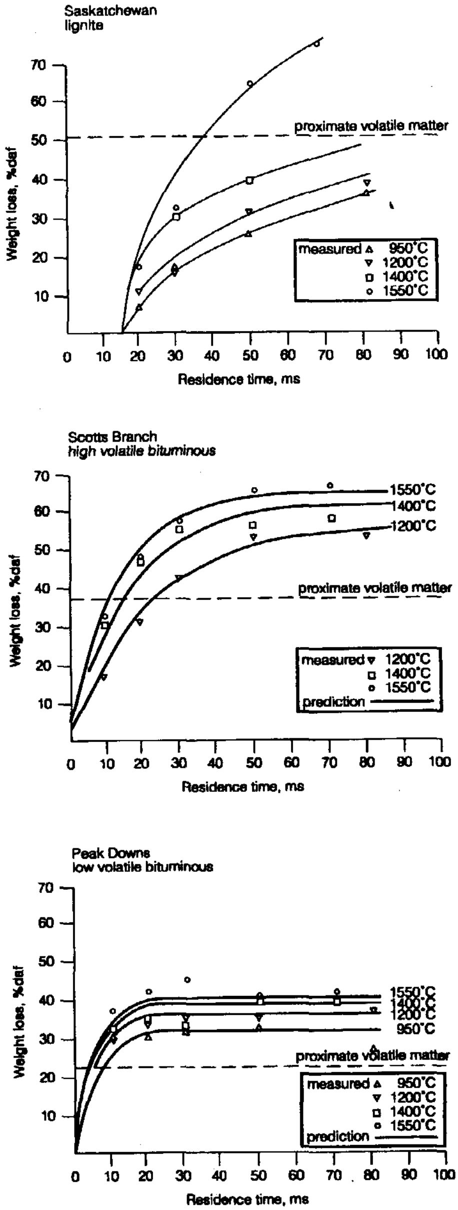


Figure 2.6 Devolatilisation yield versus residence time for three coals (Carpenter et al., 1993; Sayre et al., 1991)

Jamaluddin et al. (1986) investigated the effect of heating rate and temperature on the devolatilisation weight loss for two non-swelling bituminous coals in a laboratory-scale laminar-flow furnace at 800 to 1400 °C at a heating rate in the order of 10^4 °C/s. The weight loss was determined by both gravimetric and ash-tracer techniques. The yield factor ranged from 1.2 to 1.6 for the high-volatile bituminous coal and from 1.1 to 1.3 for the low-volatile bituminous coal. The minimum yield factors were obtained at a temperature of 1000 °C and the maximum at 1400 °C. The increased weight loss at higher furnace temperatures is a combined effect of temperature and heating rate. The coals were also tested at intermediate heating rates (250 – 1000 °C/s) in a carbolite ash-fusion furnace. The yield of volatiles at the intermediate heating rates was close to the proximate volatile yield. It was concluded that the yield of volatiles was strongly influenced by heating rate.

Thompson et al. (1993) studied the devolatilisation behaviour of four bituminous coals from the United Kingdom and three foreign coals (El Cerrejon, Rietspruit and Powder River Basin) in a drop tube furnace. The tests were carried out at three different gas compositions (pure nitrogen and 1% and 2% oxygen in nitrogen) and at a temperature of 1150 °C. The average yield factor ranged from 1.3 to 1.6, with the lowest value for the Powder River Basin coal and the highest value for the UK coals. El Cerrejon had a yield factor of 1.4 and Rietspruit of 1.3. Particle size seemed to have no effect on the volatile yield. The increased furnace oxygen content showed a slight increase in yield factors, probably due to a higher in-furnace temperature as a result of combusting volatile matter.

Brink et al. (1990) studied the devolatilisation behaviour of eight coals in a bench-scale test facility with a laminar flow burner (particle size fraction 38 - 53 μm). Temperatures ranged form 1600 °C at the burner outlet to 1350 °C further downstream. It was observed that the char samples still contained volatiles (measured with the proximate analysis test) amounting up to 10% in the weight of the char. These volatiles were considered to be part of the char, since it was suggested that the same components also remain in the particle in actual flames. The yield factor ranged from 1.2 to 1.5. The average yield factor was 1.4. The influence of particle size was also investigated. Three coals with a particle size fraction of 63 - 75 μm were compared with the particle size fraction of 38 - 53 μm. No difference in the extent of devolatilisation was observed.

A heated wire grid reactor (HTWM = high temperature wire mesh) was used to study the devolatilisation behaviour and the partitioning of nitrogen over the volatiles and char for nine coals (Gibbins et al., 1994). **Figure 2.7** shows the yield factor (here defined as R factor) as a function of temperature. It was observed that the yield factor increased with temperature, but that the extent for each coal was different. It was concluded that it is important to achieve peak temperatures representative for actual flames.

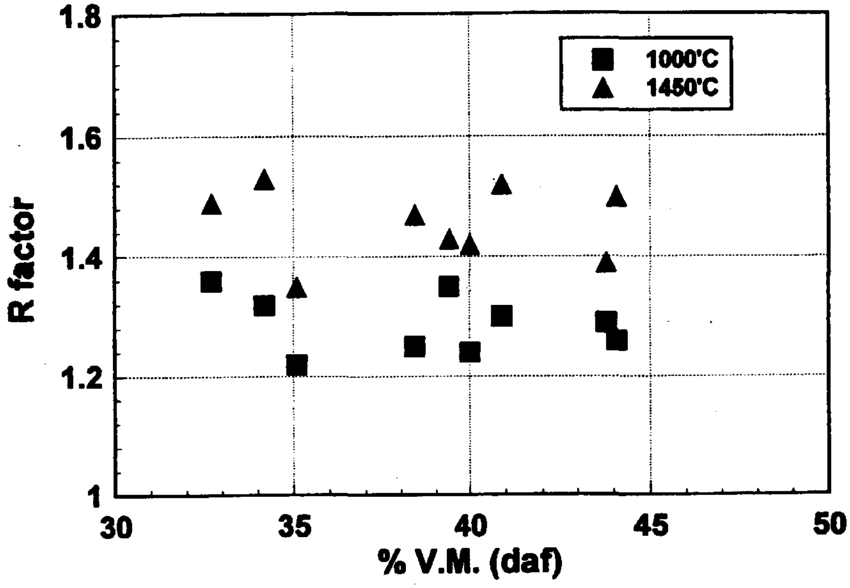


Figure 2.7 Yield factors (R factors) for world-traded coals at peak temperatures of 1000 °C and 1450 °C (Gibbins et al., 1994)

2.8 CONCLUDING REMARKS

The above-mentioned investigations make clear that the volatile matter content measured in the proximate analysis is lower than the volatile yield measured at conditions encountered in actual pulverised coal-fired furnaces. The volatile matter content of coal is a measure for the ease of ignition and flame stability, but is also of influence on NO_x emissions since the partitioning of coal nitrogen into char and volatile nitrogen controls the NO_x reduction potential in low NO_x boilers. This will be further discussed in chapter 3. The volatile matter is also related to char burnout. If more volatiles are released the amount of resulting char is less. Furthermore, an enhanced volatile release increases the porosity of the char.

The measurement of the volatile yield at elevated temperatures and rapid heating rates (or high temperature volatile matter) is at present not standardised, whereas the proximate analysis is world-wide accepted as a standard. The ratio of high temperature volatile matter to the proximate volatile matter depends, amongst others, on coal type, and varies approximately from 1.1 to 1.8 (depending on experimental conditions). It is suggested that, because of this coal dependency, coals that are different on basis of the proximate volatile matter, might be similar when the high temperature volatile matter is considered and otherwise. As a consequence, to understand and explain differences in the combustion behaviour of coals it is often necessary to determine the coal characteristics at conditions comparable to the actual conditions in a full-scale boiler.

Chapter 3 NITROGEN OXIDES IN PULVERISED COAL COMBUSTION

3.1 INTRODUCTION

Nitrogen oxides (NO_x) are formed during the combustion of pulverised coal and occur mainly in two forms: NO (nitric oxide) and NO_2 (nitrogen dioxide). NO is the most abundant nitrogen oxide under conditions typical for pulverised coal combustion, since NO_2 is formed at a much slower rate and at lower temperatures. Consequently, the majority of the nitrogen oxides is released with the flue gases in the form of NO. However, NO is almost completely oxidised to NO_2 in the ambient air.

N_2O is another oxide of nitrogen, but N_2O is of minor importance in coal combustion systems regarded in this thesis. It is known as an intermediate product in the chemical reactions prevailing in a pulverised coal flame. However, N_2O is destructed in the flame and concentrations in the flue gases leaving the stack are, apart from fluidised bed combustion, negligibly low (1 – 5 ppm) (Thomas, 1997).

The chemistry involved in the formation of NO_x in pulverised coal combustion is complex. Many different reactions are involved and depending on the local process conditions NO_x may be formed or reduced. In this thesis the nitrogen chemistry is only briefly discussed. More emphasis is placed upon the impact of coal quality and process conditions on the formation and reduction of NO_x. This chapter reviews the publicly available NO_x prediction formulas based on coal characteristics, as well as the relations predicting the unburned carbon content in the fly ash.

3.2 FORMATION OF NO

Nitrogen oxides are formed during coal combustion following three predominant mechanisms:

- thermal NO
- prompt NO
- fuel NO.

Two sources of nitrogen are available: the nitrogen in the air and the nitrogen in the fuel. Thermal NO and prompt NO are formed form the nitrogen in the combustion air. NO from fuel nitrogen is obviously formed from the nitrogen contained in the fuel. The various reaction mechanisms are briefly discussed in the next sections.

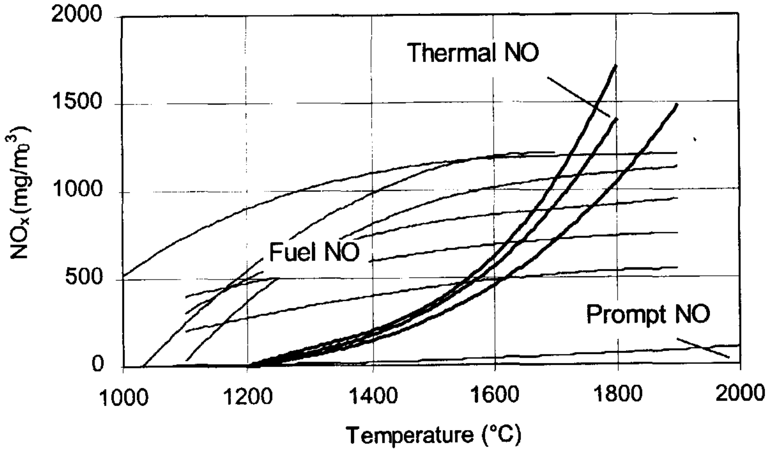


Figure 3.1 Schematic representation of the impact of flame temperature on NO formation mechanisms (Zelkowski, 1986)

3.2.1 Thermal NO

Thermal NO is formed at higher temperatures (above 1400 °C), according to the Zeldovich-mechanism (Zeldovich, 1946). Molecular oxygen from the air is, due to the high temperature, converted into two oxygen radicals. The oxygen radical reacts with molecular nitrogen from the combustion air to form NO and a nitrogen radical (reaction 3.1). The nitrogen radical reacts with molecular oxygen to form nitric oxide and again an oxygen radical (reaction 3.2).

$$N_2 + O \rightarrow NO + N \tag{3.1}$$

$$N + O_2 \rightarrow NO + O \tag{3.2}$$

The overall reaction is written as:

$$N_2 + O_2 \rightarrow 2\,NO \tag{3.3}$$

Because of the strong temperature dependency of the endothermic reaction 3.1, NO is only formed via this mechanism at higher temperatures (see **figure 3.1**). Thermal NO formation is therefore highly controlled by the peak flame temperature.

Reactions 3.1 and 3.2 only proceed in the presence of excess oxygen. In fuel rich regions in the flame the following reaction is of importance:

$$N + OH \rightarrow NO + H \tag{3.4}$$

Reaction 3.1 is the rate-determining reaction, since the reactions 3.2 and 3.4 are exothermic. The formation of thermal NO is reduced, if the residence time at the highest temperatures is rather short.

3.2.2 Prompt NO

Fenimore (1972) postulated a second mechanism for the formation of NO from atmospheric nitrogen. Prompt NO is formed via cyanide structures by the reaction of fuel radicals and molecular nitrogen under oxygen lean conditions. The main reaction is described as:

$$CH + N_2 \rightarrow HCN + N \qquad (3.5)$$

The reaction product HCN reacts to NCO and HNCO or other intermediate components and, depending on the conditions, is subsequently reduced to N_2 or oxidised to NO. Prompt NO is only significant in fuel rich flames (Phong-Anant et al., 1985). The reaction mechanisms are essentially the same as for the conversion of fuel bound nitrogen (see section 3.2.3). The contribution of prompt NO to the overall formation of NO in pulverised coal-fired boilers is small (in the order of ± 10 ppm (Pohl et al., 1983) or less than 5% (Phong-Anant et al., 1985)). Because of this small contribution, prompt NO is considered to be of minor importance.

3.2.3 Fuel NO

The third and most predominant mechanism in the formation of NO in present pulverised coal-fired boilers is the oxidation of fuel nitrogen. As explained in chapter 2, the combustion of pulverised coal comprises two major steps: combustion of the volatiles (tar and light gases) and combustion of char.

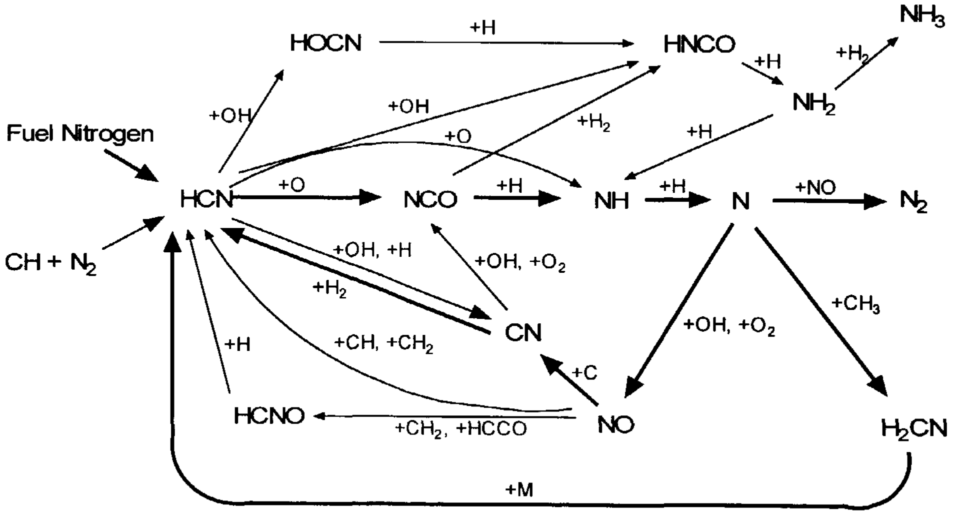


Figure 3.2 Reaction path diagram illustrating the major steps in the conversion of fuel nitrogen to NO (Miller et al., 1989)

With the release of the volatiles also part of the fuel nitrogen is released. NO formation of the volatile nitrogen species is controlled by homogeneous gas-phase reactions. The volatile nitrogen species mainly consists of hydrogen cyanide (HCN from nitrogen bound in aromatic rings) and ammonia (NH_3 from nitrogen in the form of amines). The major reactions involved in the formation of NO from volatile nitrogen are given in **figure 3.2** (The formation of prompt NO is also shown). The main reactions start with either HCN or NH_3.

HCN

$$HCN + O \rightarrow NCO + H \tag{3.6}$$

$$NCO + H \rightarrow NH + CO \tag{3.7}$$

$$NH + H \rightarrow N + H_2 \tag{3.8}$$

NH_3

$$NH_3 + OH \rightarrow NH_2 + H_2O \tag{3.9}$$

$$NH_2 + H \rightarrow NH + H_2 \tag{3.10}$$

$$NH + H \rightarrow N + H_2 \tag{3.11}$$

The nitrogen radical from the HCN route and the NH_3 route may further react to NO or N_2 depending on the conditions according to the reactions 3.12 (identical to reaction 3.4) and 3.13.

$$\text{oxidising conditions:} \quad N + OH \rightarrow NO + H \tag{3.12}$$

$$\text{reducing conditions:} \quad N + NO \rightarrow N_2 + O \tag{3.13}$$

In Miller et al. (1989) many possible reaction paths involved in the volatile nitrogen chemistry can be found. The char nitrogen chemistry is very complex. In the combustion of char nitrogen, NO is the primary nitrogen combustion product (Thomas, 1997). However, NO is partly reduced in the pores of the char particle or on the particle surface. The extent of this reduction will depend on the combustion conditions and the structural characteristics of the char.

3.3 NO REDUCTION

Application of primary and secondary measures reduces the NO_x emissions from coal-fired power plants. Primary measures decrease the amount of NO produced during combustion, while secondary measures remove NO_x from the flue gases. (Secondary measures are not considered in this thesis). Primary measures aim at reducing the formation of NO, but also promote the reduction of NO formed in the initial stages of combustion. A reduction of NO can be achieved either homogeneously by gaseous species or heterogeneously by char.

3.3.1 Homogeneous NO reduction

NO can be homogeneously reduced by OH-, CH_i- and NH_i-radicals, which are only in sufficient amounts present in fuel rich combustion regions (Grigoleit et al., 1990). The amines NH_2 and NH may reduce NO to N_2, following the reactions:

$$NH_2 + NO \rightarrow N_2 + H_2O \tag{3.14}$$

$$NH + NO \rightarrow N_2 + OH \tag{3.15}$$

A reduction with hydrocarbons is also possible according to the following reaction:

$$CH_i + NO \rightarrow HCN + OH_{(i-1)} \tag{3.16}$$

NO is reduced to HCN and is recycled into the fuel nitrogen reaction scheme (reactions 3.6, 3.7 and 3.8). HCN can be converted to either N_2 or NO dependent on whether reducing or oxidising conditions exist (reactions 3.12 and 3.13).

3.3.2 Heterogeneous NO reduction

The heterogeneous reduction of NO include the following reactions (Schulz, 1985):

$$C + 2\,NO \rightarrow CO_2 + N_2 \tag{3.17}$$

$$2\,C + 2\,NO \rightarrow 2\,CO + N_2 \tag{3.18}$$

$$2\,CO + 2\,NO \rightarrow 2\,CO_2 + N_2 \tag{3.19}$$

Reactions 3.17 and 3.18 are heterogeneous reduction reactions, whereas reaction 3.19 is in fact a homogeneous reduction reaction. These reactions occur in the pores of the char particle reducing NO that was initially formed by the oxidation of the nitrogen contained in the char.

In pulverised coal combustion the heterogeneous reduction of NO at the char surface is not as significant as the homogeneous reduction reactions (Grigoleit et al., 1990), because the particle load is too small. Also in a study performed by Glass et al. (1982) it was shown that the reduction of NO under staged combustion conditions is primarily achieved by homogeneous reactions.

3.4 CONVERSION RATIO OF COAL NITROGEN

As noted above, the contribution of prompt NO to the overall NO emission is small, and is therefore often neglected. Thermal NO is less dependent on coal quality, but is highly controlled by the residence times at high temperatures and is thus merely dependent on the furnace and burner configuration. The only source of NO formation that is strongly dependent on coal characteristics and also forms a major contribution to the overall NO formation is fuel NO (NO_{fuel}). Fuel NO is principally the sum of two other sources: volatile NO (NO_{VM}) and char NO (NO_{char}). Fuel NO can therefore be written as:

$$NO_{fuel} = NO_V + NO_{char} \tag{3.20}$$

Only part of the nitrogen in coal will react to NO. The conversion ratio is defined as:

$$NO_{fuel} = CR_{fuelN} \cdot NO_{fuel,max} \tag{3.21}$$

The maximum amount of fuel NO can be calculated using the data of the proximate and ultimate analysis. The maximum amount of NO (in ppm) from nitrogen is calculated as follows:

$$NO_{fuel,max} = N_{ar} \cdot \frac{V_0}{M_N} \cdot \frac{10^4}{V_{FG,dry}} = 1.6 \cdot 10^4 \cdot \frac{N_{ar}}{V_{FG,dry}} \qquad (3.22)$$

with:	$NO_{fuel,\,max}$	maximum NO concentration (ppm, dry, 0% O_2)
	N_{ar}	nitrogen content in coal (wt.-%, ar)
	M_N	nitrogen atomic weight (14.0 kg/kmol)
	V_0	ideal gas volume at 0 °C, 1 bar (22.41 m_0^3/kmol)
	$V_{FG,dry}$	dry flue gas volume per kg raw coal (m_0^3/kg)

The formation of NO from nitrogen in the coal can thus proceed via the volatile nitrogen species and the nitrogen remaining in the char. The partitioning of fuel nitrogen between the volatile species and the char has already for a long period been subject of many investigations (Pershing et al., 1976; Chen et al., 1982; Phong-Anant et al., 1985; Clarke et al., 1993; Man et al., 1993; Gibbins et al., 1994; Man et al., 1997). Besides the nitrogen partitioning also the conversion ratios of volatile nitrogen and char nitrogen to NO are important. The contribution of volatile N and char N to the total of fuel NO can be formulated as:

$$NO_{fuel} = CR_{VN} \cdot NO_{V,max} + CR_{CN} \cdot NO_{char,max} \qquad (3.23)$$

As illustrated in **figure 3.3**, the contribution of char nitrogen under oxidising conditions is significantly lower than the contribution of volatile nitrogen (Pershing et al., 1976; Muzio et al., 1997).

The maximum amount of NO from volatile nitrogen and char nitrogen can be calculated using expressions analogue to expression 3.22:

$$NO_V = N_{V,ar} \cdot \frac{V_0}{M_N} \cdot \frac{10^4}{V_{FG,dry}} \qquad (3.24)$$

$$NO_{char,max} = N_{char,ar} \cdot \frac{V_0}{M_N} \cdot \frac{10^4}{V_{FG,dry}} \qquad (3.25)$$

with:	$NO_{V,max}$	maximum NO concentration from volatile nitrogen (ppm, dry, 0% O_2)
	$NO_{char,max}$	maximum NO concentration from char nitrogen (ppm, dry, 0% O_2)
	$N_{V,\,ar}$	percentage of nitrogen per kg coal released with the volatiles (wt.-%, ar)
	$N_{char,\,ar}$	percentage of nitrogen per kg coal retained in the char (wt.-%, ar)

STELLINGEN

behorende bij het proefschrift

'Impact of Coal Quality on NO_x Emissions from Power Plants'

door Martin Rozendaal

1. De NO_x-emissie van kolengestookte centrales, die niet zijn uitgerust met nageschakelde NO_x-reductietechnieken, wordt in belangrijke mate bepaald door de verblijftijd en stoichiometrie in de hoofdverbrandingszone, alsmede de samenstelling van de kolen.

2. Met behulp van relatief eenvoudige kolenanalyses is het mogelijk de NO_x-emissie en de uitbrand van een poederkoolgestookte installatie te voorspellen. Een verbetering van de voorspelling is mogelijk indien kolenparameters worden bepaald onder condities die overeenkomen met de condities tijdens het verbrandingsproces.

3. Bij NO_x-arme poederkoolgestookte ketels is de NO_x-emissie van een kolenmengsel gelijk aan het gewogen gemiddelde van de NO_x-emissie van de samenstellende kolensoorten.

4. Het voornemen van de huidige regering om de CO_2-uitstoot van poederkoolgestookte centrales te reduceren tot het niveau van gasgestookte centrales getuigt van weinig realiteitszin, tenzij het beleid gericht is op het sluiten van deze centrales.

5. Een doeltreffende manier om de elektriciteitsopwekking in Nederland grotendeels te laten verdwijnen is deze sector privatiseren, belasting heffen op de brandstoffen en vervolgens de milieunormen zodanig aan te scherpen dat deze strenger zijn dan in de ons omringende landen.

6. De geloofwaardigheid van het Europees Parlement zal worden vergroot als, in navolging van de afschaffing van het belastingvrij winkelen op de luchthavens, ook de belastingvrije privileges van de leden van het Europees Parlement worden afgeschaft.

7. De toename van de communicatieve mobiliteit leidt (vooralsnog) niet tot een toename van de mobiliteit op de snelwegen.

8. Wanneer ouders grootouders worden, gaat hun gedrag meer lijken op dat van kinderen.

9. Niet het stoppen met roken is moeilijk, maar het volhouden om niet weer te beginnen.

10. Uit de toename van het aantal nietszeggende televisieprogramma's en de gelijktijdige toename van het opleidingsniveau van de gemiddelde Nederlander kan worden afgeleid dat smaak niets met opleiding te maken heeft.

11. Telefonische wervingsacties rond etenstijd zijn hinderlijk en werken daardoor juist averechts.

12. Alle kolen zijn zwart, ook bloemkolen als deze maar lang genoeg blijven liggen.

13. Ohne 'Kohle' geht es nicht.

14 oktober 1999

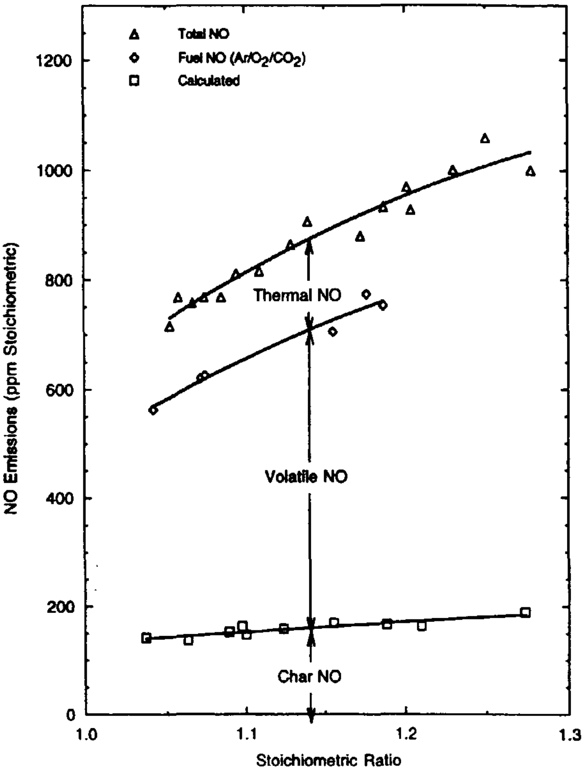


Figure 3.3 Contribution of char NO, volatile NO and thermal NO to total NO under oxidising conditions (Muzio et al., 1997)

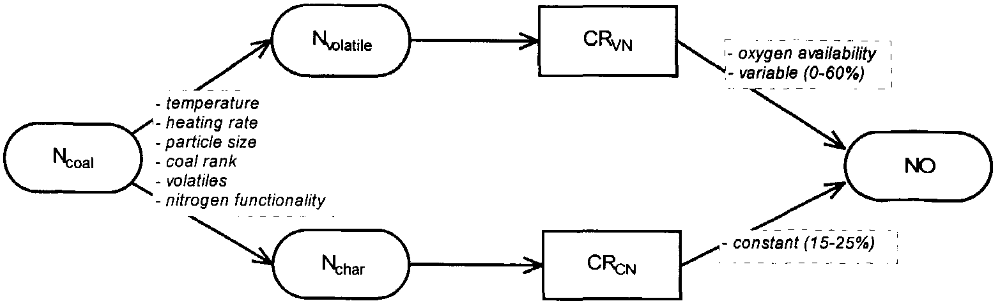


Figure 3.4 NO formation via char and volatile nitrogen

Figure 3.4 illustrates the pathways of char and volatile nitrogen to NO, including a number of important parameters. As explained in chapter 2, the heating rate and the final temperature determine the amount of volatiles released during pyrolysis. Particle (or pyrolysis) temperature and particle heating rate therefore also affects the fraction of coal nitrogen that is devolatilised and the fraction that remains in the char (Pershing et al, 1976; Blair et al., 1976). Coal rank plays an important role in the partitioning of fuel nitrogen between the volatiles and char (Kremer et al., 1986; Albrecht, 1992). Lower rank coals release nitrogen more easily than higher rank coals. Zeng et al. (1987) concluded that 70 to 90% of the nitrogen is released with the volatiles in pulverised coal-fired furnaces. Brink et al. (1990) reported a study in which the nitrogen release was compared to the release of volatiles for a number of coals. The experiments were performed in a laminar flow burner with the temperature ranging from 1350 to 1600 °C. It was observed that the extent of nitrogen release is higher than the volatile release for smaller sized particles (45 μm) and somewhat less than the volatile release for particles of 70 μm. Man et al. (1993) investigated the nitrogen and volatile release for 10 coals. Measurements in a heated wire grid reactor (HTWM = high temperature wire mesh) showed that at a pyrolysis temperature of 1450 °C coal nitrogen is partitioned proportionally between the char and the volatiles. At a temperature of 1000 °C relatively more nitrogen is retained in the char than at a temperature of 1450 °C, but the nitrogen release is also at this lower temperature a linear function of the total volatile yield. In a later study by Man et al. (1997) the nitrogen release was measured at a temperature of 1150 and 1600 °C. **Figure 3.5** shows that the ratio of volatile nitrogen release to total volatile release is close to unity for the measurements at 1600 °C. At a temperature of 1150 °C this ratio is 0.85, which indicates that at this lower temperature the nitrogen is preferentially retained in the char. A similar HTWM reactor was used for the determination of char nitrogen content of coals burned at Hemweg power plant, as will be discussed in chapter 9.

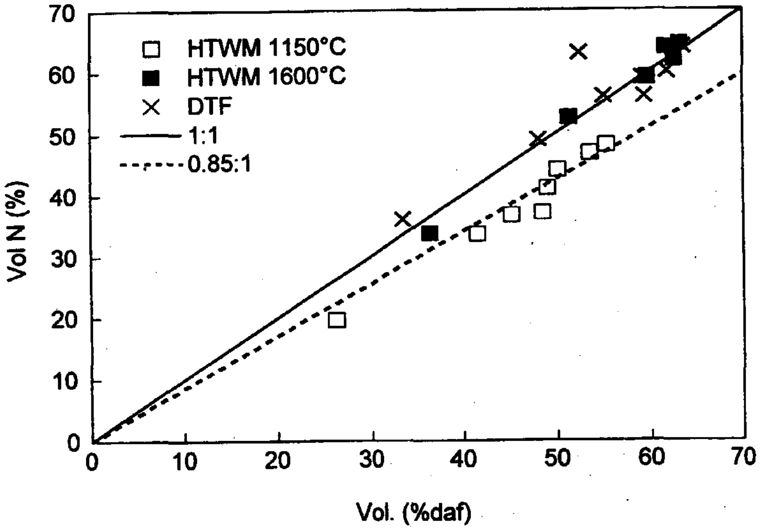


Figure 3.5 Volatile nitrogen compared to the total volatile yield. Influence of temperature (Man et al., 1997)
(HTWM = high temperature wire mesh; DTF = drop tube furnace)

Albrecht (1992) showed that at a pyrolysis temperature of 900 °C 40 to 80 % of the fuel nitrogen is released with the volatiles (depending on coal rank), whereas almost all nitrogen was released during pyrolysis at 1500 °C. Volatile nitrogen is released in the near burner region, and char nitrogen reacts downstream in the furnace. As a result the conversion ratio of volatile nitrogen is strongly influenced by the prevailing conditions in the near burner region. The aerodynamics of a burner are important. Low NO_x burners are designed to reduce the volatile NO formation by controlling both stoichiometry and temperature by changing the air-fuel mixing patterns in the near burner region. Morgan et al. (1989, 1990) investigated the conversion ratio of volatile nitrogen to NO_x for unstaged and staged combustion conditions. High NO_x emissions were measured with unstaged flames, because under oxidising conditions the efficiency of volatile nitrogen conversion to NO is higher than the conversion of char nitrogen to NO. The contribution of volatile NO to the total fuel NO was calculated to be 60 to 80 %. With the staged flames almost all of the volatile nitrogen was converted to N_2. The conversion ratio of char nitrogen to NO is fairly constant and may vary between 15 and 25% (Pohl et al., 1983).

Despite all research activities it is still unclear to what extent fuel nitrogen is partitioned between the char and volatile nitrogen. Contradicting results, as was shown above, are reported which is probably due to the different process conditions and different coals that were applied in the experiments. However, it is obvious that NO from volatiles combustion can be easily reduced by air staging, while char NO is not significantly affected by air staging (Pershing et al., 1976; Morgan et al., 1989; Chen et al., 1982). In the burnout zone enough oxygen should be present for the combustion to be completed, whereas in the near burner region a substoichiometric environment may exist, which minimises the formation of volatile NO and also enhances the reduction of already formed NO. The potential for NO reduction is therefore greater for high-volatile and high-reactive coals. A reduction of char NO can mainly be achieved by an increase of the fuel nitrogen released in the fuel rich region as a result of an increased pyrolysis temperature (Miyamae et al., 1987).

3.5 PRIMARY MEASURES FOR NO_X CONTROL

In the early 1970s primary measures were implemented in coal-fired boilers for the reduction of NO_x emissions. The objective of these measures was primarily to reduce the formation of thermal NO by:

- lowering overall excess air ratio
- lowering the flame temperature
- delayed mixing in the near burner region.

More recent fundamental research is focussed on the early stages of nitrogen release in the devolatilisation process and on the reduction of NO_x by fuel radicals above the main combustion zone.

Mainly, four different approaches can be used for the reduction of NO_x emissions from boilers (Hjalmarsson, 1990):

- flue gas recirculation
- air staging (in-furnace air staging)
- low NO_x burners (burner air staging)
- fuel staging.

These measures can be applied in new boilers. In existing boilers limitations for retrofitting may exist because of the available space and volume. The NO_x emissions from opposed-wall-fired boilers are generally higher than NO_x emissions from tangential-fired boilers (Starney-Hall, 1992; Jacobs et al., 1987). However, the development of new low NO_x swirl burners accomplished that at present NO_x emissions from opposed-wall-fired boilers comparable to tangential-fired units. In low NO_x swirl burners, the combustion air is staged to promote the release of volatile nitrogen species into a reducing environment in the early stages of combustion, which favours the conversion of fuel nitrogen to N_2 and inhibits NO formation. The flame is attached to the burner mouth and high temperatures are achieved enhancing the release of volatile nitrogen.

Generally, new boilers are built with a larger furnace volume and with an increased burner spacing in order to lower the overall flame temperature and thus, minimising the formation of thermal NO. Furthermore, the increased residence time in the primary combustion zone results in an enhanced reduction of volatile NO formed in the early stages of combustion. In the past also other NO_x control methods, like reduced air preheating or water injection into the combustion air, were applied to existing boilers (Breen, 1976). These methods lowered the NO_x emissions due to a reduced peak flame temperature, but were not widely applied since the power plant efficiency decreased dramatically.

3.5.1 Flue gas recirculation

Flue gas recirculation was one of the first applied methods to reduce the formation of thermal NO. The recirculation of flue gases to the burners lowers the overall flame temperature and the availability of oxygen. However, flue gas recirculation is of minor importance for the reduction of fuel NO. The impact of flue gas recirculation on the NO_x emissions from unit 9 of Amer power plant is briefly discussed in chapter 10.

3.5.2 In-furnace air staging

In-furnace air staging (also referred to as two-stage combustion) is applied in order to achieve a substoichiometric primary combustion zone in which fuel nitrogen is promoted to react to molecular nitrogen, because of the decreased availability of oxygen. In order to complete combustion additional air is introduced into the furnace above the main burners through overfire air ports (OFA) or after air ports (AAP). In this second stage of combustion the temperatures are relatively low because the remaining char and air are at this point diluted by combustion products from the primary combustion zone, which have lost heat through the heat absorption of the furnace walls. Because of the lower temperatures in the burnout zone the formation of thermal NO is inhibited. The substoichiometric primary combustion zone reduces the formation of fuel NO.

3.5.3 Low NO_x burners (burner air staging)

There are two types of burners: swirl and jet (or parallel flow) burners (see chapter 2). For both burner types low NO_x burners have been developed. Modern low NO_x burners are designed to reduce the availability of oxygen in the early stages of combustion. A reduction in the degree of mixing of coal and air can be achieved by the aerodynamics of the burner, although in some burners the mixing of coal and part of the combustion air is initially very intense to obtain a high temperature for an enhanced volatile nitrogen release. The coal and air are introduced through the burner in such a way that a delayed combustion is achieved. The volatile species are released under conditions of low stoichiometry. Fuel nitrogen is then converted to molecular nitrogen rather then to NO. **Figure 3.6** shows a typical low NO_x swirl burner of Babcock Hitachi (Japan) (Narita et al., 1987). This type of burner is installed in unit 8 of the Hemweg power plant. **Figure 3.7** shows a low NO_x burner for tangential-fired units (Kunimoto et al., 1991). This burner is developed by Mitsubishi Heavy Industries (Japan) and installed in unit 9 of the Amer power plant.

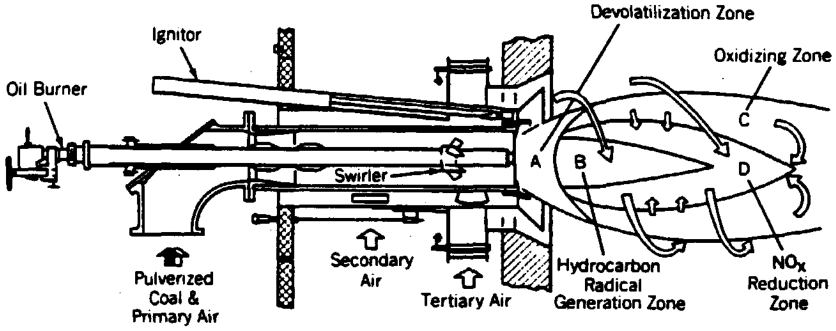


Figure 3.6 HTNR burner (Babcock Hitachi) (Narita et al., 1987)

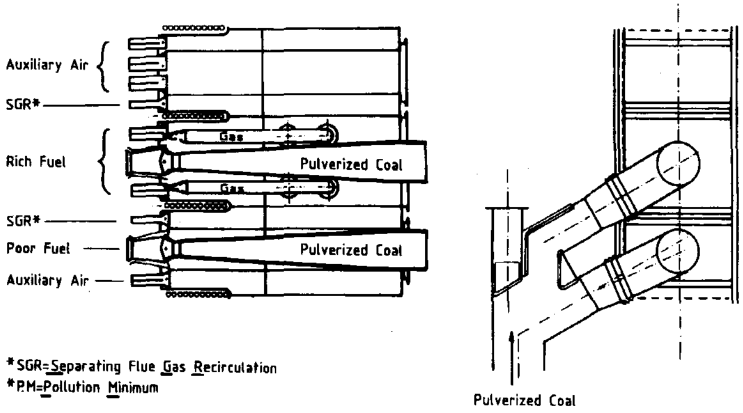


Figure 3.7 PM burner (Mitsubishi Heavy Industries) (Kunimoto et al., 1991)

3.5.4 Fuel staging

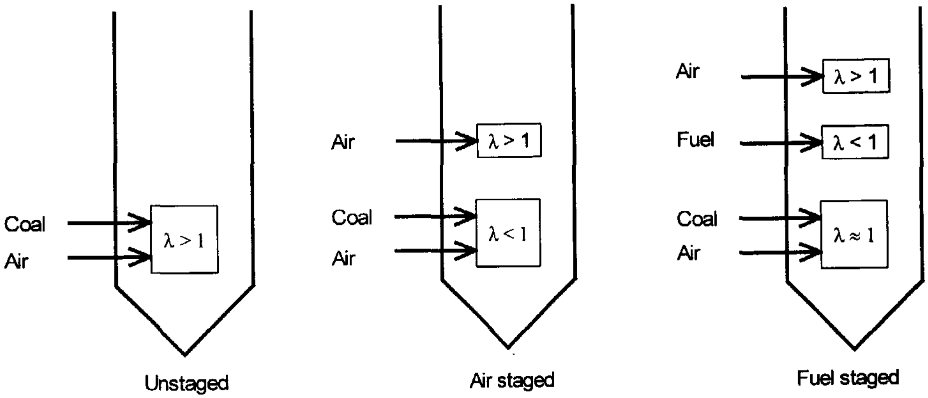


Figure 3.8 In-furnace staging principles

By means of fuel staging or reburning, nitrogen oxides formed in the primary combustion zone are reduced to molecular nitrogen by introducing reburning fuel through separate burners or injection ports above the main burners. Three zones can be distinguished. A primary zone in which coal is combusted under almost stoichiometric or slightly substoichiometric conditions. In the second or reburning zone fuel (natural gas or pulverised coal) is injected into the furnace to create a reducing atmosphere. The hydrocarbons from the reburn fuel reduce the nitrogen oxides formed in the primary combustion zone. Combustion is completed in the burnout zone by the introduction of additional air. **Figure 3.8** illustrates the concepts of the various options.

Table 3.1 Parameters affecting NO_x emissions from pulverised coal combustion (modified after Smouse et al., 1993)

Boiler design
- boiler type (wall-fired, tangential)
- capacity
- burner type (conventional burners, low NO_x burners)
- number and capacity of the burners
- burner zone (specific) heat release rate
- residence times
- air staging/fuel staging
- pulveriser type (static classifier, rotating classifier)

Boiler operation
- load
- pulverisers in operation/burners out of service (BOOS)
- excess air
- burner tilt
- burner operation (burner zone stoichiometry, swirl number, air/fuel biasing)
- soothblowing

Coal properties
- fuel ratio
- volatile matter
- nitrogen content
- char and volatile nitrogen
- others (particle size, nitrogen functionality)

3.6 PREDICTION OF NO_X EMISSIONS

3.6.1 General

NO_x emissions from pulverised coal combustion are affected by many factors (**table 3.1**). The impact of some of the above-mentioned aspects will be discussed in the next section, with the emphasis on the impact of coal quality.

3.6.2 Boiler design

Indications for differences in NO_x emissions for different boiler designs and load ranges can be derived from **figure 3.9**.

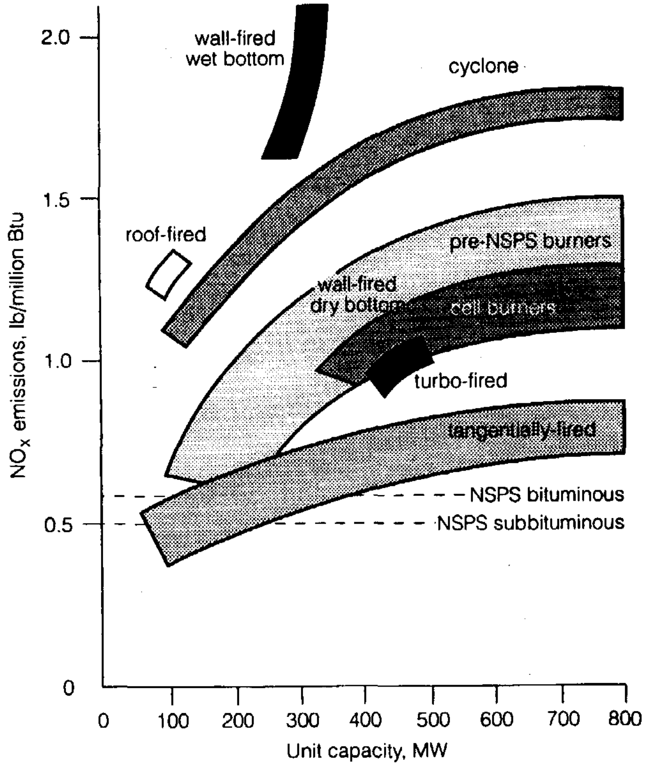


Figure 3.9 Impact of boiler design and load on NO$_x$ emissions (Soud et al., 1996)

Various attempts have been made to correlate the NO$_x$ emissions from several power plants with coal quality, boiler design and operating conditions (Starney-Hall, 1992; Smouse et al., 1993; Afonso et al., 1993).

Starney-Hall (1992) attempted to correlate the NO$_x$ emissions from thirty units at eleven coal-fired power plants (not equipped with primary low NO$_x$ measures) with the nitrogen content and the fuel ratio of the coals. No correlation could be found due to the diversity of boilers involved.

Smouse et al. (1993) reviewed some existing NO$_x$ estimation techniques. A number of correlations and equations was identified (some of them will be discussed in the next sections). They compared the use of multiple linear regression techniques and neural networks for the estimation of NO$_x$ emissions from nine tangential-fired boilers using data on boiler design, boiler operation and coal parameters. It was demonstrated that the application of neural networks gave a much better estimation of NO$_x$ emission than a developed multiple linear regression equation. The NO$_x$ emissions using the neural network were within ± 50 ppm of the measured values, whereas the NO$_x$ emissions predicted by the regression equation were within ± 175 ppm of the measured values. Smouse also concluded that existing NO$_x$ estimation techniques are generally inadequate for widespread use.

Afonso et al. (1993) described a semi-empirical model for predicting NO_x emissions. Three main independent factors were identified:

- Coal properties
- Burner design and operation
- Boiler design and operation

For the model it was assumed that each of these factors was independent of the others. Each influence is taken as a change in nitrogen oxides from a reference condition (NO_r). The model is defined as:

$$\frac{NO}{NO_r} = \left(\frac{NO}{NO_r}\right)_{coal} \cdot \left(\frac{NO}{NO_r}\right)_{burner} \cdot \left(\frac{NO}{NO_r}\right)_{boiler} \cdot \left(\frac{NO}{NO_r}\right)_{fineness} \tag{3.26}$$

The nitrogen content in the coal and the volatile matter content are the coal parameters which are used in the coal term in this equation (based on the relation developed by Pohl (see section 3.6.4.2). The other terms in this model were also described with known relations obtained by research work or derived from experiences from four utility boilers. Predicted NO_x emissions were compared with measurements with nine coals in four boilers. Afonso concluded that more data are needed and refinement is required before the model can be fully accepted.

The impact of particle size on NO_x emissions is not very obvious. Taking into consideration that smaller particles tend to burn at a faster rate, more time is available for the reduction of NO_x formed in the early stages of combustion in staged combustion systems (Heitmüller et al., 1987). Moreover, it is believed that more volatiles are released (and hence more nitrogen) in the primary fuel-rich combustion zone resulting in a higher conversion of fuel nitrogen to N_2 (Afonso et al, 1993). Based on limited data Afonso et al. (1993) state that particle fineness is of no influence on the NO_x emissions from tangential-fired boilers, whereas boilers equipped with swirl burners showed a decrease of NO_x emissions with smaller particles.

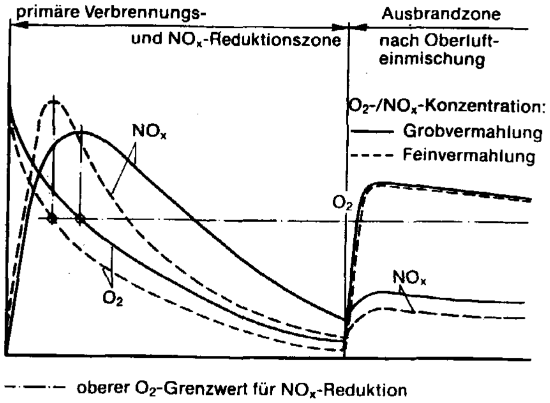


Figure 3.10 NO_x and O_2 curves for large and small particles (Albrecht, 1992)

Model calculations showed that in a low NO_x boiler larger particles result in higher NO_x emissions than smaller particles, as is shown in **figure 3.10** (Albrecht, 1992). Smaller particles are heated up faster resulting in an early release of volatile matter. Directly after the ignition of the volatiles the char starts to burn resulting in a rapid decrease of oxygen. Consequently, more nitrogen reducing species are formed which reduce the NO_x formed in the near burner region.

Others found that the impact of particle size on NO_x emissions is strongly dependent on the aerodynamics and the process conditions (Abbas et al., 1993; Maier, 1997). Maier (1997) investigated, the impact of particle fineness on NO_x emissions in a pilot-scale facility (500 kW_e). It was observed that under burner air staged conditions the NO_x emissions decreased between 0 and 25% (particle size distribution varied from 20% > 90 μm to 2% > 90 μm). The maximum increase of the NO_x emissions for unstaged conditions was 25%. With in-furnace air staging experiments it was observed that the impact of fineness decreased with increasing residence times in the primary combustion zone. A full-scale test in an opposed-wall-fired boiler in Denmark showed that smaller particles resulted in an increase of the furnace temperature, but did not result in significant differences in NO_x emissions (Lans et al., 1998). Tests in a pilot-scale furnace equipped with a dual register swirl burner showed that NO_x emissions were not dependent on particle size (Mereb et al., 1992).

3.6.3 Operating conditions

Operating conditions have a major influence on NO_x emissions. The impact of boiler settings on NO_x emissions is highly dependent on the type of boiler and burner system. Based on experiences from eleven tangential pulverised coal-fired units Mazzi et al. (1997) listed the NO_x reductions possible with a modified operating regime (see **table 3.2**).

When operating conditions are changed for a further reduction of NO_x emissions it must be avoided that other aspects of plant performance deteriorate. Reducing NO_x emissions by plant operation may result in a reduced burnout, enhanced corrosion rates of furnace walls and problems with flame stability.

Table 3.2 Effect of changing operating conditions on NO_x emissions (modified after Mazzi et al. (1997))

Technique	Typical NO_x reduction (%)	Possible limiting factor(s)
BOOS	25-50	Low windbox pressure at low loads Pulveriser capacity at full load
Decreased excess air	5-15	Slagging/fouling, CO emission, unburned carbon
Air biasing	5-15	Windbox pressure
Fuel biasing	5-10	Pulveriser capacity

3.6.4 Coal quality

3.6.4.1 General

Considerable work has been done to identify the influence of coal quality on NO_x emissions. Makansi (1991) gives several reasons for the extensive research work:

- In order to evaluate the effectiveness of NO_x reduction techniques power plants have to evaluate the impact of coal properties.
- Fuel switching for any reason may lead to increasing NO_x emissions.
- A keen understanding of the influence of coal characteristics on NO_x emissions may reduce the need of expensive post-combustion techniques.
- Plant operation will be easier if the influence of coal properties is known.
- Coal purchasers may buy cheaper coals on the spot market without adversely affecting NO_x emissions.
- Especially, new low NO_x burners require more precise operation for a high combustion efficiency, good flame stability and fly ash quality in combination with low NO_x emissions.

Smith et al., (1996) classified NO_x prediction methods into four groups:

- Fundamental quantitative relationships. Models should ideally include forms of nitrogen in coal, coal rank, relevant physical and chemical properties, nitrogen partitioning, formation and fate of nitrogenous species, combustion behaviour and effects.
- Empirical algorithms and statistical relationships. Such models or relationships are generally only valid for the envelope (coals and boiler(s)) for which they were developed. Many of the empirical models are developed on basis of a small set of data. Most of the models published in literature belong to this group.
- Computational Fluid Dynamics (CFD) and kinetic modelling (with/without chemistry). Considerable efforts have been made on describing the combustion process and the formation of NO_x by mathematical modelling of the combustion process. Lans et al. (1997) recently reviewed the use of chemical reaction engineering models and models based on computational fluid dynamics. They concluded that at this point still major uncertainties exist in applying such models for the prediction of NO_x emissions. Basically because there is a lack of accurate measurement data in the furnace and the near burner region for the validation of CFD models.
- Artificial intelligence methods (expert systems and artificial neural networks). Expert systems and neural networks are increasingly applied for NO_x prediction. An expert system follows logical rules to reach a defined goal. Examples of such programs are NO_x advisor (Pfahler et al., 1995) and Ultramax (Boyle et al., 1995). Also neural networks are used to relate NO_x emissions with coal characteristics and operating conditions (Reinschmidt et al., 1994; Holmes et al., 1995; Pfahler et al., 1995; Frenken et al., 1996, 1997). Complex non-linear and co-dependent relationships are incorporated within the system. The system seeks iteratively for patterns and trends between the defined input and output data set.

Smith et al. (1996) concluded on basis of a review of existing published NO_x models/predictors that all of these possess one or more limitations (a small data set, small-scale equipment and invalid assumptions). The following section briefly reviews the published literature on predicting the impact of coal quality on NO_x emissions and related research in pilot- and full-scale applications. Prediction of coal quality effects by CFD modelling and artificial intelligence methods is not considered.

The coal characteristics used for predicting NO_x emissions are often based on the:

- proximate and ultimate analysis
- volatile yield measured at high temperatures and/or high heating rates
- partitioning of the nitrogen between the volatiles and remaining char
- functionality of nitrogen in coal.

An overview of relevant work on the prediction (or estimation) of NO_x emissions on basis of coal characteristics is listed in **table 3.3**. A comparison has been made of the different research activities concerning the facilities applied, the coal range considered, number of coals used and the applied combustion conditions. Also the major coal parameters which were identified to affect NO_x emissions are listed. It should be noted that in a number of cases complex correlations were derived which included also other coal characteristics than the ones mentioned in the table. Some correlations also included operating parameters. The dominant coal parameters in the table are labelled to indicate whether NO_x emissions increase (▲) or decrease (▼) with an increase of the parameter considered. In the last column of the table the reader is referred to the related equation, when appropriate, otherwise the reader is referred to the literature cited. If no quantitative relationship is presented, then this is indicated with n.a. (not available).

Table 3.3 Overview of research work on the impact of coal quality on NO_x emissions

Source	Equipment	Coal range	No. of coals	Combustion mode	Dominant coal parameters	Equation
Chen et al. (1982)	21 kW_{th} tunnel furn.	lig. - ant.	50	premixed	N▲ char N▼	see ref.
				staged	char N▲	see ref.
Phelan et al. (1983)	IFRF furnace no.1	HVB - LVB	7	unstaged	volatile N▲ (volatile-N*O▲)	n.a.
Pohl et al. (1983)	Bench scale	lig. – bitum.	25	swirl unstaged	N▲ VM▲ FC▼	3.27
				swirl staged	N▲ VM▼ FC▲	3.28
Nakazawa et al. (1984)	T-fired 500 MW_e	bituminous	9	SGR burner (**figure 3.11**) OFA (20%)	N▲ FR▲	3.29
Kremer et al. (1986)	Electr. heated furn. (feed rate 2 kg/hr)	lig. - ant.	5	unstaged	N▲ VM▲	n.a.
				staged	char-N▲	n.a.
Nakata et al. (1987)	Cyl. test furnace (feed rate 100 kg/hr)	bituminous	23	HTNR burner (**figure 3.11**)	FR▲ N▲	3.32
			5	SGR burner (**figure 3.11**)	FR▲ N▲	3.33
Okazaki et al. (1988)	Cyl. furnace (feed rate 3 kg/hr)	bituminous	3	unstaged ($0.6 < \lambda < 1.4$)	VM▲ ($\lambda > 1$) VM▼ ($\lambda < 1$)	n.a.
Morgan (1990)	Pilot 2.5 MW_{th}	lig. – LVB	5	swirl (EASB) unstaged	HTVM▲	n.a.
				swirl (EASB) staged	no coal effect	n.a.
			4	swirl (AASB) unstaged	HTVM▲	n.a.
				swirl (AASB) staged	no coal effect	n.a.

Table 3.3 Overview of research work on the impact of coal quality on NO_x emissions (continued)

Source	Equipment	Coal range	No. of coals	Combustion mode	Dominant coal parameters	Equation
Grigoleit et al. (1992)	Electr. furn. (2 kg/hr)	HVB - ant	19	unstaged	N▲ VM▲	see ref.
Man et al. (1993) Gibbins et al. (1994)	Test rig+full-scale	bituminous	6	low NO_x burner staged	char N▲	n.a.
NN (1994)	Opp. wall-fired 1000 MW_e	bituminous	7	HTNR burner + OFA	FR▲ N▲	see **figure 3.13**
Gibb et al. (1994)	1 MW_e test facility	bituminous	7	low NO_x *burner* unstaged	FR*N▲	n.a.
				low NO_x burner staged	FR*N▲	n.a.
Jones et al. (1995)	(see Gibb et al. 1994)	bituminous	8	see (Gibb et al., 1994)	char N▲	n.a.
Kambara et al. (1993, 1995)	turb. flow furnace (7 kg/hr)	lig. – semi-ant.	20	unstaged and staged	N-functionality	3.35
Hesselman (1997a)	160 kW_{th} test facility	bitum. - petcoke	11	low NO_x axial swirl burner	N▲ FR▲	see ref.
Schlessing et al. (1997)	T-fired	bituminous	?	low NO_x burners	VM▼	see ref.
Knudsen (1998)	T-fired 400 MW_e	bituminous	3	swirl burner	volatile N ▲ char N ▼	see ref.
	Opp. wall-fired 350 MW_e	bituminous	3	swirl burner	volatile N▲	see ref.
O'Connor et al. (1998)	Wall-fired 500 MW_e	bituminous	4	low NO_x swirl burner	char N▲	**figure 3.15**

The majority of the NO_x relations published in literature contain coal characteristics measured with the proximate and ultimate analyses, such as the volatile matter, fuel ratio and nitrogen content. A general rule of thumb is that high-volatile coals produce higher NO_x emissions under unstaged combustion conditions and lower NO_x emissions under staged combustion conditions compared to low-volatile coals. Higher nitrogen contents of the fuel are often associated with higher NO_x emissions. In the following section a number of these straightforward relations will be discussed.

Table 3.3 also shows that in a number of cases NO_x emissions are correlated with non-standard coal characteristics as the volatile matter content measured at higher temperatures (HTVM) or the nitrogen content in the char. Especially under staged conditions (in-furnace staged, burner air staged or both) char nitrogen may provide a better estimation. This will be discussed in section 3.6.4.3. Kambara et al. (1995) related NO_x emissions with the nitrogen functionality of the coal. This will be discussed in section 3.6.4.4.

3.6.4.2 NO_x correlations based on proximate and ultimate analysis data

Pohl et al. (1983) developed empirical correlations for predicting NO_x emissions on basis of coal properties. The experiments showed that both in staged and in unstaged flames, the NO_x emissions correlated with the nitrogen content, the volatile matter content and the fixed carbon content of coal. The relations are formulated as follows:

Radial diffusion flames (unstaged)

$$NO = 340 + 835 \cdot \left(\frac{N_{0,daf}}{1.5}\right) + 20 \cdot \left(\frac{VM_{daf}}{40}\right) \cdot \left(\frac{NO_{fuel,max}}{3200}\right) - 395 \cdot \left(\frac{FC_{daf}}{60}\right) \cdot \left(\frac{NO_{fuel,max}}{3200}\right) \qquad (3.27)$$

Staged flames

$$NO = 150 + 80 \cdot \left(\frac{N_{0,daf}}{1.5}\right) - 30 \cdot \left(\frac{VM_{daf}}{40}\right) \cdot \left(\frac{NO_{fuel,max}}{3200}\right) + 100 \cdot \left(\frac{FC_{daf}}{60}\right) \cdot \left(\frac{NO_{fuel,max}}{3200}\right) \qquad (3.28)$$

with:	NO	NO emission (ppm, dry, 0% O_2)
	$N_{0,daf}$	nitrogen content of coal (daf)
	VM_{daf}	volatile matter (wt.-%, daf)
	FC_{daf}	fixed carbon (wt.-%, daf)
	$NO_{fuel,max}$	maximum NO concentration from the nitrogen in coal (ppm, dry, 0% O_2)

Fuel nitrogen forms the major contribution to the overall NO_x emissions. Regarding the volatile matter of the coal it was concluded that in unstaged flames an increase in volatile matter content resulted in an increase of the NO_x emissions, whereas in staged flames an increase in volatile matter corresponds to lower NO_x emissions.

Experience with the Japanese Matsushima power station boilers burning a large number of world-traded and domestic coals showed that the NO_x emissions depend on the fuel ratio and the nitrogen content of coal (Nakazawa et al., 1982). The Matsushima power station consists of two tangential-fired boilers (design of Mitsubishi/Sulzer/CE, 500 MW$_e$ each) equipped with SGR burners (see **figure 3.12**) and overfire air ports supplying 30% of the total combustion air. The NO$_x$ prediction is:

$$NO_x = 100 \cdot (N_{db} - N_0) + A \cdot (FR - FR_0) + NO_{x_0} \tag{3.29}$$

with:
NO_x NO$_x$ emission (ppm, as measured)
N_{db} nitrogen content of coal (db)
N_0 nitrogen content of design coal (db) (from the paper it is derived that N_0 is 0.8)
FR fuel ratio of the coal
FR_0 fuel ratio of the design coal (from the paper it is derived that FR_0 is 2.0)
NO_{x0} NO$_x$ emission of the design coal (ppm)
A = 50 for $FR \geq 1.6$
= 80 for $FR < 1.6$

NO$_x$ emissions increase with an increase of the nitrogen content and an increase of fuel ratio, as is shown in **figure 3.11**. It is assumed that the NO$_x$ emissions from the design coal are 250 ppm.

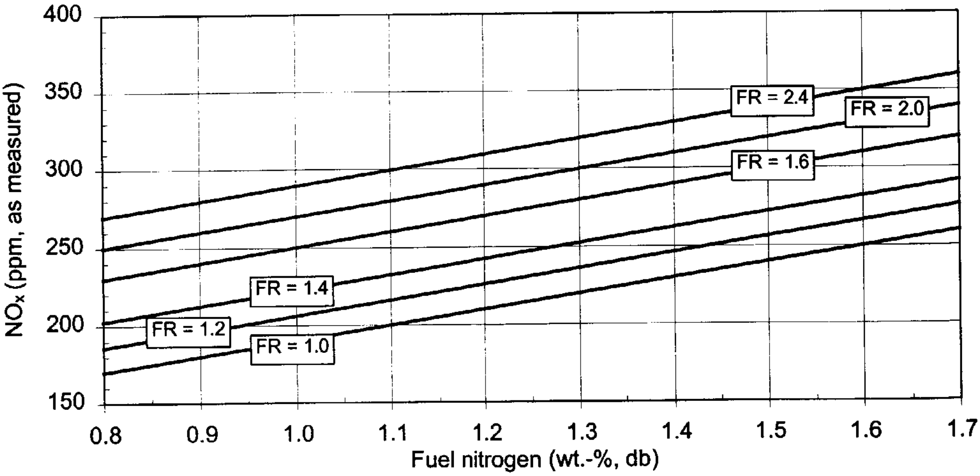


Figure 3.11 Prediction of NO$_x$ emissions as function of nitrogen content and fuel ratio for a 500 MW$_e$ tangential-fired boiler equipped with SGR burners (Nakazawa et al., 1982)

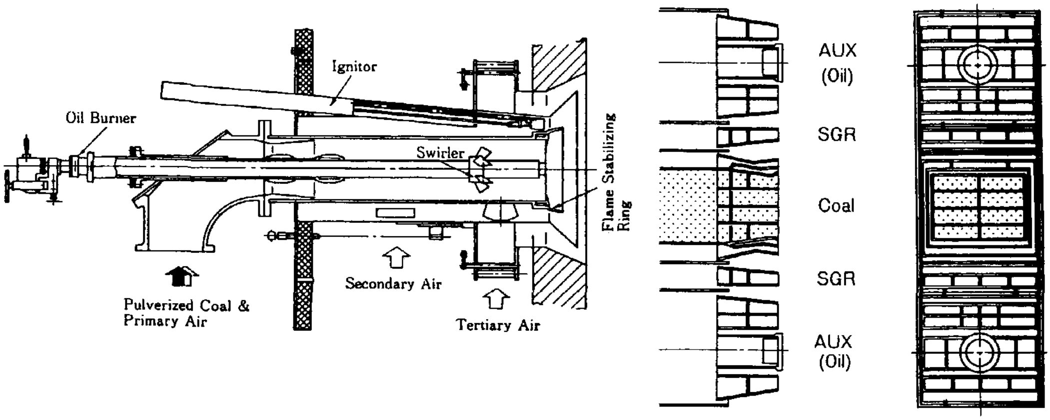


Figure 3.12 Burners used in study of Nakata et al. (1987) (left side: HTNR burner; right side: SGR burner)

The impact of coal properties on NO_x emissions and unburned carbon content was investigated by Nakata et al. (1987). Twenty-eight bituminous coal types, ranging in volatile matter from 24.6 to 48.3 wt.-%, were investigated in a test furnace (coal feed rate is 100 kg/h). Two burners, a swirl burner (23 coals) *and a parallel flow burner (5 coals) (shown in* ***figure 3.12****) were investigated under unstaged* operating conditions. The swirl burner is comparable to the HTNR burner of Babcock Hitachi (Japan) and the parallel flow burner is comparable to the SGR burner of Mitsubishi Heavy Industries. For both burners an empirical formula was derived by means of linear regression analysis. The conversion ratio of fuel nitrogen to NO_x for the swirl burner is expressed as:

$$CR_{fuelN} = 10.94 \cdot \frac{FR}{N_{ar}} + 6.77 \tag{3.30}$$

The conversion ratio for the parallel flow burner can be expressed as:

$$CR_{fuelN} = 4.89 \cdot \frac{FR}{N_{ar}} + 4.57 \tag{3.31}$$

with: FR fuel ratio

N_{ar} nitrogen content in coal (wt.-%, ar)

The NO_x emissions (in ppm) are calculated using formula 3.21. Combining these relations yields the following equation for the swirl burner:

$$NO_x = \frac{160}{V_0} \cdot \left(10.94 \cdot FR + 6.77 \cdot N_{ar}\right) \tag{3.32}$$

and for the parallel flow burner:

$$NO_x = \frac{160}{V_0} \cdot \left(4.89 \cdot FR + 4.57 \cdot N_{ar}\right) \tag{3.33}$$

For both burners NO_x emissions are linear dependent on the fuel ratio and the nitrogen content. The swirl burner, however, is more sensitive for variations in fuel ratio and nitrogen content.

Shinchi power station (Japan) consists of two 1000 MW_e boilers. In (NN, 1994) results are presented of one of these units. The boiler is an opposed-wall-fired boiler with 56 HTNR burners (Babcock Hitachi) and 32 after air ports. Results on seven coals are reported. **Figure 3.13** shows the expected (or guaranteed) NO_x emissions as function of the fuel ratio and nitrogen content.

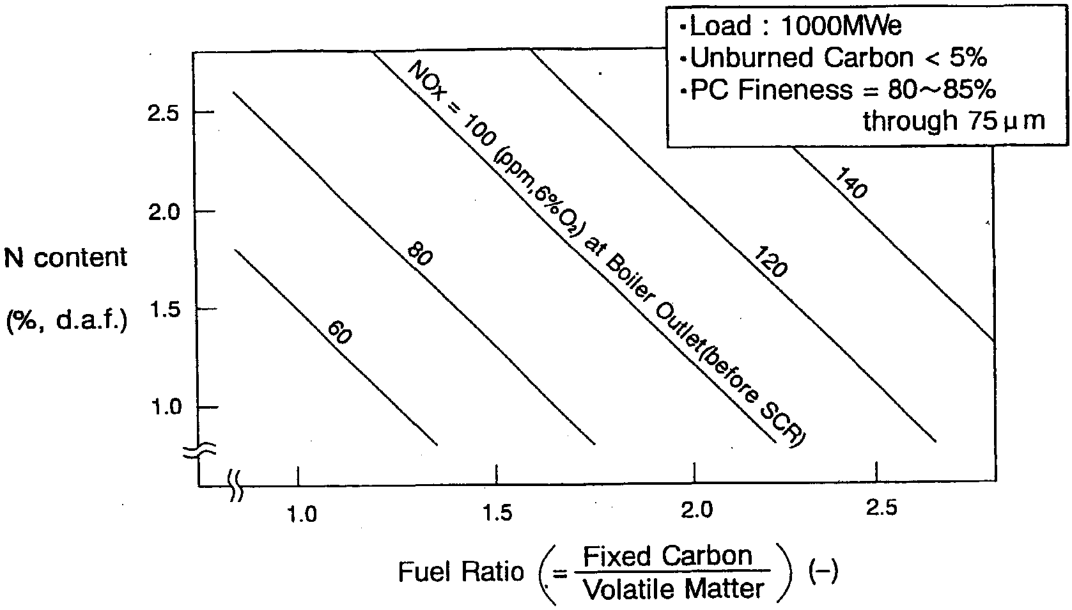


Figure 3.13 NO_x emissions as function of the fuel ratio and nitrogen content for a 1000 MW_e boiler (NN, 1994)

Hesselman (1997a) showed that the NO_x emissions from a 160 kW_{th} test facility with a low NO_x swirl burner correlated under both burner air staged and in-furnace air staged conditions linearly with the fuel ratio. The NO_x emissions were normalised to a standard fuel nitrogen content. In Hesselman (1997b) it was shown that NO_x emissions also correlated with the volatile matter content. Furthermore, it was shown that the NO_x reduction efficiency (burner air staged NO_x emissions versus uncontrolled emissions) correlated to the volatile matter content. The NO_x reduction efficiency obtained by air staging relative to burner air staging (low NO_x burners) was only slightly dependent on coal characteristics.

In this context also a development sponsored by EPRI should be mentioned. A software tool is developed to predict coal quality impact on NO_x emissions and LOI (loss on ignition) (Niksa et al., 1997; Irons, 1997). This model requires only standard coal analysis as inputs (proximate and ultimate analysis and Hardgrove grindability index). This model predicts changes in NO_x emissions and LOI due to switching to an alternate coal. Baseline coal properties and baseline boiler performance data are required as inputs. When the predictions are validated it is required that the baseline and alternate coal are burned at the same operating conditions; such as load, excess air, mills in operation, overfire air ratio, burner tilt and burner damper settings. The heart of the NO_x model, is formed by the FLASHCHAIN model, that calculates volatile gas yield, volatile tar yield, tar nitrogen yield and HCN production based on the proximate and ultimate analyses. The results from the FLASHCHAIN model are then used along with a series of correlations to predict the expected change in NO_x emissions for the alternate coal.

Zelkowski (1999) related the NO_x emissions from a full-scale power station boiler to the ignition characteristics of coals. It was observed that the more heat was liberated in the initial phase of the flame (generally, with higher volatile coals), the lower the NO_x emissions.

3.6.4.3 NO_x correlations based on HTVM and char nitrogen

High temperature volatile matter

Morgan et al. (1989, 1990) investigated the effect of coal quality on NO_x emissions from a 2.5 MW_{th} furnace for seven coals, ranging from lignite to low-volatile bituminous coals. It was observed that NO_x emissions under unstaged combustion conditions could be correlated very well with the HTVM, determined with an isothermal plug flow reactor.

The volatile nitrogen showed a secondary effect. Under staged conditions, it was observed that the highest NO_x reduction (compared to unstaged condition) was achieved with the coals with the highest volatile matter content. The variation in NO_x emissions was, however, under staged conditions much smaller. All coals were tested with the same burner settings (swirl, primary air ratio). The authors suggested that the residence time in the fuel-rich zone was probably too short for the high-volatile coals to have the opportunity for all volatile nitrogen to react to N_2.

Char nitrogen

Char nitrogen is long known to have a major impact on NO_x emissions under staged combustion conditions (Chen et al., 1982). A heated wire grid reactor (HTWM = high temperature wire mesh) was used at the Mechanical Engineering Department, Imperial College (IC) to determine the nitrogen content in char. The chars were produced under conditions simulating the conditions in pulverised coal-fired burners (i.e. high heating rate and temperature (Man et al., 1993; Gibbins et al., 1994; Man et al., 1997; Gibbins et al., 1998). The NO_x emissions from a test rig and a full-scale boiler were correlated with the nitrogen content in the char. **Figure 3.14** shows the correlation of char NO_x (assuming 100 % char nitrogen conversion to NO_x) and the measured NO_x. It is observed that the conversion ratio of char nitrogen is approximately 25%. In a later paper a similar HTWM reactor was used, but other coals and results from a test rig and full-scale plant were used in the correlation (O'Connor et al., 1998). **Figure 3.15** shows the measured NO_x versus the calculated NO_x emissions assuming that the nitrogen content in the char is completely oxidised to NO_x. Again a trend between char NO_x and measured NO_x can be seen. The NO_x emissions are rather high and if the conversion ratio of char is calculated it varies from 40 to 65%. This means that a large fraction of the measured NO_x results from thermal NO_x or volatile nitrogen.

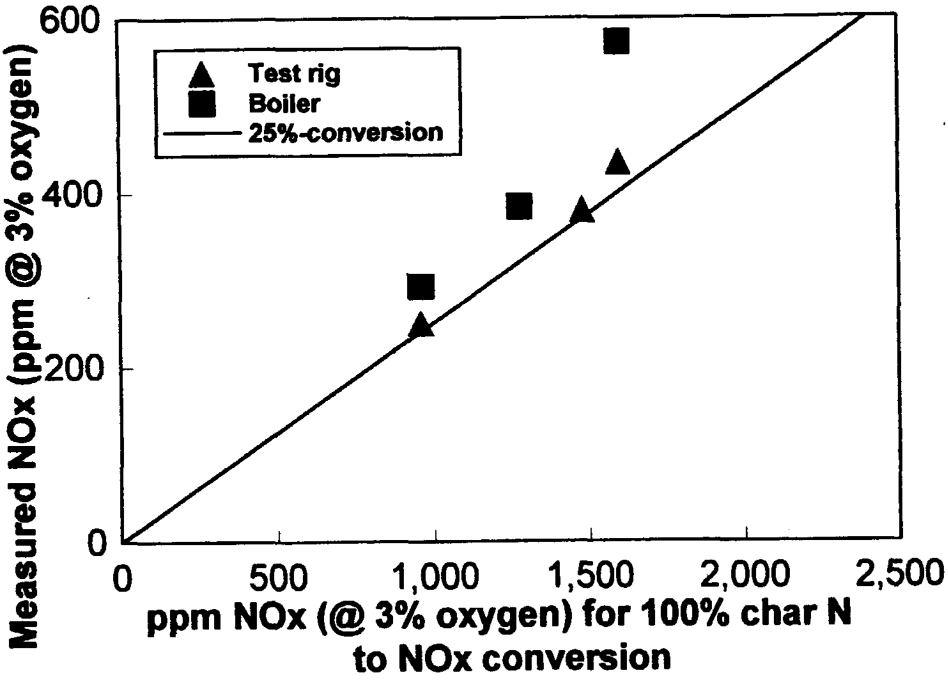


Figure 3.14 Correlation of char NO_x with measured NO_x (Gibbins et al., 1994)

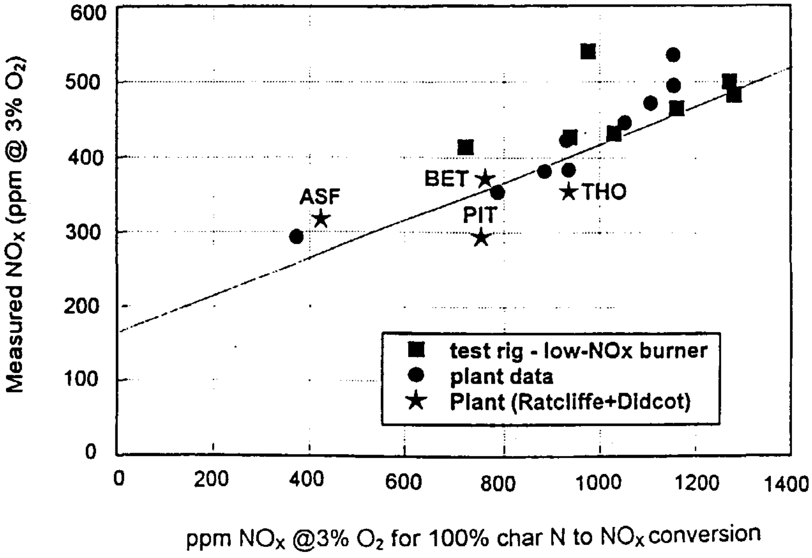


Figure 3.15 Correlation of measured NO_x emissions with calculated NO_x emissions assuming 100% char nitrogen conversion (O'Connor et al., 1998)

3.6.4.4 NO_x correlations based on nitrogen functionality

The nitrogen in coal is contained in the organic fraction. Several types of nitrogen functional forms are identified. X-ray photoelectron spectroscopy (XPS) is believed to be the best technique for determining the nitrogen functional groups (Davidson, 1994). Knowledge about the nitrogen functional forms may help to understand the nitrogen chemistry during coal combustion and may even help predicting NO_x emissions (Nelson et al., 1992; Kambara et al., 1993; 1995; also Yamada et al., 1994). The nitrogen functional forms are sometimes used to obtain a better understanding of the nitrogen release during pyrolysis and char combustion (Hämäläinen et al., 1994; Wójtowicz, et al., 1995). A number of investigations on nitrogen functionality is reviewed by Davidson (1994). Pyrrolic nitrogen seems to be the most abundant nitrogen species in coal followed by pyridinic nitrogen and quaternary nitrogen (or amino groups). In **figure 3.16** some of the possible nitrogen functionalities are shown (Hämäläinen et al., 1994). The investigations summarised by Davidson (1994) show no clear trend between nitrogen functional forms and coal rank.

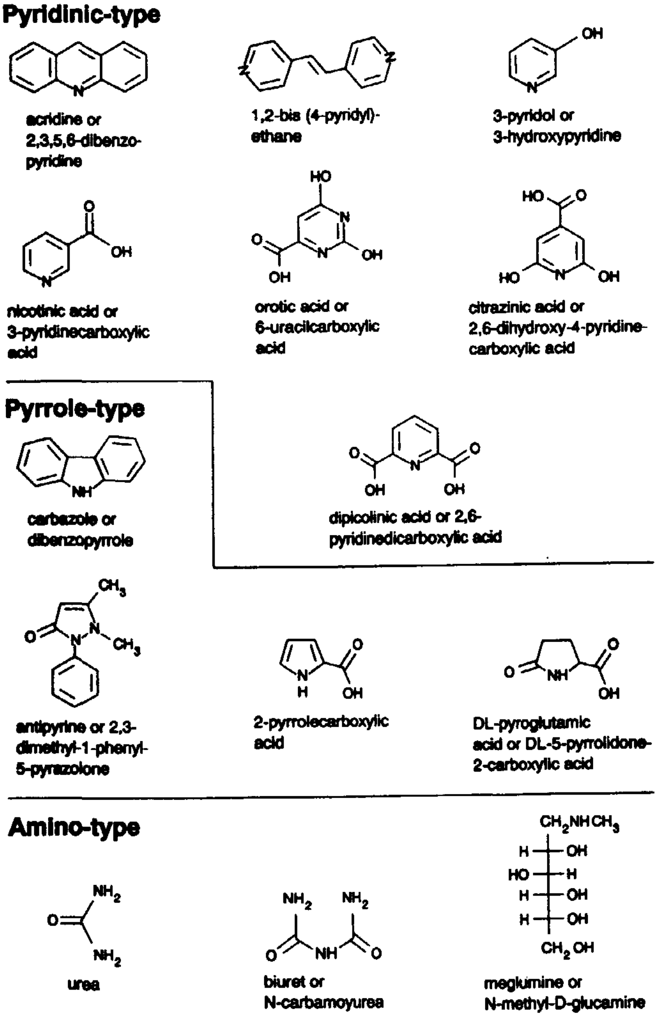


Figure 3.16 Nitrogen functional forms (Hämäläinen et al., 1994)

Kambara and co-workers (Kambara et al., 1993, 1995; Yamada et al., 1994) developed a NO_x prediction index based on the nitrogen functionality in coal. First a relation was developed between the NO_x emissions and the nitrogen containing species released with the volatiles (NH_3 and HCN). Subsequently, these species were correlated with the nitrogen functionality. The NO_x index is calculated as follows:

$$\mathrm{NO_x\ index} = \frac{\left(\mathrm{QN} + \mathrm{PdN} + \frac{\mathrm{PrN}}{\mathrm{C}}\right) \cdot \mathrm{QN}}{\mathrm{PdN} + \frac{\mathrm{PrN}}{\mathrm{C}}} \tag{3.34}$$

with:

QN	quaternary nitrogen (wt.-%, daf)
PdN	pyridinic nitrogen (wt.-%, daf)
PrN	pyrrolic nitrogen (wt.-%, daf)
C	carbon content (wt.-%, daf)

Kambara and co-workers claimed that NO_x emissions could be predicted using this relation without the need of doing pyrolysis experiments. **Figure 3.17** shows the correlation of the NO_x index with the fuel nitrogen conversion of NO_x emissions measured in a turbulent flow furnace for three different runs.

Work by others showed, however, that under severe pyrolysis conditions (present in pulverised coal-fired burners) the nature of the nitrogen in the precursors (NH_3, HCN) is not related to the distribution of nitrogen functional groups either in the coal or in the char (Thomas, 1997). No conclusive evidence exists for a direct link between nitrogen functionality and the formation of NO_x during combustion.

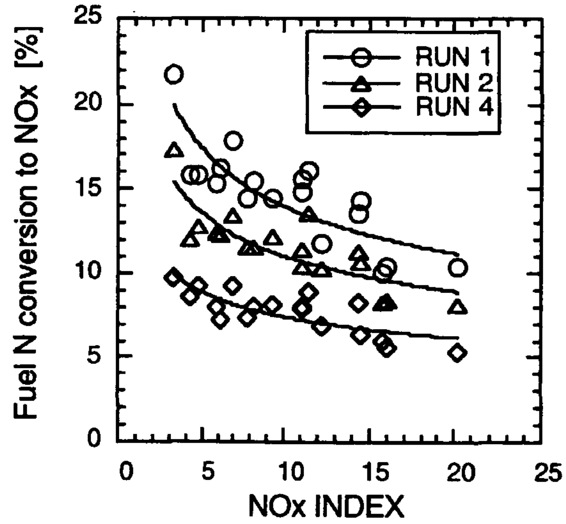


Figure 3.17 NO_x index in relation to the fuel nitrogen conversion to NO_x (Yamada et al., 1994). Run 1 is unstaged, in run 2 and 4 staged conditions are applied

3.7 EFFECT OF COAL QUALITY ON BURNOUT

3.7.1 General

Due to the application of low NO_x burners and air staging the burnout of coal may be reduced. Therefore, in many investigations mentioned above the impact of coal quality on burnout has also been addressed.

The burnout is closely related to the unburned carbon content in fly ash and the ash content in coal (see equation 3.35 and **figure 3.18**).

$$Bu = 100 \cdot \left(1 - \frac{Ash_{db}}{100 - Ash_{db}} \cdot \frac{UBC}{100 - UBC}\right) \tag{3.35}$$

with: Ash_{db} ash content in coal on a dry basis (wt.-%)
Bu burnout (wt.-%)
UBC unburned carbon in the fly ash (wt.-%)

Burnout is affected by several factors:

- particle size
- macerals
- coal rank
- reactivity
- combustion conditions (excess air, temperature)
- residence time
- minerals
- char morphology
- swelling behaviour.

Char combustion is by far the slowest step in coal particle combustion and requires enough residence time at sufficiently high temperatures for complete burnout. It is a well-known fact that higher volatile coals generally burn faster and easier compared to lower volatile coals.

Particle size is known to affect burnout, particularly when the pulverised coal contains significant amounts of particles > 150 μm or > 200 μm (Reuther et al., 1995; Chow et al., 1996). Particles are classified in the pulveriser by a static or by a dynamic rotating classifier. Depending on the terminal velocity particles are separated and returned to the milling section or they pass the classifier and are transported to the burners. The terminal velocity is related to the size of the particle as well as to the density. In that sense the mineral matter distribution also plays an important role in case the mineral matter is not evenly distributed over the particles. Depending on how the minerals are distributed within the coal (matrix) larger mineral-matter-free particles may pass the classifier without being separated and returned to the grinding zone.

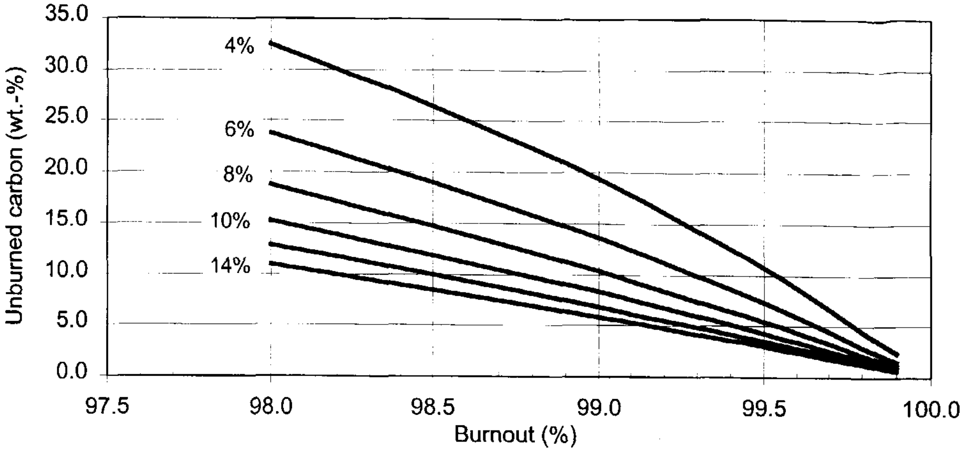


Figure 3.18 Relation between burnout and unburned carbon content as function of the ash content (wt.-%, db)

Wigley et al. (1997) reviewed the impact of the distribution of mineral matter in pulverised coal particles on char combustion. Two mechanisms are described by which included minerals may reduce char reactivity and hence reduce burnout:

- Coal particles containing included mineral matter will have a greater specific heat capacity than particles consisting of organic material alone. Mixed particles would therefore be expected to heat up and combust more slowly.
- Included minerals may fuse and coat the surface of burning char particles, reducing the rate of char combustion.

Wigley et al. (1997) also postulated a number of mechanisms by which included minerals have a positive effect on char combustion:

- Included mineral matter may catalyse char combustion (also suggested by Milligan (1997)).
- The difference in thermal expansion between included minerals and their organic matrix may cause stress concentrations, leading to increased char fragmentation during pyrolysis. The resulting decrease in char particle size may lead to more complete combustion.
- The presence of included mineral matter could alter the size distribution of pulverised coal particles leaving the mill classifier and entering the boiler. Mineral inclusions will increase the average density of a coal particle. Classification of pulverised coal particles is based on the size and density of the particles. Denser coal particles due to the presence of inorganic material would be expected to be smaller. Very large particles are often purely organic.

Pulverised coal samples of eighteen world-traded coals were analysed using Computer Controlled Scanning Electron Microscopy (CCSEM) to determine the distribution of mineral matter in pulverised coal particles. Particles were classified in organic-rich particles, organic particles with included minerals and excluded mineral particles. Organic-rich particles were the most abundant. It was observed that the excluded mineral particles had a considerably finer size distribution than the other particles. Australian and South African coals showed higher levels of mineral-organic association than British and North American coals. Fourteen of these coals were burned in the PowerGen Combustion test facility and the burnout was compared to the weight fraction of organic-rich particles, organic particles with included minerals and excluded mineral particles. No evidence was found that supported one of the postulated mechanisms.

The impact of the reactivity of the individual maceral groups on burnout has been studied by Cloke et al. (1997). They suggested that coal burnout can be predicted using a rapid and objective image analysis technique which measures the reflectance of the whole coal sample. They correlated the combustibles remaining (100% - burnout) of sixteen coals burned in a 1 MW combustion test facility of PowerGen's Power Technology Centre with various parameters including the fuel ratio. The fuel ratio correlated with the combustibles remaining with an R^2 value of 0.470 (two coals were excluded). However, they showed that if the combustibles remaining were correlated with a parameter based on the reflectance of the macerals the R^2 value was 0.801 (also without the two outliers). Incorporation of these outliers in the regression analysis resulted in a R^2 value of 0.211. The impact of char morphology on burnout was also related to burnout behaviour. It was observed that thick-walled chars corresponded to a poor burnout. Also others tried to relate char morphology to burnout (Rosenberg et al., 1996; Alvarez et al., 1997). The reactivity of single macerals was investigated by Crelling et al. (1992) to obtain a better understanding on the impact of coal quality on burnout. Milligan et al. (1997) concluded, however, that the reactivity of a coal could not be predicted from the reactivities of its maceral components, due to interaction effects of the macerals.

The free swelling index is used to indicate the agglomerating characteristics of a coal when heated (Skorupska, 1993). A high swelling number suggests that the coal particle may expand to form lightweight porous particles that are entrained in the flue gas flow and contribute to a high carbon content in the fly ash. Recent experiments on coal devolatilisation showed, however, that the swelling behaviour during coal devolatilisation at heating rates higher than 10^4 °C/s, typical for commercial furnaces, was shown to decrease significantly (Smoot, 1997).

Since the prediction of burnout based on simple coal characteristics is not always satisfactorily, more advanced test procedures have been developed to give a better insight in the burnout behaviour of coals (Skorupska, 1993). For instance, thermal gravimetric analysis and drop tube furnaces are used to obtain information on the burnout behaviour of a coal. Information collected from these types of apparatus are used for developing char oxidation models based on reactivity parameters (Smoot, 1997). In a recent overview by Smoot (1997) it was stated that generalised char reaction models have been developed, but the relationship between devolatilisation conditions and char reactivity is still not well understood. Predictive models are mostly based on a reactivity of coal or char that is assumed to be constant over the time that the particles are completely burned out. Those models often overpredict the burnout since the reactivity of the char deteriorates with increasing burnout rates. Models are now being developed which accounts for the deactivation of char as function of the temperature history (Hurt et al., 1998). Walsh et al. (1994) described a model for char combustion in a boiler furnace, using a single char reactivity. The model accounts for the volatile matter content, the volumetric heat release of the furnace, particle fineness and excess air. Experiments showed that primarily volatile matter and particle fineness determined the burnout at approximately constant load and excess air. It was concluded that the calculation might be improved by including a char reactivity distribution.

In the next section a number of burnout correlations with coal characteristics found in literature is discussed. More complex models based on char reactivity are not considered.

3.7.2 Burnout predictions based on proximate and ultimate analysis data

A linear relationship between fuel ratio and burnout has been developed by Nakata et al. (1987) for two burner types: a swirl burner and a jet burner (see **figure 3.11**). The relationship for the swirl burner was formulated as:

$$\mathrm{Bu} = 99.998 - 0.25 \cdot \mathrm{FR} \qquad (3.36)$$

and for the jet burner as:

$$\mathrm{Bu} = 97.71 - 2.95 \cdot \mathrm{FR} \qquad (3.37)$$

The unburned carbon in fly ash can be calculated as follows (comparable to equation 3.35):

$$\mathrm{UBC} = \frac{(100 - \mathrm{Bu}) \cdot (100 - \mathrm{Ash}_{db})}{(100 - \mathrm{Bu}) \cdot (100 - \mathrm{Ash}_{db}) + 100 \cdot \mathrm{Ash}_{db}} \cdot 100 \qquad (3.38$$

with: Bu burnout (wt.-%)
UBC unburned carbon in the fly ash (wt-%)
Ash_{db} ash content in coal on a dry basis (wt-%, db)

From these formulas it is clear that the jet burner results in a higher unburned carbon content and is also more sensitive to fuel ratio than the swirl burner.

From the experiences of the Matsushima power station two equations were derived that describe the impact of coal quality and to a minor extent the effect of operating conditions on the unburned carbon content in the fly ash (Nakazawa et al., 1982):

$$\mathrm{UBC} = 0.7 \cdot \frac{\mathrm{FC}}{\mathrm{CF} \cdot \mathrm{Ash}} \qquad (3.39)$$

and

$$\mathrm{UBC} = 10 \cdot \frac{(\mathrm{FR})^2}{\mathrm{Ash}} \qquad (3.40)$$

with: FC fixed carbon (wt-%)
Ash ash content of coal (wt-%) (not clear on what basis, probably db)
CF combustibility factor
FR fuel ratio.

The combustibility factor is defined as:

$$CF = \frac{HHV}{FR} \cdot \frac{(115 - Ash)}{1540} \tag{3.41}$$

with: HHV higher heating value (dry, MJ/kg).

The factors 0.7 *and* 10 *in equations* 3.39 *and* 3.40 *are a* function of the amount of overfire air (the particle size is as 95-97% smaller than 150 μm). With an OFA ratio of 20% equation 3.39 should be used and with an OFA ratio of 25% equation 3.40.

Schlessing (1997) developed an empirical relation to predict the impact of coal quality on the unburned carbon content in the fly ash. For the Mannheim power plant the unburned carbon content of a coal depends on the reciprocal of ash content times the square of volatile matter content. Higher volatile coals and coals with a higher ash content result in lower unburned carbon contents in the fly ash. This is in agreement with general experiences.

Hesselman (1997a) related the unburned loss of a 160 kW_{th} test facility equipped with a low NO_x *burner with the fuel ratio for* 9 *coals fired* under furnace-air staged and unstaged conditions. In both situations a general trend was observed, an increase of the unburned loss with an increase in fuel ratio.

3.8 DISCUSSION

NO_x emissions from pulverised coal-fired boilers are affected by boiler and burner design, boiler and burner operation and coal characteristics. A lot of research has already been performed to identify the nitrogen chemistry during combustion with respect to the above-mentioned factors. Unfortunately, still no universally valid model is available that accounts for all effects and is capable of predicting NO_x emissions accurately. Furthermore, the mathematical models that are under development are comprehensive, based on mixing rates and chemical reactions (chemical reaction engineering models) or based on computational fluid dynamics (CFD) and cannot be used reliably by non-experts (Lans et al., 1997).

Focussing on *coal characteristics it can be concluded* that high-volatile coals generally result in higher NO_x emissions in unstaged combustion processes, whereas under staged conditions the opposite is true. These rules are generally valid for tangential-fired boilers as well as for (opposed) wall-fired boilers. An increase in nitrogen content generally results in higher NO_x emissions for both unstaged and staged processes.

Although boiler specific prediction formulas based on standard coal characteristics have been developed, it is generally believed that more advanced coal characteristics should be used to obtain more accurate predictions. The main objection towards using standard coal characteristics is that they are obtained under conditions that are not in agreement with the practical conditions. NO_x emissions from low NO_x boilers in particular originate mainly from the nitrogen retained in the char. The volatile *matter* and nitrogen content in coal, although closely related to the nitrogen content in the char, may fail in predicting the nitrogen content in the char for two reasons. First, the proximate volatile matter is substantially lower than the volatile yield released at higher temperatures and heating rates in actual boilers, as is explained in chapter 2. Furthermore, the ratio of actual volatile yield to the proximate volatile yield is not a constant value, but may vary depending on coal characteristics. Secondly, during pyrolysis only part of the coal-bound nitrogen is released with the volatiles. The partitioning of nitrogen into char and volatile nitrogen is related to the volatile release. Generally, if more volatiles are released also more fuel nitrogen is released with the volatiles, but, as with the volatile yield, the ratio of nitrogen release to the volatile release is dependent on coal characteristics. The extent of nitrogen release may be different from one coal to the other, which could be caused by differences in the functionality of nitrogen in the coals.

No standardised equipment or validated method is currently available to determine the nitrogen content in the char. The char nitrogen content in world-traded coals is, therefore, generally not available. Coal purchasers have to base their decision on other information such as experiences gained in the past with that particular or a similar coal. Another possibility is to perform a test burn with that specific coal in a pilot-scale furnace, but test burns are expensive and extrapolation of pilot-scale results to full-scale practice is difficult. To address the suitability of a specific coal, predictions, based on coal characteristics determined with the standard analyses, is still the only tool available. With the use of such predictions it has to be kept in mind that these predictions may be valid for the boiler considered, but that extrapolation to other boilers should be applied with caution.

The burnout of coal is governed by the oxidation of char. In a recent overview of combustion research by Smoot (1997) it was shown that a lot of research has been carried out to model carbon burnout. Smoot suggested that models based on single char reactivity overestimate the burnout, since the char reactivity declines with progressing burnout. Models are under development that take into account changes in reactivity as function of burnout and coal type. In this chapter the impact of coal quality on burnout has only been briefly discussed. Correlating burnout data with coal characteristics has shown that, generally, burnout is related to the volatile matter content or fuel ratio.

3.9 CONSEQUENCES

At present, no universal model is available for predicting NO_x emissions from pulverised coal-fired boilers as a function of the boiler and burner design and operation and coal characteristics. General trends have been identified on the impact of coal quality and burner parameters on NO_x emissions, but generalisation of results is difficult because of related and compensating effects (Lans et al., 1997). A limited amount of full-scale experiences is publicly available on predictions of NO_x emissions based on coal characteristics determined with the proximate and ultimate analysis. At present research activities are employed to obtain data on the char nitrogen content under conditions simulating the conditions prevailing in a full-scale boiler, since the nitrogen in the char forms the major and in low NO_x boilers possibly the only contribution to overall NO_x emissions.

Consequently, it can be concluded that full-scale tests are required under well-defined and constant conditions with a large number of coals to obtain NO_x emissions that can be related to coal characteristics. Results of full-scale test trials and the models developed for two coal-fired units in the Netherlands are presented in chapter 7. The models are based on the coal characteristics measured with the proximate and ultimate analysis. Subsequently, more advanced coal characteristics are correlated with the NO_x emissions in chapters 8 and 9.

Chapter 4 EXPERIENCES WITH COAL BLENDING

4.1 INTRODUCTION

The Netherlands have no economically recoverable coal deposits, and rely therefore completely on imported world-traded coals. In 1992 a central blending facility was commissioned in the harbour of Rotterdam to blend the imported coals for the majority of the Dutch coal-fired power plants. Only Borssele and Hemweg power plant are supplied with coals in an alternative way. Borssele power plant receives coals in a harbour nearby the power plant and, since the plant itself is not equipped with a blending installation, burns the coals unblended. A stevedore in the harbour of Amsterdam receives the coals for the Hemweg power plant (occasionally also for the Gelderland power plant). Coals can be blended by the stevedore or with the blending facility on the site of Hemweg power plant.

The main objectives for the power plant in the Netherlands to blend coals are:

- to minimise fuel costs by blending cheaper coals
- to enhance fuel flexibility and to extend the range of acceptable coals
- to diversify coal supplies for reasons of security.

Also in countries with power plants burning indigenous coals, coal blending is becoming increasingly common (Carpenter, 1995). But they might have other motives then noted above to blend coals, including:

- to meet emission regulations (for instance, blending low- and high-sulphur coals)
- to improve boiler performance
- to provide a fuel of a more consistent quality.

It should be noted that coal suppliers or producers blend coals, for instance, to meet the specification requirements of the customer or to reduce the quality variations of a coal. In fact, a 'single' coal delivered to international customers is often a blend of coals from different seams or different mines.

Due to differences in geological background, the quality of coals may vary significantly. Boilers are often designed to burn a specific coal or range of coals. Many of the world-traded coals do not (exactly) meet the desired properties. This implies that only a limited number of coals are qualified, which eventually could lead to increasing prices. Coal blending is therefore a valuable instrument for extending the range of suitable coals and reducing costs. Off-design low quality coals (including, for instance, rejects from coal cleaning plants) can be used in blends together with higher quality coals without adversely affecting plant performance. The number of different coals burned in the Dutch power stations amounted to nearly thirty in 1993 and more than forty in 1998. The increasing number of coals reflects the move from long-term coal contracts towards more spot market acquisitions with the main objective to reduce fuel costs.

Blending of coals is achieved with stockpiles, bins and/or conveyors (Carpenter, 1995). In stockpiles coals are systematically stacked in different layers and during reclamation of the coal pile the actual blending takes place. Various blending schemes for stockpile blending exist, such as the Chevron method (see, for instance, Carpenter, 1995 and STEAG, 1988). In bins, coals are being added in the required proportions. Coals are discharged from the bottom of the bin. At the EMO coal terminal in the harbour of Rotterdam coals are being stored in six bins. The coals are then blended by discharging them simultaneously, in required amounts, from the bottom of (some of) the bins onto a conveyor belt. Generally, instead of using bins, coals can also be stored on a stockyard and subsequently be discharged onto the belt. A less elegant way of blending coals is mixing the coals 'manually' with shovels.

Although blending of coals is already a common practice in the Netherlands and is also becoming a common practice in other countries, knowledge about the effect of blending on combustion performance is still limited. In general, coal blends are composed meeting the specification requirements, which are based on design (and guarantee) specifications and operational experiences. However, the blending of coals may result in undesirable operational problems if the blend does not burn as expected or predicted from the parent coals. The combustion behaviour can seriously deviate from the behaviour of the parent coals, due to interactions in the blend. In other words, the coal properties and combustion behaviour of the parent coals are not (always) additive. Furthermore, the prediction of the performance of a single coal on basis of traditional analyses as proximate, ultimate and ash analysis is not always conclusive. Consequently, due to (unknown) interactions during blend combustion, the assessment of the combustion behaviour of a blend is inherently complex.

This chapter reviews the experiences with coal blending and on basis of these experiences the additivity of coal properties and combustion behaviour is addressed.

4.2 MEETING SPECIFICATION REQUIREMENTS BY COAL BLENDING

Blending of coals is primarily the mixing of two or more single coals to compose a homogeneous mixture, with the aim to satisfy certain quality requirements, imposed by the design and condition of the boiler. The blend should be homogeneous to avoid unacceptable short-term fluctuations in the quality of the feedstock, since otherwise flame stability problems may arise.

Table 4.1 lists, the fuel quality requirements for the units of Maasvlakte power plant. The last column of the table addresses possible problems, which may occur burning a fuel (coal or blend) that does not meet the specification requirements.

Table 4.1 Specification requirements of the Maasvlakte units

Coal parameter	Specification	Area of concern
Size of the raw coal	≤ 50 mm	Pulveriser performance, capacity
Lower heating value	≥ 23 MJ/kg	Capacity, ignition
Volatile matter	20-30%	Ignition, flame stability, burnout
Sulphur content	0.3-1.5%	Emissions, corrosion, slagging, electrostatic precipitators
Ash content	≤ 12%	Pulveriser capacity, wear, erosion, electrostatic precipitators
Moisture content	6-12%	Pulveriser capacity, fan capacity, flame stability
Hardgrove grindability	45-55	Pulveriser performance, burnout

The list of possible problems is far from complete. In general, burning coals or blends outside the design specifications may lead to unscheduled outages, increase of maintenance costs, derating of the unit and a lower efficiency.

Some blend specifications can be calculated straightforward from the specifications of the parent coals. If q represents the number of constituents in the blend and the proportion of the ith constituent in the blend is represented by x_i then

$$x_i \geq 0, \qquad 1 = 1,2,....q$$
$$\sum_{i=1}^{q} x_i = x_1 + x_2 + ... + x_q = 1 \tag{4.1}$$

Assuming that a property (P) of a blend can be calculated as the weighted average of the properties of the constituents then

$$P_{blend} = \sum_{i=1}^{q} (x_i P_i) \tag{4.2}$$

This equation is generally valid for any given property, based on the elemental analysis of the coals (exceptions are discussed in the next sections).

It should be noted that the basis on which a coal parameter is expressed is important. Usually, coals are blended in specific ratios based on the weight of the raw coals. The properties in equation 4.2 should therefore be expressed on an as received basis (ar), otherwise, especially when coals with high ash or moisture content are considered, erroneous results are obtained.

Blending of different coals results in a change of the:

- Chemical composition
- Mechanical and physical properties
- Combustion characteristics.

The chemical composition and the physical and mechanical properties of coal affect the combustion characteristics of coal. The next sections deal with the question whether the behaviour of a blend is similar to the "average behaviour" of the parent coals. Or, in other words, can the performance of a blend be assessed in view of the performance of the parent coals?

4.3 COAL BLENDING AND CHEMICAL COMPOSITION

Generally, the chemical composition of coal is determined with the ultimate analysis (discussed in chapter 2). The ultimate analysis yields an elementary breakdown of coal and is therefore, generally speaking, additive.

In tests performed at the Western Kentucky University with seven coals ranging from lignite to high-volatile bituminous coals (Riley et al., 1989), it was found that the moisture content, calorific value, carbon, hydrogen, nitrogen and sulphur values are additive for coal blends. The analytical values determined for the various coal blends were the same, within experimental error, as those calculated using the weighted averages of the analytical values of the individual coals. The authors stated that these analyses are based on the measurements of elements in the products of complete combustion, or the heat produced during complete combustion and that the analyses are not based on an empirical method (except for the moisture content). The volatile matter and ash content in the blends were not similar to the weighted average (see section 4.4.2).

4.4 COAL BLENDING IN RELATION TO MECHANICAL AND PHYSICAL PROPERTIES

The mechanical and physical properties are often determined by means of empirical procedures developed primarily for the carbonisation industry and not for pulverised coal combustion. With some analyses the coals are exposed to high temperatures and therefore changes in the physical condition may occur, leading to interactions between the coals in the blend. However, this does not necessarily implicate that similar interactions will occur in practical applications, since the test conditions are often not representative for pulverised coal combustion.

4.4.1 Heating value

The heating or calorific value of coal is measured as the heat produced during combustion. The heat liberation during coal combustion is the sum of the heat liberated by the exothermic reactions of the hydrocarbons and sulphur with oxygen and heat consumption of endothermic reactions. The determination of the heating value is measured by complete combustion of the sample. The heating value is therefore additive. This was confirmed by tests with seven coals and 63 binary blends (Riley et al., 1989).

4.4.2 Proximate analysis

The moisture, ash, and volatile matter content (proximate analysis) are determined by empirical methods (see chapter 2). Interactions between the coals in a blend during sample preparation or analysis result in values of the proximate parameters deviating from the weighted average.

Riley et al. (1989) found that blending subbituminous coals with bituminous coals resulted in a higher ash content in the blend than the weighted average . Comparable results were found by Artos et al. (1993). In this study the combustion behaviour of blends of lignite, subbituminous and bituminous coals was investigated using a thermal gravimetric analyser (TGA) and a drop tube furnace (DTF). It was observed that the ash content in the blends of bituminous coals and the lower rank coals (lignite and subbituminous) was somewhat higher than the weighted average value calculated from the ash content in the parent coals. The increase in ash content was due to the retention of sulphur from the bituminous coals by the alkaline minerals in the subbituminous and lignite coals. Artos (1993) found that the sulphur content in the ash of the blend were higher compared to the values predicted from the sulphur content in the ash of the individual coals. Riley et al. (1989) also suggested that sulphur retention by the mineral matter in the subbituminous coals caused the higher ash content in the blend.

Riley et al. (1989) also found that the volatile matter is not always an additive parameter. The volatile matter was determined using the ASTM method D 3175 using a vertical tube furnace and with a LECO MAC-400 analyser. The volatile matter values determined with the ASTM method were generally higher (on average 1.05%-point) than the calculated values and were generally lower (on average 0.26%-point) than determined with the LECO MAC-400 method. An example is shown in **figure 4.1**. The moisture content in the coals shown in this figure is comparable (15 - 17%). An explanation for the differences in volatile matter was not presented, but the study showed that some care is required in using the additivity rule for volatile matter (Carpenter, 1995).

The relevance of the volatile matter content to characterise the combustion behaviour of pulverised coal has been questioned (Carpenter, 1995). As was indicated in **table 4.1** the volatile matter is often associated with ignition, flame stability and burnout, but as pointed out in chapter 2, the volatile matter is measured under conditions that are not comparable to the actual conditions in flames. Consequently, the extrapolation of the possible non-additive behaviour of volatile matter to actual combustion behaviour is difficult or even impossible.

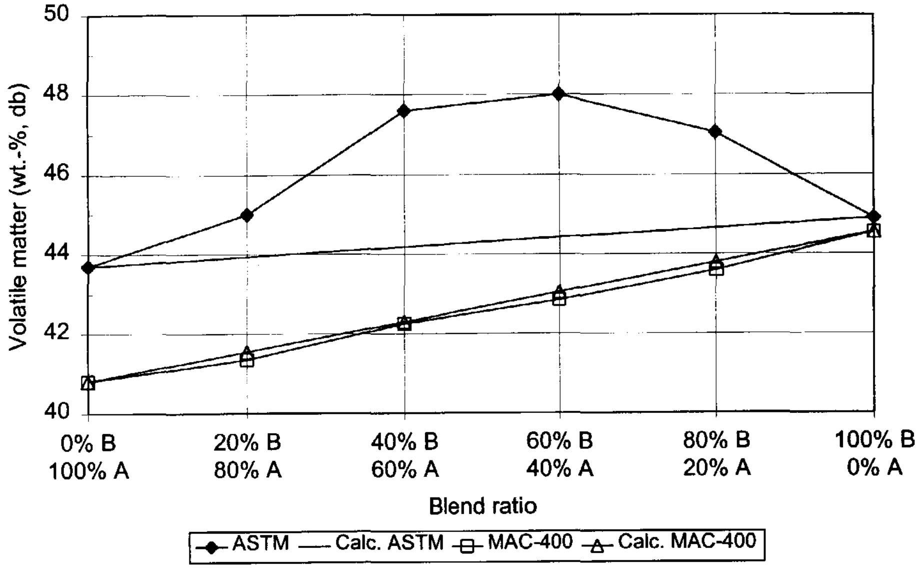


Figure 4.1 Volatile matter content in blends of a subbituminous coal (B) and a lignite (A) (Riley et al., 1989)

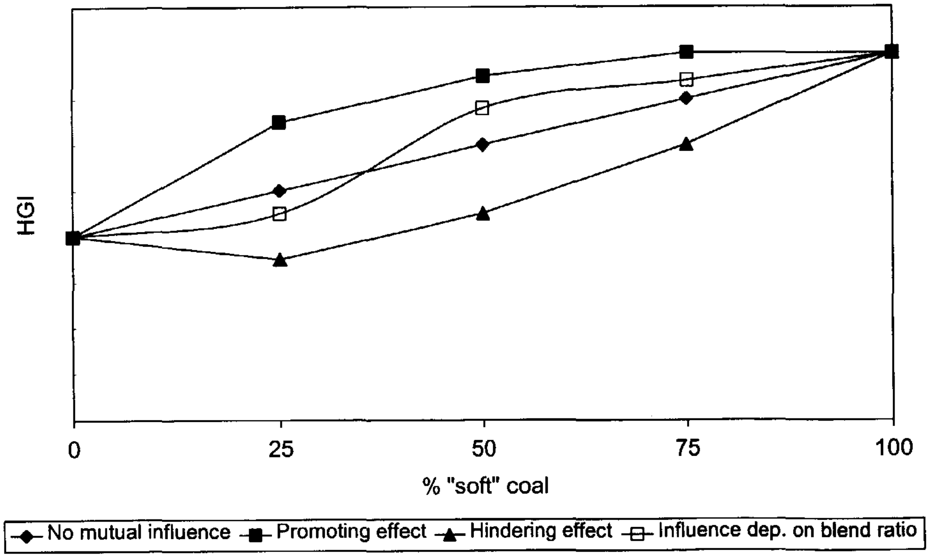


Figure 4.2 Possible effects of blending on HGI (adapted from Beke (1981))

Table 4.2 Influence of various factors on HGI (Zelkowski et al., 1993)

Parameter	Maximum influence on HGI (%)
Coal hardness	51
Total moisture content	40
Particle fineness (100 μm – 2800 μm)	5
Others	4

4.4.3 Grindability

4.4.3.1 Literature review

The Hardgrove grindability index (HGI) is commonly used as a measure for the grindability of coal. A high HGI corresponds to an easy-to-grind or soft coal. The applicability of the HGI test is sometimes discussed (Werner et al., 1997, 1999; Krausz, 1995). For example, only a narrow-sized fraction of coal is used in the test that may not be representative of the size fractions of the pulverised coal in practice. The build-up of fines in the batch-grinding process may cause cushioning resulting in a change of grinding conditions during the test. Test conditions such as moisture content and temperature have strong influences on the measurements, which makes it difficult to correlate results with full-scale operation. **Table 4.2** shows the influence of various factors on HGI (Zelkowski et al., 1993). The total moisture content has apparently a large effect on the determination of HGI. Although others found that moisture content is of minor influence (Tsai, 1982; Unsworth et al., 1991; Falcon et al., 1987). Despite the disadvantages the Hardgrove grindability test is still widely used for predicting changes in the pulveriser throughput when different coals are being evaluated.

Beke (1981) described four possible effects of coal blending on the Hardgrove grindability index, as illustrated in **figure 4.2**. A promoting effect indicates a better grindability of the blend than is expected from the individual coals, whereas a hindering effect indicates a worse grindability than expected. The hindering and promoting effects may also occur in combination depending on the blend ratio.

Tests performed by others showed that for the coals tested and under specific circumstances the Hardgrove grindability index is additive (Arnold et al., 1994; Douglas et al., 1990; Douglas et al., 1994; Hower, 1988; Riley et al., 1989, Livingston et al., 1998; Conroy et al., 1991; Unsworth et al., 1991; Tumati et al., 1993; Zelkowski, 1999).

Riley et al. (1989) found that the HGI of blends from coals of different rank is additive when the HGI of the individual coals did not differ more than 10 units. In addition, Waters (1986) found that the HGI of a blend is additive only if the mass fractions in the test sample are comparable to the mass fractions of the raw coal blend and if there are no large density differences between the components. The particle size of raw coal is smaller than 50 mm. The particle size range of the HGI test sample is 0.6 – 1.18 mm. The raw coal is crushed to obtain the HGI test sample and hence segregation may occur during sample preparation. Some researchers found that the HGI is additive, but that disproportionation occurred during the test (Conroy et al., 1991; Maitra et al., 1983; Douglas et al., 1994; Cho et al., 1995). Larger particle size fractions of the blend contained a disproportionate percentage of the hard coal.

Some studies reported that the HGI is not additive for blends containing coals with very different HGI values (Waters, 1986; Riley et al., 1989). Measurements on four coals by Monroe (Monroe et al., 1997a) showed that, the HGI of a blend is somewhat lower than the weighted average. In one case (CR-JW blend; **figure 4.3**) the tested blend consisted of coals of two different ranks (CR is a sub-bituminous coal from the Powder River Basin; JW is a bituminous coal). A vitrinite reflectivity analysis of sieved fractions of the other blend showed that the softer coal dominated the smaller size fractions and the harder coal the larger size fractions.

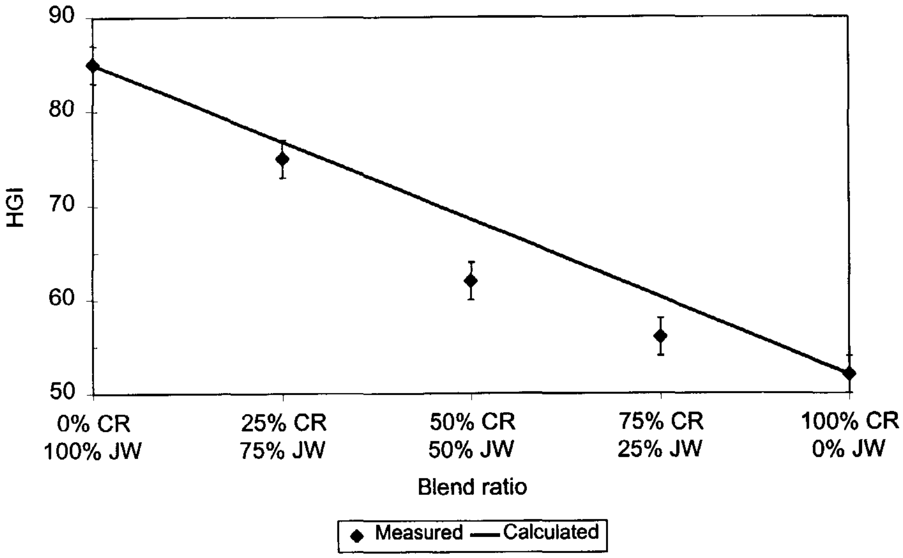


Figure 4.3 Additivity of HGI for two coals and a number of blends (Monroe et al., 1997a)

4.4.3.2 Dutch experiences with the additivity of HGI

In chapter 10 the impact of coal blending on NO_x emissions and burnout is discussed on basis of experiments performed in Dutch full-scale boilers. Apart from these tests, a number of measurements has been carried out to investigate the additive behaviour of the Hardgrove grindability index. In this section the results of these investigations are presented.

The Hardgrove grindability index was measured of four single coals and a number of blends. All experiments were performed in a standard Hardgrove mill. Air dried test samples of the single coals were prepared according to the International Standard (ISO, 1980), using Retsch sieves of 1180 μm and 600 μm. The test samples of the blends were composed in mass ratios 25/75, 50/50 and 75/25 from the dried test samples of the single coals.

The grinding bowl of the Hardgrove mill was loaded with 8 steel balls and filled up with 50 grams of test material (ISO, 1980). Remaining material on top of the balls was brushed off into the grinding zone before placing the upper grinding ring. A total load of 29 kg was applied before starting the mill for 60 (± 0.25) revolutions. The speed of rotation of the mill was determined at 19.8 revolutions per minute, which falls within the tolerance as stated in the International Standard (19 to 21 revolutions per minute). Immediately after each experiment, the sample was taken out of the grinding bowl, and placed upon a 75 μm Retsch sieve. The sample was sieved on a Retsch mechanical sieving machine. After sieving, the sieve residual was used to calculate the percentage passing 75 μm. Subsequently, the Hardgrove grindability index was calculated. The results are listed in **table 4.3**.

Table 4.3 Measured HGI of four single coals and their blends

	Illawara	Hobet	Koornfontein	El Cerrejon
El Cerrejon				**43**
75%	44	46	43	
50%	52	46	42	
25%	57	48	43	
Koornfontein			**43**	
75%	48	46		
50%	53	48		
25%	57	49		
Hobet		**54**		
75%	57			
50%	58			
25%	57			
Illawara	**62**			

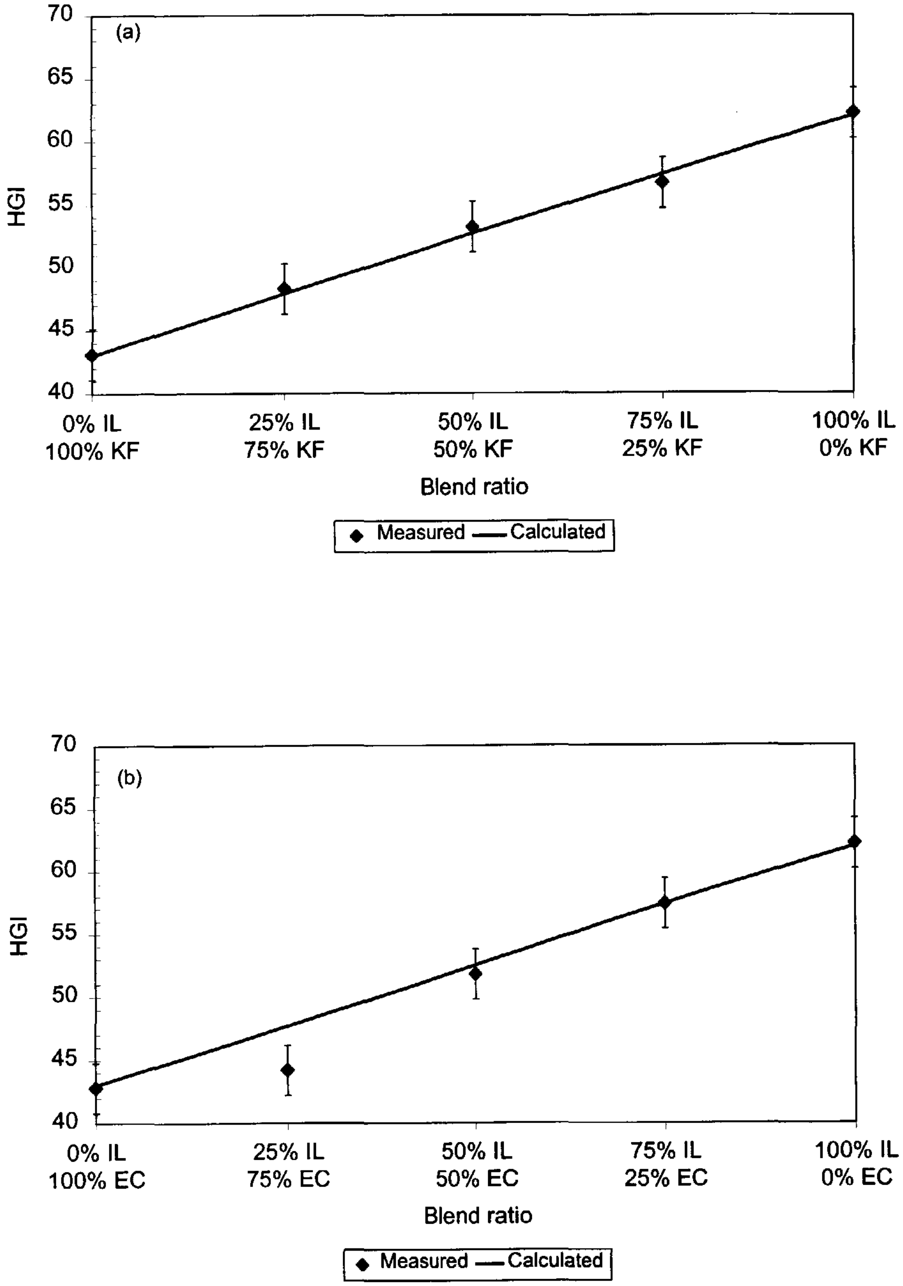


Figure 4.4 Additivity of HGI for the blend: (a) Illawara (IL) and Koornfontein (KF)
(b) Illawara (IL) and El Cerrejon (EC)

In **figure 4.4** the HGI of the blends Illawara/Koornfontein and Illawara/El Cerrejon are plotted against the weight percentages of the single coals in the binary blends. The straight line through the HGI values of the single coals represents the calculated HGI of the blend if additivity is assumed. It is observed that for a number of blends the HGI is lower than the weighted average. However, no general trend can be deduced from the results.

Yamada et al. (1994) suggested a new grindability Index to overcome some limitations of the standard Hardgrove test. After 60 revolutions in the HGI-test mill only 2 to 12% of the material is below 75 μm, whereas in a commercial pulveriser approximately 80% of the material is below 75 μm. Consequently, the energy requirements for milling can not be predicted from the HGI-test. They suggested to continue grinding in the HGI-test mill. The Yamada grindability index (YGI) is defined as the number of revolutions required to obtain a particle size distribution with 80% < 75 μm (**figure 4.5**). In a later paper the YGI is referred to as the Idemitsu grindability index (IGI) (Kambara et al., 1997).

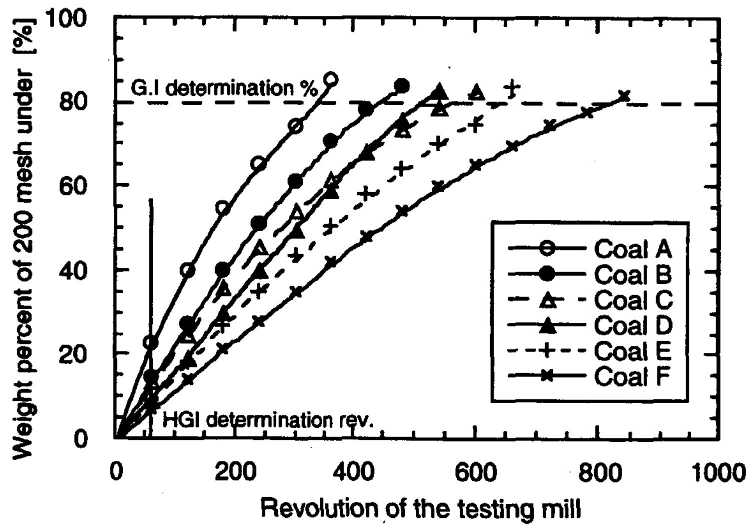


Figure 4.5 Grindability index according to Yamada et al. (1994)

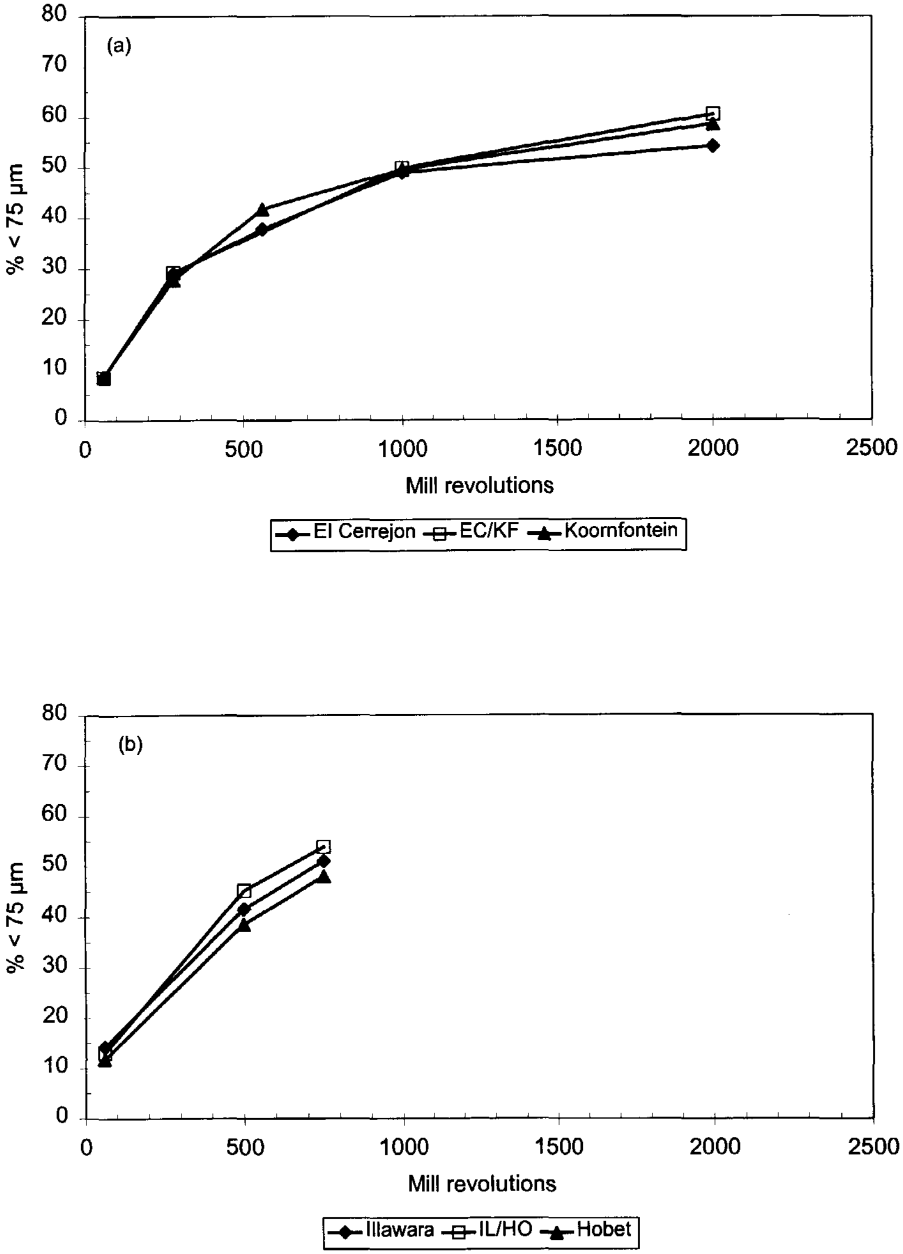


Figure 4.6 Product fineness as function of the number of revolutions in a Hardgrove mill:
a) El Cerrejon and Koornfontein
b) Illawara and Hobet

To evaluate the YGI-test, samples were prepared according to the Hardgrove method with the following coals and blends:

- El Cerrejon (EC)
- Koornfontein (KF)
- 50/50 EC/KF
- Illawara (IL)
- Hobet (HO)
- 50/50 IL/HO.

In a series of experiments, the test samples were ground for a certain number of revolutions of the Hardgrove mill, in order to obtain a product fineness of 80% below 75 μm. The product fineness was measured by sieving and weighing the sieve residue. **Figure 4.6** shows the results. A product fineness of 80 per cent below 75 μm could not be achieved for any of the coals or coal blends, despite the larger number of revolutions compared to the values reported by Yamada et al. (1994) (see **figure 4.5**). Although the required fineness could not be achieved, it can be observed from **figure 4.6** that Illawara is easier to grind than Hobet as could be expected from the HGI-values. It is also shown that Koornfontein is easier to grind than El Cerrejon although both coals have a similar HGI. The blend of Illawara and Hobet shows a higher grindability than is expected from the single coals. At a larger number of revolutions this is also true for the blend of El Cerrejon and Koornfontein. This is probably caused by the hard coal grinding the softer coal.

4.4.3.3 Discussion on the additivity of HGI

The additivity of the HGI for blends is questionable as was shown in the previous sections. Additionally, it appeared in a number of cases that the coals were segregated, as a result of which the harder coal dominated the larger particle size fractions and the softer coal the smaller particle size fractions, although it was observed that the HGI was additive.

Many pulveriser manufacturers relate the HGI to pulveriser capacity at a desired fineness for their particular pulveriser design. The maximum output increases with increasing HGI (i.e. easier-to-grind coal). The relationship between the HGI and pulveriser capacity is often non-linear as is shown in **figure 4.7** (Schüler, 1990; Smith et al., 1992).

Figure 4.7 illustrates a typical correlation of pulveriser capacity and HGI. In practical situations this figure may be used to predict the capacity factor as function of the blend quality. An example is shown in the figure. A binary blend of coal A (HGI = 80) and coal B (HGI = 40) (with equal mass fractions in the blend) has a HGI of 60 if additivity is assumed. However, as can be seen from **figure 4.7**, it is more likely to assume that the capacity factors should be used to assess the grinding behaviour of the blend. In that case the blend will behave more like a coal with a HGI of 51, instead of a coal with a HGI of 60.

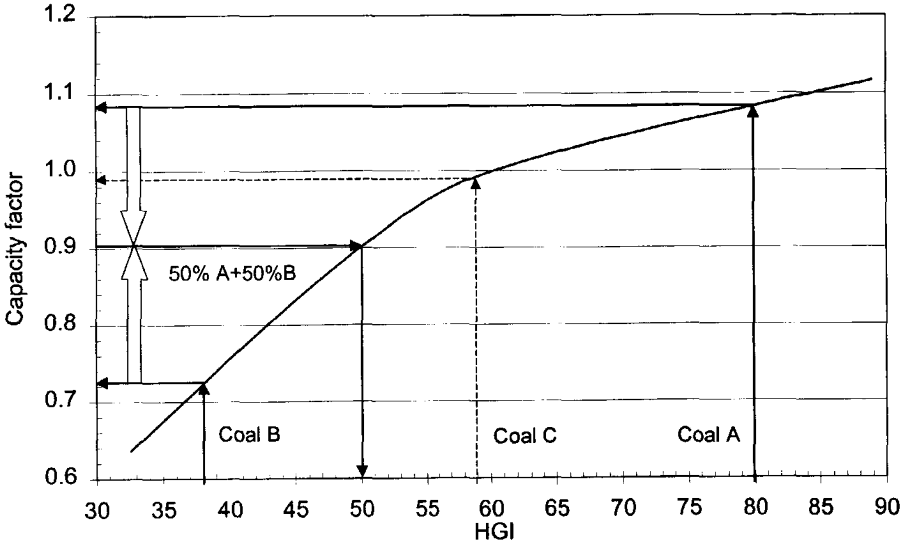


Figure 4.7 Relation between HGI and pulveriser capacity (impact of blending)

The utilities in the Netherlands burned blends composed of coals with widely different HGI-values (Rozendaal et al., 1997b). Tests were carried out at Maasvlakte power plant with an Australian coal with a HGI of 93 and a blend with a HGI of 63. The experiments showed that an increase of the amount of Australian coal in the blend resulted in a finer particle size and a reduced power consumption of the pulveriser. However, also negative experiences are reported (Rozendaal et al. 1997b). In some cases the blending of low and high HGI coals resulted in rumbling of the pulverisers, which forced the operators to lower the grinding pressure. The particle size increased and burnout became worse. Consequently, constraints were placed on the difference in HGI of the coals in a blend (± 20). In view of the opposite results, the relevance of the Hardgrove grindability test is disputable for comparison of widely divergent coals and coal blends.

4.4.4 Free swelling index

The free swelling index (FSI) or crucible swelling number (CSN) gives an indication of the swelling behaviour of coal during heating. A specific amount of pulverised coal is heated in a cup. The size and shape of the heated product is compared to a standard. The FSI is a value between 0 (no swelling) and 9 (high swelling) (Berkowitz, 1994). The FSI is measured under slow heating conditions, which do not correspond with the conditions in actual boilers. The FSI is sometimes associated with a high carbon content in the fly ash (Skorupska, 1993). It is suggested that, due to the swelling behaviour, lightweight porous particles are formed that are easily transported out of the combustion zone. The swelling of coals is sometimes associated with burner blockage (King, 1996;

Lindhardt et al., 1994; Rozendaal et al., 1997a). Coals may become sticky at lower temperatures. A high FSI is an indication for the plasticity of a coal and hence the stickiness.

The impact of blending on the FSI has been investigated by Riley (Riley et al., 1989). **Figure 4.8** shows the differences between the measured and the calculated FSI values for two bituminous coals. The measured FSI values are less than the calculated FSI values. It is reported that also other blends showed the same trends, especially blends involving low rank coals.

Since Unit 9 of Amer power plant experienced burner blockage problems (Rozendaal et al., 1997a), probably initiated by sticking coal particles, a number of tests has been carried out to test the additivity of the FSI for blends consisting of bituminous coals (Moret, 1997). **Figure 4.9** shows the measured and calculated FSI of two bituminous coals and their blends. No linear relationship exists between the FSI of the blend and the FSI of the individual coals. It should be noted here that the FSI is expressed as a value between 0 and 9 and can not be expressed with decimal values (except for halves). **Figure 4.10** shows the calculated and measured FSI for two other coals and their blends. Again, the FSI of the blend can not be calculated using the blend ratio and the FSI of the individual coals.

Generally, it is suggested that the FSI is not additive for blends (Carpenter, 1995). In addition, it is doubtful whether the FSI provides an indication of the swelling behaviour of coal particles under pulverised coal combustion conditions (Tørslev, 1997). However, coals with a high FSI may result in the deposition of tar-like substances causing uncontrolled fires in the burner.

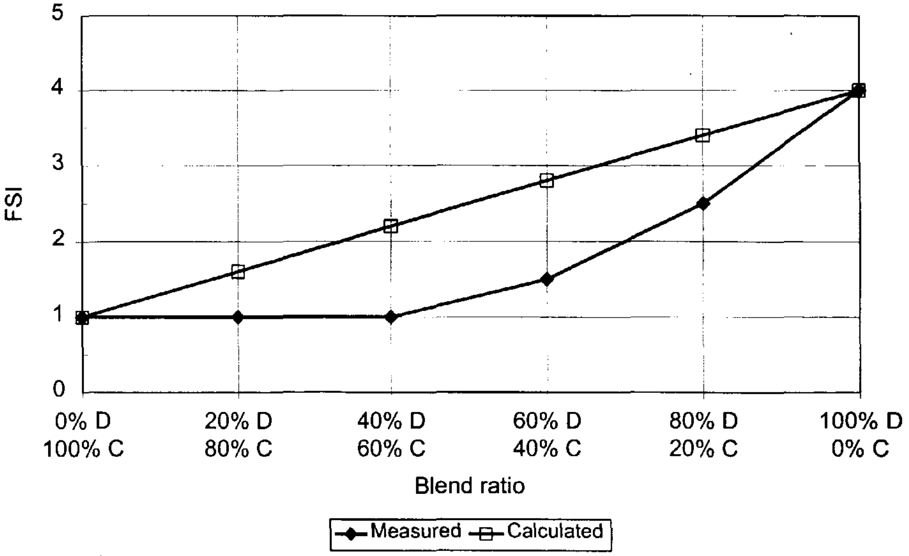


Figure 4.8 Measured and calculated FSI of two coals and their blends (Riley et al, 1989)

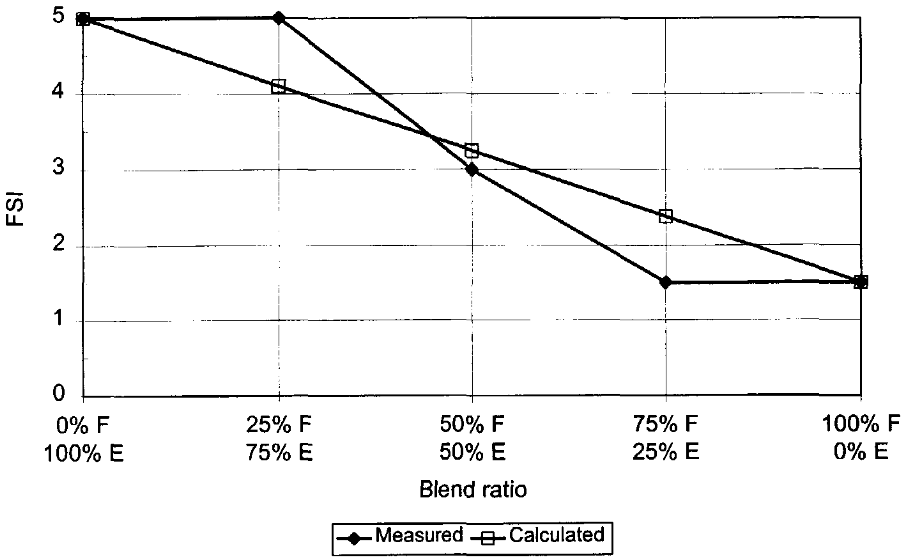


Figure 4.9 Measured and calculated FSI for two coals and their blends (Moret, 1997)

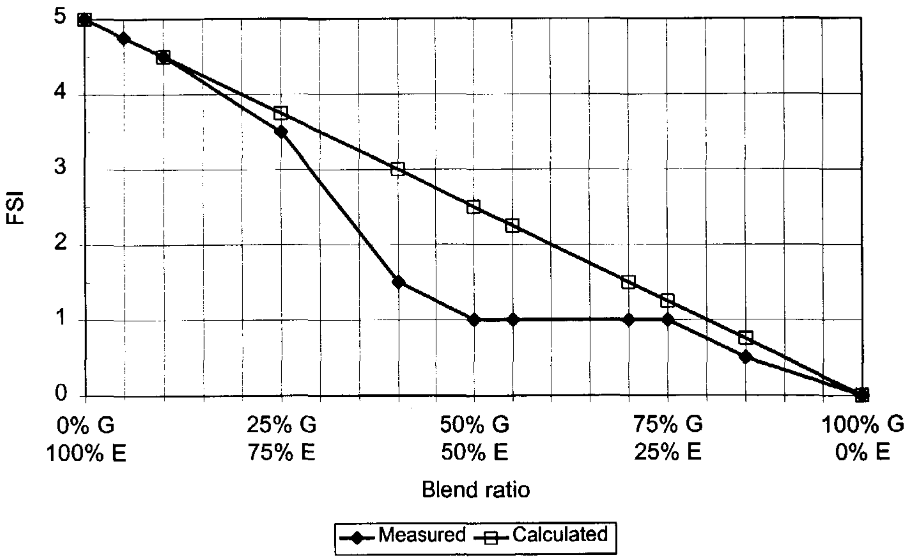


Figure 4.10 Measured and calculated FSI of two coals and their blends (Moret, 1997)

4.4.5 Slagging and fouling

Two basic types of ash deposits may occur in coal-fired boilers; (a) slagging deposits which are generally formed in the radiant section of the boiler and consist of molten ash and (b) fouling deposits which are formed in the convection pass of the boiler and consist of powdery or sintered ash. Ash deposition leads to a reduced heat transfer in the boiler and corrosion of boiler tubes, which can result in a reduced generating capacity and unscheduled outages.

Ash deposition depends on many factors, such as the composition of the mineral matter in coal, the operating conditions and the particle size and shape. Severe slagging of pulverised coal-fired boilers is usually associated with coal ashes rich in iron. In a reducing environment slagging may occur at lower temperatures, mainly since FeS is formed which has a low melting temperature. The initial deposit layer is significant and involves several mechanisms such as condensation of alkalis, sticking of fly ash particles, formation of low melting point complexes. The temperature of the outer surface of the deposit increases as the thickness of the deposit increases. The retention of larger fly ash particles increases since the outer surface becomes more fluid. Organically-bound sodium and sodium chloride are usually the cause of fouling in the convective pass (Skorupska, 1993). Many of the alkali metal compounds vaporise at typical furnace temperatures. They can react with SO_3 in the gas phase to form sulphates. Generally, sodium and calcium sulphates dominate the initial layer of the deposits. The deposits may grow in thickness and sinter into a strong fused mass.

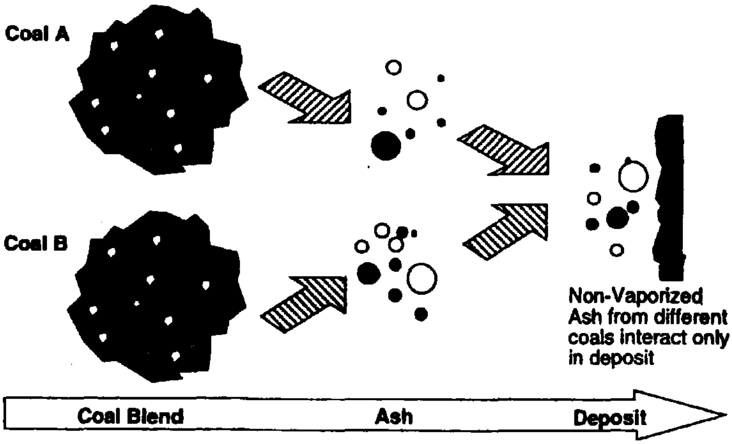


Figure 4.11 Interactions of mineral constituents during blend combustion (Johnson et al., 1993)

Because of the many processes and reactions involved the prediction of slagging and fouling is difficult. Nevertheless, several coal parameters or indices based on laboratory measurements are used to predict the slagging or fouling propensity of coal. Skorupska (1993) gives a large number of such slagging and fouling indices. These indices mainly provide an indication for slagging and fouling to occur. Some of the indices are based on experiences with coals from specific regions and should therefore not be generally applied.

Coal contains many different kinds of minerals, each having different slagging and fouling propensities. Each coal particle burns independently and produces ash particles of different sizes and composition. The blending of ash particles therefore takes place only within the deposit as is illustrated in **figure 4.11** (Johnson et al., 1993). As a result, it is possible that the composition of the deposit is different from the bulk of the ash. Once deposited low-melting eutectics may be formed with the minerals in the fly ash from the other blend components that aggravate the slagging.

Taking into consideration that prediction of the slagging and fouling potential of single coals is already inherently complex one will understand that this is almost impossible for blends (Zelkowski, 1982). Barnes et al. (1992) investigated the slagging behaviour of coal blends in an ash deposition test rig, simulating the conditions prevailing in a front wall-fired utility boiler. A non-slagging and a slagging coal were blended in the proportions 4:1 and 10:1. The slagging characteristics of the two blends were more pronounced than expected on basis of proportionality. Even the blend with a very small fraction of the slagging coal showed slagging whereas the deposits of the non-slagging coal were only in the form of a light dust. Also, the predicted performance of the coal blends, based on commonly used slagging and fouling indices, underestimated the slagging tendency of the two blends.

Baxter (1994) investigated the ash deposit properties of blends of subbituminous and bituminous coals. The elemental composition of ash deposits of the blends was compared to the mass-weighted average of the blend components. It was observed that the deposits were enriched in iron, potassium and sulphur, elements associated with the bituminous coals. Baxter suggested that this enrichment was caused by segregation of the coals. The bituminous coals were more difficult to grind resulting in an abundance of bituminous coal particles in the larger size fractions. Due to the larger particle size of the bituminous coals, fly ash of these coals was more easily collected on the heat transfer surfaces.

Ash fusion temperatures are sometimes used to predict the slagging potential of coals. Lloyd and co-workers (Lloyd et al., 1993) found that particularly with ash from blends of high-calcium and low-calcium high-sulphur coals the ash fusion temperatures lie far below the linearly interpolated values, due to the capture of sulphur by the high-calcium ash. Livingston et al. (1998) also investigated the ash fusion temperatures for a number of coals and blends. They concluded that the ash fusion temperatures (measured under oxidising and reducing conditions) of the blends were significantly lower than the additive value, especially for the reducing conditions. Already a relatively small addition of ash with low fusion temperatures dramatically reduced the ash fusion temperatures of the blend. Qiu et al. (1999) studied the ash fusion characteristics and mineral behaviour of three Chinese coals and a series of binary blends. They found that the ash softening temperatures of the blends can lie between, lower or higher than that of the parent coals. The lower ash fusion temperature of some combinations was caused by the formation of low-meting eutectic minerals at high temperatures (consistent with the results from the ternary system phase diagram).

More work on the impact of blending subbituminous and bituminous coals on slagging and fouling has been reported by Zygarlicke et al. (1993) and Johnson et al. (1993). They also concluded that blend behaviour could not be calculated from the single coals.

To conclude, it is generally acknowledged that predicting the slagging and fouling behaviour of coal blends is inherently complex. Using ash fusion temperatures or other simple laboratory measurements for the prediction of the slagging and fouling behaviour of blends may lead to unreliable results, since the tests are performed under conditions different than in a boiler. Empirical and ASTM indicators for ash slagging and fouling should not be applied to blended coals without experimental verification. For studying the behaviour of blends, testing in bench- or pilot-scale facilities is the best option (Lee et al., 1983).

4.5 COAL BLENDING IN RELATION TO EMISSIONS AND COMBUSTION BEHAVIOUR

4.5.1 Coal blending and SO_2 emissions

Blending of low- and high-sulphur coals has become a common practice in the United States of America to meet the requirements of SO_2 emission legislation. Low-sulphur subbituminous coals are often blended with high-sulphur bituminous coals to lower the total sulphur content in the fuel. SO_2 emissions from a coal blend can be, unlike NO_x emissions, calculated from the sulphur content in the fuel, since nearly all sulphur reacts to SO_2. (Morgan et al., 1981; Baxter, 1992; Gunderson et al., 1992; Brimer et al., 1992; Bryers et al., 1994). Except, if high-sulphur coals are blended with coals containing a large amount of alkali and alkaline earth metals then the SO_2 emissions may be lower, because part of the sulphur that is in the form of SO_3 is captured in the fly ash.

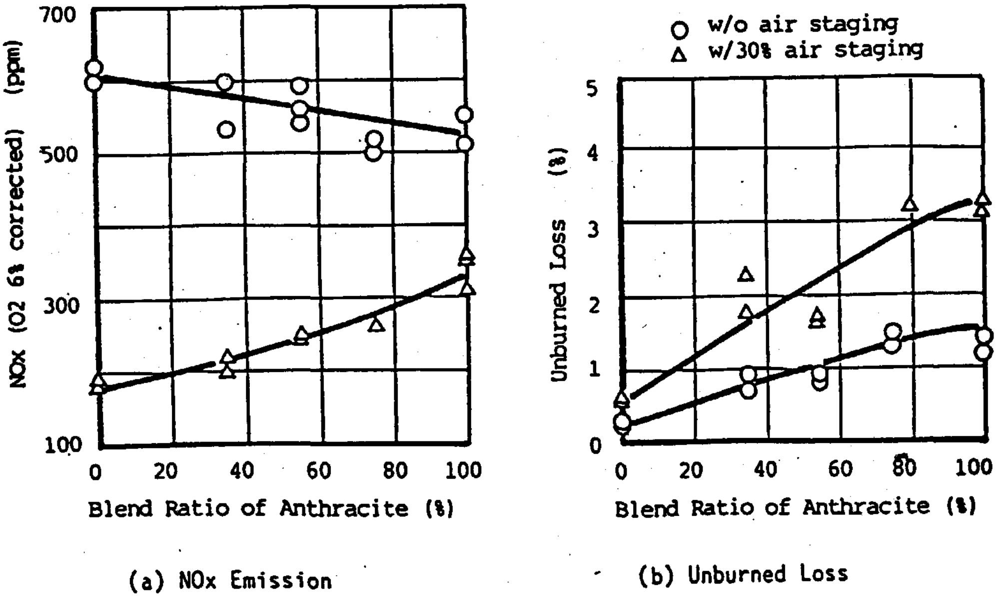
4.5.2 Coal blending and NO_x emissions

NO_x emissions are affected by a large number of parameters, including coal quality, boiler design and operating conditions. In chapter 3 this is covered in more detail. The mechanisms involved in the formation and reduction of NO_x are still not completely understood since many interrelated reactions are involved, which are influenced by the conditions imposed by the design of the boiler and burners as well as by the operating conditions.

Because of this complexity it is difficult to predict the NO_x emissions of coal under specific conditions. Generally, in low NO_x boilers most of the NO_x emitted with the flue gases originates from fuel nitrogen. However, only a relatively small amount of the nitrogen in the coal is oxidised to NO_x. The operating conditions and the reaction products involved determine how much of the fuel nitrogen is reduced to N_2. Especially, the conditions prevailing in the early combustion stages are decisive. The amount of volatiles released, the residence times, the availability of oxygen and the flame characteristics in general affect the reduction of nitrogen released with the volatiles during the first stages of combustion. Because of the many interrelated effects, it is not surprising that the effect of coal blending on NO_x emissions is not very obvious.

A number of studies has been performed to study the impact of coal blending on NO_x emissions (Miyamae et al., 1989; Nakamura et al., 1990; Smart et al., 1993; Ma et al., 1993; Kopparthi et al., 1994; Maier et al., 1995; Kambara et al., 1997; Monroe et al., 1997a; Monroe et al., 1997c; Allen, 1998). Most of the research and blending trials reported has been carried out using laboratory or pilot-scale facilities. Difficulties may arise in extrapolation of laboratory or pilot-scale results to utility operation.

Koppharti and Gollahalli (1994) investigated the impact of blending different coals (ranging from lignite to anthracite) on NO_x emissions using a laboratory-scale burner. A diffusion flame of a mixture of nitrogen and propane in air was used to ignite and stabilise the coal flame. The feed rate of coal was 9.5 g/min. The propane and nitrogen mixture carried the pulverised coal (< 150 µm) to the burner. Combustion air with a temperature of 25 °C was supplied through an annulus surrounding the burner tip, using a honeycomb section for minimising turbulence. Radial concentration profiles were measured in the far-nozzle region of the flame. The tests were carried out under unstaged conditions. Correlation of the NO_x emissions of the single coals showed that the highest NO_x emissions were measured with the bituminous coal having the highest nitrogen content. Four types of blends were composed (anthracite+bituminous, anthracite+lignite, lignite+bituminous, bituminous+bituminous) in different ratios. It appeared that the NO_x emissions of the blends could be higher or lower than the weighted average, depending on the types of coal in the blend. The authors stated that the NO_x emissions were not additive. They suggested that the non-additivity of the NO_x emissions was a result of the highly non-linear behaviour of NO_x forming reactions with temperature and that the reactive species concentration levels controlled the formation of NO_x in the fuel rich zones.



(a) NOx Emission (b) Unburned Loss

Figure 4.12 Effect of coal blending on NO_x (w/o is unstaged and w/30% is staged combustion with 30% tertiary air) (Miyamea et al., 1989)

Miyamea et al. (1989) studied the impact of blending a semi-anthracite and a bituminous coal on NO_x emissions and burnout in a 1.8 MW_{th} test furnace under staged and unstaged combustion conditions. Blends with 35, 55 en 75% semi-anthracite were burned. **Figure 4.12** shows the effect of the blend ratio on NO_x emissions and unburned loss (100% - burnout). NO_x emissions of the blends are approximately linear to the blend ratio and the NO_x emissions of the parent coals. Tests performed in a utility boiler with a bituminous coal and a blend with 30% semi-anthracite were in accordance with the data of the test furnace.

Nakamura et al. (1990) and Smart et al. (1993) investigated the impact of coal blending on NO_x emissions, using an aerodynamically air staged burner (AASB) in a 2.5 MW_{th} semi-industrial scale furnace of the International Flame Research Foundation. The pulverised coal injector in the centre of the AASB can be moved forwards and backwards or in- or outside the internal flame recirculation zone (IRZ; see chapter 5). Placing the injector at the burner throat (gun position is zero) the coal particles will preferentially pass around the IRZ and devolatilise under oxygen rich conditions. By moving the injector forwards into the IRZ coal particles will devolatilise in a reducing environment inside the IRZ. The nitrogen in the coal is then preferentially reacted to N_2.

Four coals ranging from semi-anthracite to high-volatile bituminous coal and six blends were burned under unstaged and aerodynamically air-staged conditions. **Figure 4.13** shows the effect of coal quality and blend ratio on the NO_x emissions for two coals and blends of these coals (coal A is semi-anthracite and coal B is a high-volatile bituminous coal). For the unstaged combustion

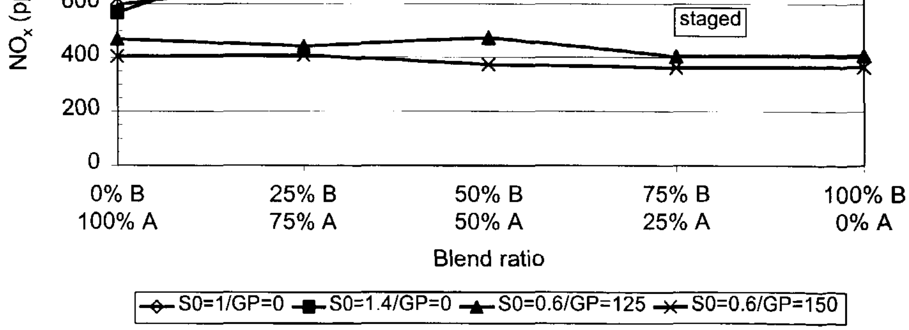


Figure 4.13 Effect of coal quality and blend ratio on NO_x emissions under unstaged and staged conditions with different swirl numbers (S0) and injector positions (GP = gun position) (Nakamura et al., 1990)

mode NO_x emissions increased as the fraction of the high-volatile coal in the blends increased as a result of the fact that under unstaged combustion conditions the coal-particle trajectories are predominantly on the boundary of the internal recirculation zone. Under these unstaged conditions the NO_x emissions from the blends can be calculated straightforward from the mass fractions of the component coals in the blend and the respective NO_x emissions when burning these coals independently. Under aerodynamically air-staged conditions the NO_x emissions from the coals and the coal blends were almost identical. The low local stoichiometry in the internal recirculation zone enhances the formation of molecular nitrogen instead of NO. Similar results were obtained with blends of a high- and a low-volatile coal.

Monroe et al. (1997a, b, c) investigated the behaviour of blends in a pilot-scale research facility (equipped with a low NO_x swirl burner) in Alabama. Four coals were used in this study: Shoal Creek, Mina Pribbenow, Jim Walter no. 3 and Caballo Rojo. Mina Pribbenow is a Colombian coal, Shoal Creek and Jim Walter no. 3 are bituminous coals from Alabama and Caballo Rojo is a Powder River Basin coal.

Figures 4.14 and 4.15 show the NO_x emissions as function of the blend ratio and furnace exit oxygen concentrations. As can be seen from **figure 4.14**, NO_x emissions of the blends generally decreases with increasing amounts of the Powder River Basin coal, except for the 75/25 blend. The coal particle size of that specific blend was slightly finer than the other blends and coals. In this furnace a finer coal particle size results in higher NO_x emissions. **Figure 4.15** shows, however, that the NO_x emissions of the blends of Shoal Creek and Mina Pribbenow are lower than the NO_x emissions of the parent coals. The NO_x reduction is most apparent at the blend ratio 50/50, but is also observed at the other blend ratios. It is suggested that the NO_x reduction of the blend was caused by particle size segregation of the two coals during pulverisation. Vitrinite reflectance analyses of different particle size fractions showed that the Colombian coal dominated the larger particle size fractions (see also section 4.5.3.1). The Hardgrove grindability index of Mina Pribbenow and Shoal Creek is 45 and 75, respectively. The authors suggest that internal staging of the flame may occur. The higher volatile Mina Pribbenow coal, concentrated in the larger particle sizes will penetrate further into the furnace, releasing volatiles during the combustion of the smaller Shoal Creek particles. The volatiles released may reduce the NO_x formed by the Shoal Creek coal.

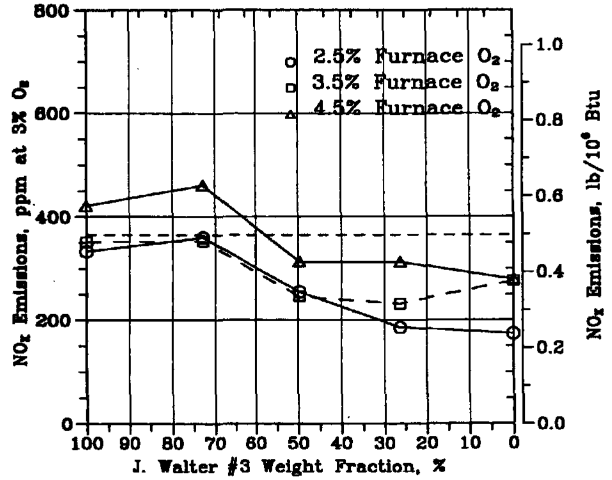


Figure 4.14 NO$_x$ emissions from Jim Walter no. 3 and Caballo Rojo coals and blends (Monroe et al., 1997a)

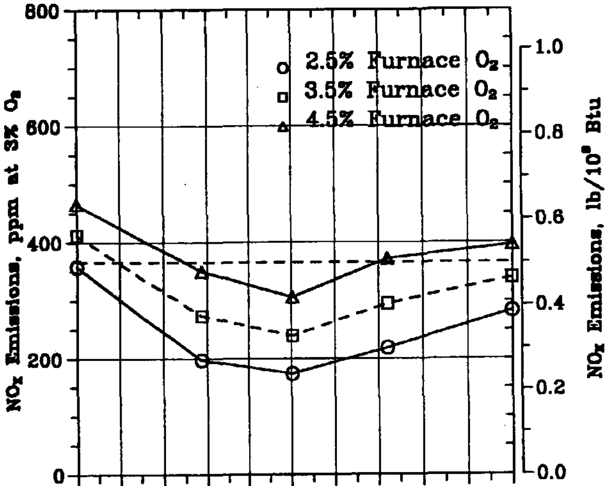


Figure 4.15 NO$_x$ emissions from Shoal Creek and Mina Pribbenow coals and blends (Monroe et al., 1997a)

Measurements performed in a 0.5 MW_{th} semi-industrial combustion facility at the University of Stuttgart with three German and one South African coal showed that the NO_x emissions of blends were not predictable from the blend ratios and the NO_x emissions of the single coals (Maier et al., 1995). The behaviour of the blends depended on the primary air ratios and the operating regime (burner air staging and in-furnace air staging). Especially, operation with a primary air ratio below 1 resulted in lower NO_x emissions for the blends than the weighted average. The authors suggested that reburning effects occurred due to the different ignition and devolatilisation behaviour of the parent coals.

Kambara et al. (1997) investigated the effect of coal blending on NO_x emissions and burnout in a turbulent flow furnace (coal feed rate is 6 kg/hr) under unstaged and staged conditions. The blends consisted of a low- and a high-volatile bituminous coal. As can be seen from **figure 4.16** higher NO_x emissions are observed for the blends with unstaged combustion, whereas in the staged combustion mode the NO_x emissions of the blends are linearly related to the NO_x emissions of the single coals. Tests were also performed in a 100 MW boiler under air staged conditions burning blends of a low- and high-volatile bituminous coal. As can be seen from **figure 4.17** NO_x emissions of the blend are the weighted average of the NO_x emissions of the single coals. The authors concluded that the impact of blending on NO_x emissions was dependent on the boiler operating conditions and the NO_x reduction technology applied.

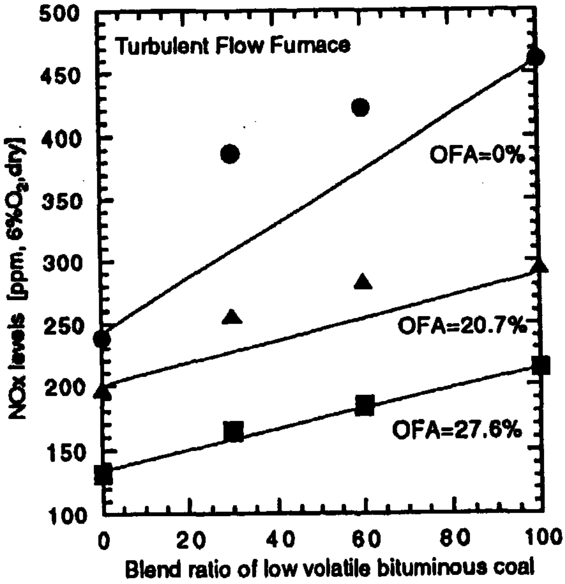


Figure 4.16 Effect of coal blending on NO_x emissions under unstaged and staged conditions (Kambara et al., 1997)

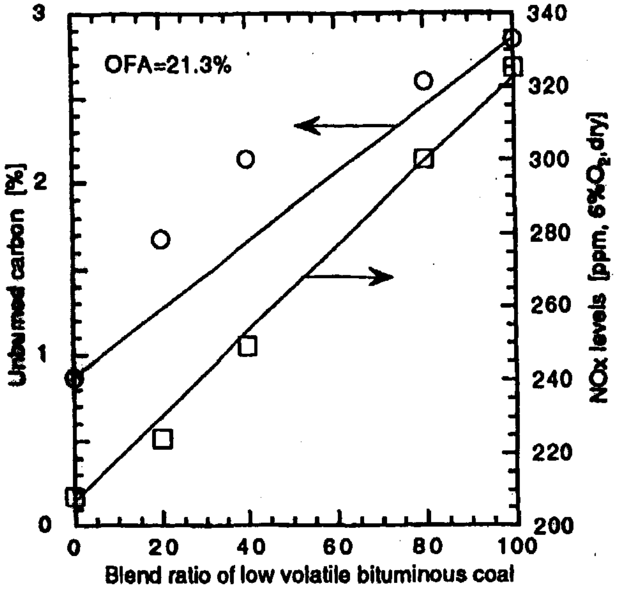


Figure 4.17 Effect of coal blending on unburned carbon and NO_x emissions from a full-scale boiler (Kambara et al., 1997)

Coal blend trials were performed in a 35 MW_{th} low NO_x swirl burner (designed by International Combustion Limited, UK) installed in a large-scale combustion test facility (Allen, 1998). In-flame and furnace exit combustion/emissions species and temperatures were taken with two single coals and a blend. The single coals were Shamrock (USA) and Rand (South Africa) with a fuel ratio of 1.63 and 2.13, respectively. The blend contained 67% Rand and 33% Shamrock coal. The in-flame measurements showed that the high-volatile Shamrock coal was more reactive, generating heat and consuming oxygen faster during the initial stages of combustion. The low-volatile Rand coal burned slower, but produced a higher peak flame temperature (1400 °C versus 1300 °C). The blend behaved similar to the Shamrock coal, even though the proportion of the low-volatile Rand coal in the blend was higher. The in-flame measurements with the blend showed an initial peak in NO_x at a distance of approximately 1 m from the burner exit, which was higher than both the initial peaks of the single coals. The NO_x peak of the low-volatile Rand coal was higher, but occurred at a longer distance from the burner exit. The furnace exit NO_x emissions for the Shamrock coal, Rand coal and the blend were 270, 350 and 276 ppm (@ 3% O_2), respectively. Reburning effects possibly caused the lower NO_x emissions of the blend compared to the weighted average of the single coals. The unburned carbon content in the fly ash was similar for both coals and the blend.

In general, it can be concluded that the impact of coal blending on NO_x emissions is not very well understood. Research in pilot-scale facilities has shown that blends combustion may result in higher, lower or similar NO_x emissions compared to the weighted averaged NO_x emissions of the parent coals. The mechanisms involved in the formation and destruction of NO_x are very complex as well as the combustion reactions in the first stages of the flame. Factors which may have an effect on NO_x forming and NO_x reducing reactions are, for instance, particle size, availability of oxygen, volatile release rate and nitrogen release rate. Blending different types of coal may result in interactions during grinding, causing segregation of coals over the different size fractions, which may have a large impact on most factors, mentioned above. Unfortunately, information on coal blending effects is mainly available for laboratory- or pilot-scale facilities and only limited information is available on utility experiences. A complicating factor is that pilot-scale results are difficult to extrapolate to utility applications. The burners used in pilot-scale facilities often have different designs than commercial burners and burner-burner interactions are often not simulated.

4.5.3 Coal blending and combustion characteristics (reactivity and burnout)

Boilers are designed for a specific coal or range of coals. The design is such that combustion is (next to) completed before the flue gases enter the convection zone of the furnace. The reactivity of the coal (or char) particle plays a dominant role. Reactivity is often associated with the volatile matter of coal, but also the maceral composition, particle size and operating conditions affect the reactivity and hence burnout.

Thermal gravimetric analysers (TGA) and drop tube furnaces (DTF) have been used to investigate the combustion behaviour of coal blends (Artos et al., 1993; Pan et al., 1991). Artos et al. (1993) investigated the combustion behaviour of a number of blends (coals ranging from lignite to bituminous coals) in a TGA and a DTF. The experiments in the TGA were performed in air at a temperature of 450 °C. It was observed that coal blending under these chemically controlled conditions did not affect the reactivity of the individual coals. Three characteristic temperatures from the burning profile were defined: (a) the onset temperature (temperature at which the rate of weight loss is $> 0.1\%\ \mathrm{min}^{-1}$), (b) the temperature at the maximum rate of weight loss and (c) the burnout temperature. It appeared that the burnout temperature of the blend was similar to the burnout temperature of the less reactive coal in the blend. The onset temperature of the blend linearly reduced with increasing fractions of the higher reactive coal in the blend. The experiments in the DTF at 900 °C showed that the combustion efficiency of the blends was linearly predictable from those of the individual coals. The authors concluded that blending did not affect the combustion behaviour of the single coals. The question remains to what extent these results can be extrapolated to full-scale applications.

The impact of coal blending on combustion reactivity, fly ash resistivity, ash precipitability and slagging and fouling tendencies was investigated by Lee et al. (1983). Three bituminous coals and eight blends were tested in a pilot-scale research boiler (coal feed rate is 60-70 kg/hr). The experiments showed that the burnout was positively affected by coal blending. The burnout of the lower reactive coal was enhanced by the addition of the other coals. No explanation for this behaviour was given.

Zelkowski (1989) reported that in a boiler operating with low excess air levels, the burnout of a blend of a high- and a low-volatile coal was negatively affected. The burnout could be improved by increasing the fraction of the high-volatile coal in the blend. In another boiler designed for burning a coal blend composed of widely different coals the burnout was worse than expected. Reduction of the particle size resulted in an increase of the burnout. Jacobs et al. (1987) used an example to explain the impact of blending on burnout. Assuming that two coals (volatile matter of 15 and 30%, respectively) in a blend have a similar reactivity then the burnout of the blend is not affected by blending. But when the reactivity of the low-volatile coal is lower than the high-volatile coal then burnout is reduced by coal blending, especially with low excess air levels.

Many researchers who investigated the impact of coal blending on NO_x emissions (described in section 4.5.2) also investigated the burnout of the blends. Occasionally it was found that the impact of coal blending on burnout is additive (Miyamae et al. 1989). Kambara et al. (1997) observed that for the test rig experiments the burnout is additive under both unstaged and staged conditions. In the full-scale trials under staged combustion conditions it was observed that burnout was not additive. Monroe et al. (1997a) found in their pilot-scale tests that in one case burnout was additive whereas in the other case burnout was not additive. This was in agreement with the effect on NO_x emissions. Segregation of the different coals over the particle size fractions probably caused the non-linear effect. Smart et al. (1993) found that in the IFRF test facility the high-volatile coal was preferentially burned in the early part of the flame. As a result, the combustion of the low-volatile coal was delayed, what resulted in a reduced burnout.

To conclude, it is suggested that coal blending may influence the oxygen availability, reaction temperature and particle size in a full-scale boiler, which may affect the burnout of the parent coals in the blend. As was already mentioned earlier in this chapter, coal blending may result in segregation of the coals over the smaller and larger particle size fractions. If a lower reactive coal (as a result of the grinding process) dominates the larger size fractions it can be assumed that the low-reactive coal needs more time to burnout. This time may not be available in a boiler with its specific dimensions. As soon as the burning low-reactive particles enter the superheater zone, the combustion process is slowed down due to the lower flue gas temperatures and eventually it will be terminated leaving part of the low-reactive particles unreacted.

It becomes even worse if the oxygen availability decreases, due to the faster rate of oxygen consumption of the higher reactive coal particles and the release of combustion products. The lower reactive coal particles burn in an oxygen diluted environment, slowing down the rate of combustion. Especially, in low NO_x boilers the oxygen availability in the early stages of combustion is reduced, which make these boilers more sensitive with respect to the burnout of coal blends.

The higher temperatures due to a high combustion rate of the reactive particles may enhance the reactivity and burnout of the low-reactive coal. This may compensate to some extent the negative effects mentioned above.

The impact of blending different coals on reactivity and burnout depends on several aspects. The actual boiler design (residence time), the burner design, air staging, the pulveriser equipment as well as coal parameters play a decisive role in the reactivity and burnout of a blended coal. In general, it can be concluded that reactivity and burnout are not additive.

4.6 DISCUSSION AND CONCLUDING REMARKS

Many coal characterisation tests are performed in standardised laboratory equipment. Bench-scale or pilot-scale tests are performed to investigate the combustion behaviour and NO_x forming potential of coal. The (standard) test conditions often do not reflect the conditions experienced in pulverised coal-fired boilers. The tests are performed, for instance, with lower heating rates, lower temperatures, larger particle sizes, higher stoichiometries etc. which all affect the combustion process and hence the outcome of the tests. Pilot-scale tests provide a better simulation of full-scale conditions, although also in pilot-scale tests the conditions may still be quite different from full-scale applications (burner design, burner-burner interactions, particle size, flow pattern, heat absorption profile, etc.). Extrapolation of standard characterisation tests or pilot-scale results to full-scale plants is therefore difficult for single coals as well as for coal blends. However, coal characterisation and in some cases also pilot-scale tests have to be performed to obtain at least an indication what might happen if blends are burned in full-scale plants.

Prediction of the impact of coal quality and coal blending on power plant performance is complex. However, research and full-scale experiences have shown that various general trends in performance can be determined with changing coal quality and coal blending.

The findings on the additivity of coal blending presented in this chapter are listed in **table 4.4**. This table is based on an overview of the impact of coal quality on plant performance given by Tørslev (1997). It can be concluded that on many important performance aspects the additive rule may not be applied if two or more coals are blended. Grinding behaviour, NO_x emissions, reactivity, burnout, slagging and fouling are aspects which may be additive under specific conditions but may also be highly non-additive in other cases. Since some of the aspects noted above, are mutually related, it is even more difficult to predict the combustion behaviour of the blend. Knowledge of the characteristics of the single coals and their combustion behaviour and understanding of the characteristic features of the boiler are required before the combustion behaviour of coal blends can be predicted. This holds particularly for coal blends composed of coals with widely divergent characteristics.

The impact of coal blending on NO_x emissions and burnout has mainly been studied in a laboratory environment. Because there is a general lack of knowledge on the impact of coal blending on full-scale plant performance, full-scale coal blending experiments at three pulverised coal-fired boilers were performed. The results are presented in chapter 10.

Table 4.4 Impact of coal parameters on plant components and additivity of coal parameters

		Pulveriser	Low NO_x burner	Boiler	FGD-plant	ESP	Additive
Calorific value	low	low capacity					Yes
	high						
Volatiles	low		Flame stability, High NO_x	Poor burnout			Yes, but effect on UBC and NO_x is questionable
	high	Explosion	Flash back				
Ash	low			Poor burnout			Yes
	high	Erosion	Erosion	Erosion Slagging Fouling		Emission Erosion	
Moisture	low						Yes
	high	Drying cap.		Efficiency			
Sulphur	low				Gypsum quality	Precipitation efficiency	Yes, but additivity of SO_2 emissions depends also on alkalis in ash
	high		Burner slagging	Slagging Fouling	Capacity		
Nitrogen	low						Yes, but additivity of NO_x questionable
	high		High NO_x				
Chlorine	low						Yes
	high			Corrosion	Capacity		
Sodium & Potassium	low						Yes
	high			Superheater corrosion			
HGI	low	Pulv. cap. p.f. fineness		Poor burnout			Probably, but segregation may occur, leading to high UBC (and NO_x)
	high	Mill stability					
FSI	low						No, individual coals still may cause problems
	high		Burner blockage	Poor burnout			
Coal reactivity	low		High NO_x	Poor burnout			No
	high	Explosion	Excessive heat load				
AFT	low		Slagging & blockage	Slagging			No, but extrapolation of test results is questionable
	high						
Ash composition		Erosion	Erosion Slagging	Erosion Slagging Fouling		Resistivity	Yes, but particles only interact after deposition
Ash resistivity	low						No
	high					Precipitation efficiency	

Chapter 5 EXPERIMENTAL EQUIPMENT AND FULL-SCALE INSTALLATIONS

5.1 INTRODUCTION

In this chapter the experimental facilities are described which were used for coal characterisation. In addition, the pulverised coal-fired boilers are described which were used to obtain full-scale experimental data.

Coal characterisation experiments were carried out at KEMA in a drop tube furnace (DTF) and a 1 MW_{th} pulverised coal-fired pilot-scale facility (hereafter referred to as the 1 MW_{th} test rig). Full-scale combustion trials were performed at three pulverised coal-fired power plants: Maasvlakte units 1 and 2, Amer unit 9 and Hemweg unit 8. Additional coal characterisation experiments were performed using heated wire grid reactors (HWG) at DMT (Deutsche Montan Technologie, Essen, Germany) and at IC (Mechanical Engineering Department, Imperial College, London, UK). The HWG reactor of IC is hereafter referred to as HTWM (high temperature wire mesh). **Table 5.1** lists the experimental equipment and the full-scale installations, the companies that operate the installations, the related chapters and a brief description of the experiments.

Table 5.1 Overview of the main equipment/installations used for the investigations described in this thesis

Equipment	Owner	Chapters	Description of experiments
DTF	KEMA	6	HTVM and char-N (1 MW_{th} test rig coals)
		8	HTVM and char-N (coals Amer unit 9)
1 MW_{th} test rig	KEMA	6	NO_x and burnout as function of coal quality
Maasvlakte unit 1 and 2	EZH	7	NO_x and burnout as function of coal quality
		10	Coal blending experiments
Amer unit 9	EPZ	7	NO_x and burnout as function of coal quality
		8	NO_x emissions (correlation with char-N)
		10	Coal blending experiments
Hemweg unit 8	UNA	9	NO_x emissions (correlation with char-N)
		10	Coal blending experiments
HWG reactor	DMT	8	HTVM and char-N (coals Amer unit 9)
HTWM reactor	IC	9	HTVM and char-N (coals Hemweg unit 8)

5.2 DROP TUBE FURNACE (DTF)

5.2.1 *Introduction*

A drop tube furnace (DTF) is a vertical reactor in which combustion, pyrolysis or gasification conditions are simulated. The essential characteristics are high heating rates (10^4 – 10^5 °C/s), high temperatures (up to 1800 °C) and a dilute particle phase. A DTF can be used for several combustion-related studies, such as (Carpenter et al., 1993):

- pyrolysis/devolatilisation mechanisms
- coal ignition, burnout and char combustion mechanisms
- nitrogen oxide formation mechanisms
- ash deposition mechanisms.

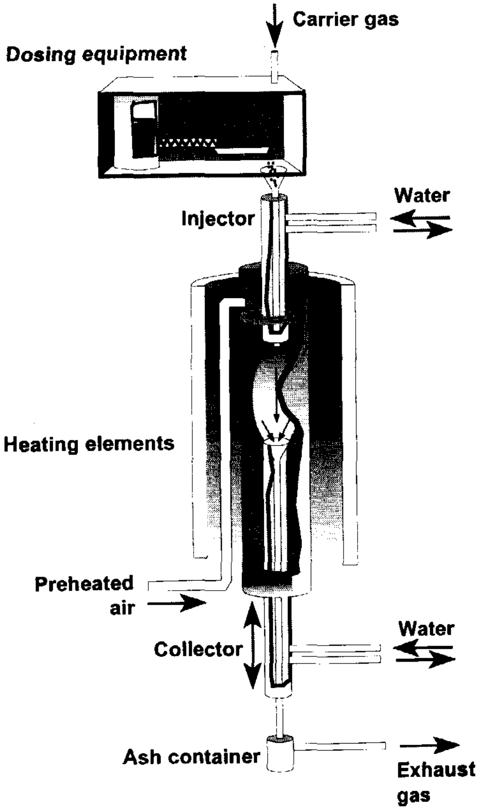


Figure 5.1 KEMA drop tube furnace (DTF)

5.2.2 Layout of the DTF

The main components of the DTF at KEMA include (**figure 5.1**):

- a fuel feeding system
- an injector
- gas heating elements
- a furnace
- a collector.

The feeding system consists of a bunker containing the pulverised material, a screw feeder and a vibrating feeder. The screw feeder transports the particles from the storage bunker onto the vibrating feeder that transports the coal to the injector. This feeding system (designed by DMT, Essen, Germany) can be operated with a satisfactorily accuracy of dosing (Wagner, 1987). The feeding system is placed in a transparent house and is operated with a slight overpressure. The transport or carrier gas for the particles is nitrogen.

The injector is water-cooled to avoid preliminary heating of the particles. The reaction gas is initially preheated in an electrically heated oven. Additional heating takes place in the reactor tube. The reaction gas is guided through a flow straightener and mixes with the carrier gas and particles downstream the injector. The flow straightener ensures a flat velocity profile at the tip of the injector. The reactor itself is electrically heated by six elements. A thermocouple in the ceramic tube controls the temperature of the tube, whereas a thermocouple in the entrance region of the reactor measures the gas temperature.

The movable collector consists of a metallic tube enfolded by a ceramic shell and is water-cooled in order to quench the collected material rapidly. The maximum distance between the injector and collector is 97.5 cm. The inner diameter of the furnace is 7.5 cm. The larger particles are collected in a container under the collector. Smaller particles entrained with the exhaust gas are removed by two cyclones.

5.2.3 Experimental procedures

The DTF was used to obtain data on the high temperature volatile matter (HTVM) and to produce chars for the determination of the nitrogen retained in the char (chapters 6 and 8). The collector was fixed in the most downward position (reaction length of 97.5 cm) to obtain a residence time of several seconds.

The coal samples were dried for four hours in an oven at 35 °C. Subsequently, the coals were ground in a Retsch mill to particles smaller than 500 μm. The desired fraction of 53 to 106 μm was obtained by sieving.

The weight loss of tested material was measured indirectly by the ash-tracer method and is calculated as:

$$V_{DTF} = 100 \cdot \left(1 - \frac{(100 - Ash_{char})}{(100 - Ash_{coal})} \cdot \frac{Ash_{coal}}{Ash_{char}}\right) \tag{5.1}$$

with: Ash_{coal} ash content in coal (wt.-%, db)
Ash_{char} ash content in char (wt.-%, db)
V_{DTF} high temperature volatile matter or volatile yield in the DTF (wt.-%, daf)

The accuracy of this method is low with low-ash coals. Knill et al, (1990) calculated the accuracy of the ash-tracer method as function of the ash content in the coal, assuming that the accuracy of the ash determination was ± 0.5%. **Figure 5.2** illustrates the decreasing accuracy with a decreasing ash content (Knill et al., 1990). Nevertheless, the ash-tracer method is widely applied since alternative methods are more complicated and more expensive. Furthermore, many coals have an ash content larger than 10%.

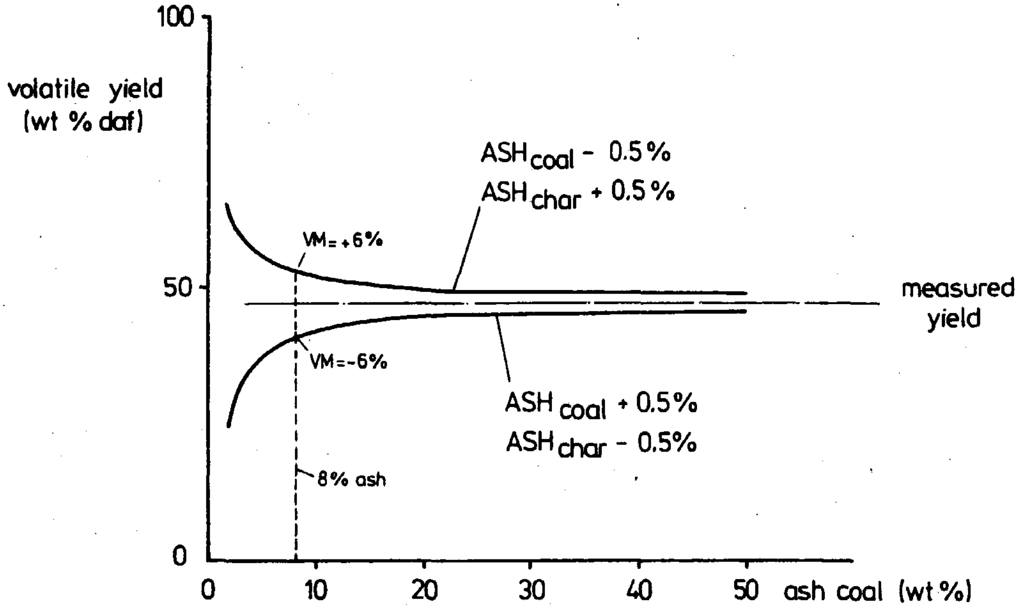


Figure 5.2 Influence of ash measurement errors on volatile yield (Knill et al., 1990)

5.3 THE 1 MW$_{th}$ TEST RIG

5.3.1 General layout

The 1 MW$_{th}$ test rig was designed by the IFRF (International Flame Research Foundation) and is in operation since 1989 (Krebbers, 1989). The furnace and the burner are designed to burn a wide range of pulverised coals. Excess air levels are adjustable in the range from 5 to 40%. The furnace exit temperature is normally 1150 °C, but may be as low as 900 °C. The residence time of the particles in the furnace is about 1.7 s (at full load), but varies with the coal flow and the excess air ratio.

The installation consists of two coal bunkers, a coal feed pipe, a burner, a furnace, a flue gas cooler, an ash removal system and a desulphurisation unit (see **figure 5.3**). The swirl burner is placed in the top of the furnace and the flue gases are extracted from one side of the furnace near the bottom. The 'cold' end of the furnace consists of a conical opening through which the bottom ash is removed. A special cylindrical section has been designed for the injection of tertiary air to simulate in-furnace air staging conditions. This section is equipped with four ports spaced at 90° around the shell. The furnace with an inside diameter of 1.4 m consists of several concentric rings (variable from 9 to 12 rings), which are individually water-cooled. Each section contains two observation ports. These ports can also be used for temperature measurements, gas and solids sampling.

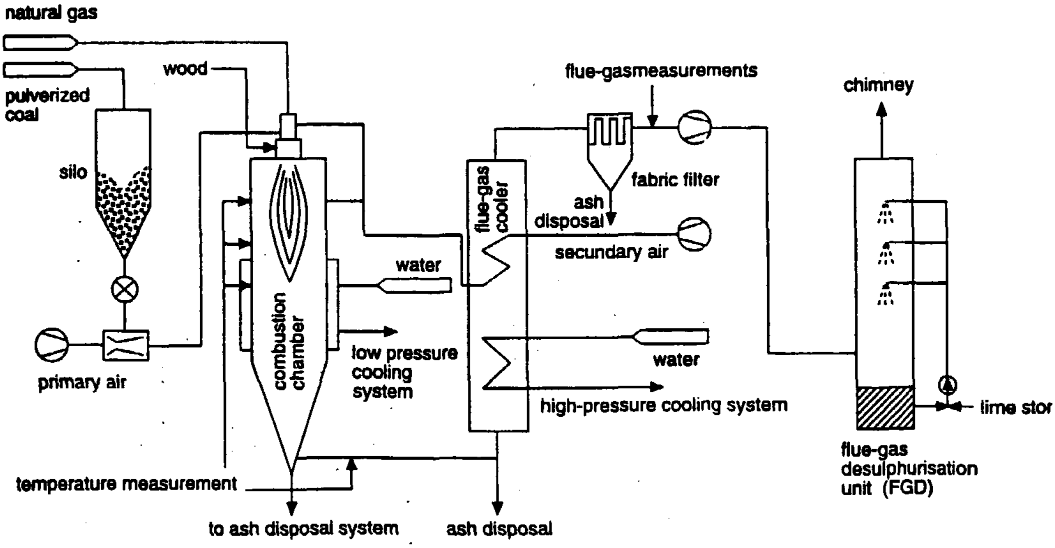


Figure 5.3 Overview of the 1 MW$_{th}$ test rig

5.3.2 Burner design and performance features

The burner consists of concentric gas, coal and secondary air transport pipes discharging into a water-cooled quarl fitted in the top of the furnace. The aerodynamically air staged burner (AASB) is shown in **figure 5.4**. A movable block swirl generator is located above the quarl inside a windbox. The coal gun is movable within the windbox so that this position within the quarl is adjustable. The swirl number of the secondary air is adjustable from zero to more than two. The swirl number for a coal flame typically ranges from 0.6 to 1.2.

NO_x emissions are affected by a number of burner and operation parameters. A similar burner as applied in this study was applied in various investigations performed by the IFRF. Morgan (1989) listed the design and operation parameters affecting the NO_x emissions of such a burner:

- quarl design
- swirl of the secondary air
- primary air velocity and momentum
- secondary air velocity and momentum
- coal injector design
- coal injector position
- temperature in the near burner zone.

The basic principle of swirl burners is that above a certain swirl level, part of the flow is recirculated back to the burner in an internal recirculation zone (IRZ), which offers high combustion efficiency and good flame stability. The recirculating combustion products heat the incoming fuel and primary air flow needed to ignite the coal. The highly turbulent shear layer between the internal recirculation zone and the surrounding forward flow further enhances the mixing. The shape of the quarl, especially the quarl exit angle, determines to a large extent the flow in the internal recirculation zone. With a proper design substoichiometric conditions prevail in the IRZ. The coal particles devolatilise in this zone and the nitrogen containing species released with the volatile matter react to molecular nitrogen due to the lack of oxygen.

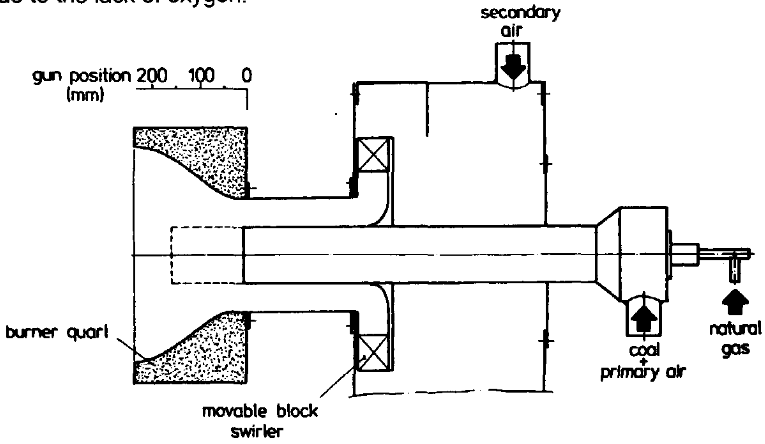


Figure 5.4 Aerodynamically air staged burner (Knill et al., 1988)

Particle trajectories are very important to understand the NO_x formation mechanisms in the AASB. Typical particle trajectories are shown in **figure 5.5** (Morgan et al., 1989). Path 1 corresponds to a particle that pass the internal recirculation zone, but is heated in the shear layer between the IRZ and the secondary air. High NO_x levels will be produced due to the high temperatures and the abundance of oxygen. Path 2 shows the trajectory of the particles, which partially penetrates the internal recirculation zone, but after loosing momentum the particle is transported out of the internal recirculation zone into the secondary air. If the heating rate is fast enough the particle is completely devolatilised inside the IRZ and the volatile nitrogen species react to N_2 because of the substoichiometric conditions. Path 3 illustrates the particles that fully penetrate the internal recirculation zone. If particles follow this path the NO_x formation will be low, because the volatile nitrogen species react in the internal recirculation zone to form molecular nitrogen. There is a chance, however, that some volatiles escape the IRZ and react with the oxygen rich secondary air (over penetration).

5.3.3 Measuring equipment

The temperature and the flow rate of the primary, secondary and tertiary air were measured. The temperature and the flow rate of the cooling water of each section were measured continuously. The temperatures in the furnace were measured with a suction pyrometer. Gas and solids were sampled using water-cooled probes.

The NO_x emissions were measured with an Eco Physics CLD700 EL ht monitor. The SO_2, CO and CO_2 concentrations were measured with a Rosemount Binos 100. The O_2 concentration was measured with a Teledyne monitor.

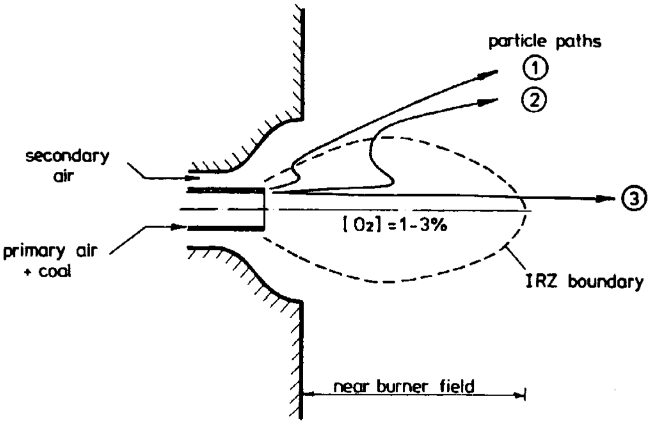


Figure 5.5 Typical particle trajectories in an AASB (Morgan et al., 1989)

5.3.4 Operating conditions

In 1989 the first test results were obtained with the 1 MW_{th} test installation (Benneker et al., 1992). The objective of these trials was to gain experience with the influence of burner settings, swirl number, coal injector position, air ratio and air staging on furnace operation, flue gas composition and coal burnout. That programme resulted in the burner settings as they were used for the coal characterisation experiments, described in chapter 6. These experiments were performed with a swirl number of 0.6 and a gun position of 60 mm. The tertiary air ports were located at a distance of 1.35 m below the top of the furnace. The residence time in the primary combustion zone was approximately 1.5 seconds with 30% tertiary air.

5.4 COAL-FIRED POWER PLANTS

5.4.1 General

The coal-fired power plants in the Netherlands have to operate with a number of restrictions, such as:

- meeting the emission limits for NO_x, SO_2 and dust
- dealing with a wide variety of world-traded coals
- fly ash and bottom ash may not be dumped but have to be applied.

Table 5.2 General features of Maasvlakte unit 1 and 2, Amer unit 9 and Hemweg unit 8

	Maasvlakte unit 1+2	Amer unit 9	Hemweg unit 8
Company	EZH	EPZ	UNA
Location of plant	Rotterdam	Geertruidenberg	Amsterdam
Year of commissioning	1988/1987	1993	1994
Capacity (MW_e)	518 (per unit)	600 (582 MW_e + 350 MW_{th})	630
Burner arrangement	tangential-fired	tangential-fired	opposed-wall-fired
Low NO_x burners	CE burners	PM burners (MHI)	HTNR burners (Babcock Hitachi)
No. of pulverisers	5	6	6
Pulveriser type	CE Bowl mill (with rotating classifier)	Deutsche Babcock MPS 235 (with rotating classifier)	Deutsche Babcock MPS 225 (with rotating classifier)
Boiler type	forced circulation	once-through Sulzer	once-through Benson
Live steam prod. (kg/s)	444	554	550
Live steam temp. (°C)	540	535	540
Live steam pres. (bar)	185	230	260
Reheat steam temp. (°C)	540	568	568

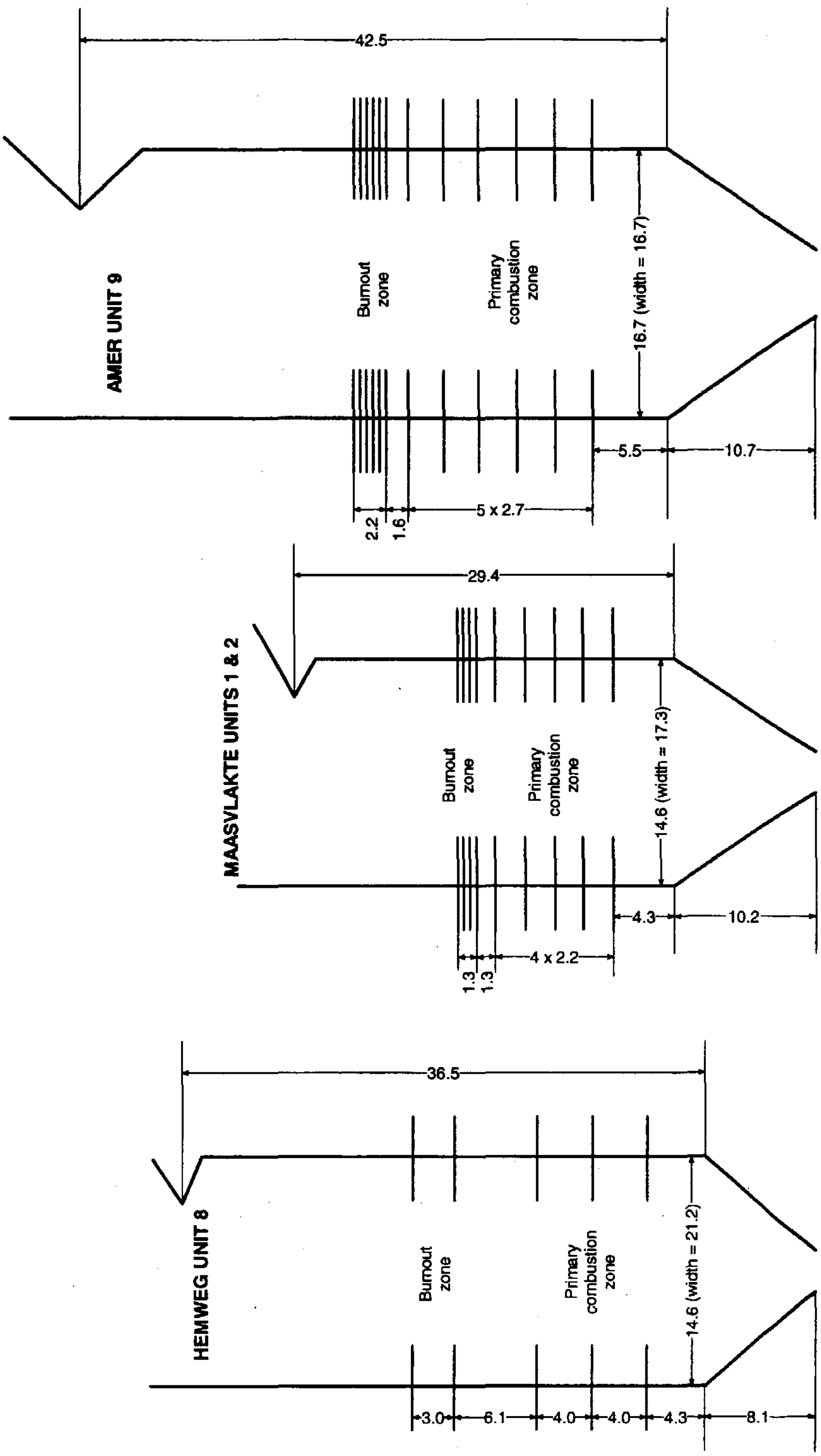


Figure 5.6 Dimensions of the boilers (in metres)

Operational experience with the low NO_x burners applied in the Dutch coal-fired power plants was reviewed by Kluyver et al. (1995). The authors concluded that despite the primary low NO_x measures, applied in the boilers, corrosion of the furnace walls had not been detected so far. However, after three years of operation fireside corrosion occurred in the furnace of Hemweg unit 8, probably caused by flame impingement (Huijbregts et al., 1998). Besides the above-mentioned restrictions, coal-fired power plants also face new challenges such as the need to reduce CO_2 emissions, which can be achieved by increasing the thermal efficiency and by the co-combustion of renewables (biomass). In addition, as a result of the decreasing gas prices and the opening of the European electricity market, more operating flexibility is required.

This thesis focuses on the impact of coal quality and coal blending on NO_x emissions and burnout with the emphasis on full-scale test trials at three coal-fired power plants Maasvlakte unit 1 and 2, Amer unit 9 and Hemweg unit 8. **Table 5.2** lists some general features of the units. The dimensions of the boilers are illustrated in **figure 5.6**. Hereafter, a brief description is given of the units.

5.4.2 Maasvlakte power plant

5.4.2.1 General

Maasvlakte power plant consists of two identical pulverised coal-fired units (Maasvlakte unit 1 and Maasvlakte unit 2), constructed by Royal Schelde in the Netherlands (license of Combustion Engineering). The units are tangential-fired and were retrofitted from gas/oil to coal firing in 1987 and 1988 and equipped with the low NO_x combustion technology developed by Combustion Engineering (Colette, 1985). The only parts remaining from the period before the retrofit are the medium- and low-pressure turbines. The two-pass boiler is tangential-fired and equipped with five burner levels. The coal is supplied by five pulverisers, of which four are needed to maintain full load. The pulverisers are of the type CE Bowl mill 943 RPB. The maximum capacity is 54 ton/hr. In the early 90's the pulverisers were equipped with rotating classifiers developed by MHI.

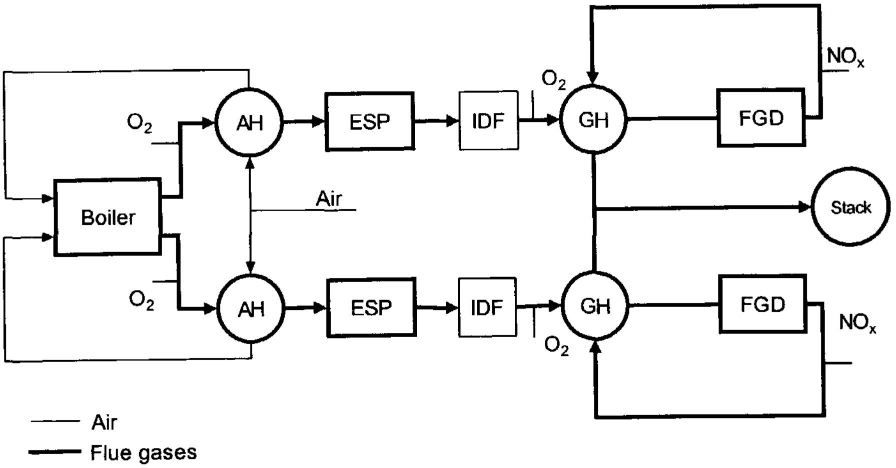


Figure 5.7 Flow diagram of the Maasvlakte units

Figure 5.7 shows a simplified flow diagram of the Maasvlakte units. This figure also shows the location of the main flue gases monitors used for the experimental data. The O_2 monitors before the air heaters an after the induced draft fan are Westinghouse monitors. The NO_x monitors are located after the FGD-units and are Lear Siegler monitors. The flue gases are sampled using a single point sample system.

The flue gas monitoring during the blending experiments at Maasvlakte power plant, described in chapter 10, was performed with additional sample grid measurements, installed in the flue gas ducts downstream the FGD units. During these experiments the O_2 concentration was measured with a Maihak OXOR 6N monitor, the CO and CO_2 concentration with a Maihak UNOR 6N monitor and the NO and NO_x concentration with a TECAN CLD 700 EL ht (Ecophysics) monitor.

5.4.2.2 Boiler settings

The air distribution has a major impact on NO_x emissions and burnout. **Figure 5.8** illustrates the windbox with the various air valves.

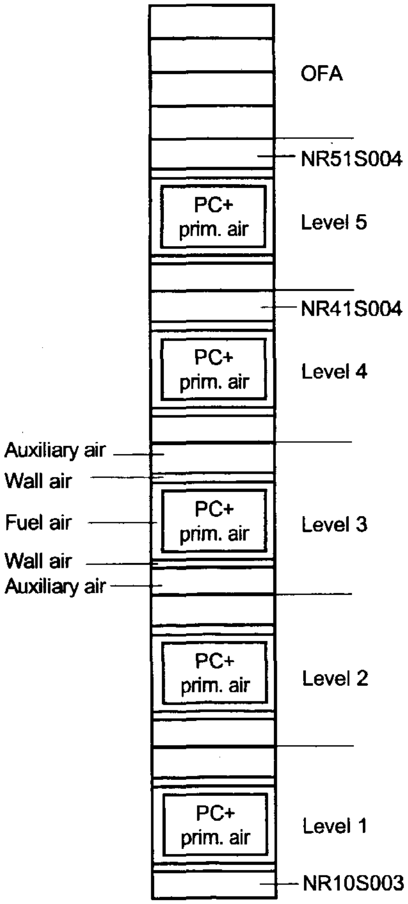


Figure 5.8 Windbox of the Maasvlakte units

The windbox consists of five burner levels and four overfire air ports. Each burner level consists of one primary air/pulverised coal burner, one fuel air compartment, two wall air nozzles and two auxiliary air nozzles. The wall air nozzles were installed to avoid reducing conditions near the furnace walls. However, after a few years of operation it was decided to reduce the amount of wall air since gas measurements near the furnace walls had shown that with a reduced wall air oxidising conditions still prevailed. Furthermore, it was demonstrated that the wall air had a negative effect on burnout. At present, a minor part of the combustion air is introduced into the furnace through these air ports for cooling purposes. The auxiliary air dampers are used to control the windbox-to-furnace pressure differential. Three dampers can have a different setting than the others. The dampers NR10S003, NR41S004 and NR51S004 (shown in **figure 5.8**) can be individually closed, fully opened or in control. If one of these dampers is fully opened, than all the other auxiliary air dampers close somewhat to maintain the desired windbox-to-furnace pressure differential. The windbox-to-furnace pressure differential is used to control the OFA ratio. An increase of the pressure differential results in an increase of the amount of overfire air when the OFA ports are fully opened. The fuel air dampers are controlled by the feed rate of the coal feeders. If the amount of coal is increased the amount of fuel air is increased proportionally.

The burner tilt and the OFA tilt can be adjusted separately and are generally used to control the steam temperatures. Soothblowing is another important factor in maintaining the steam temperatures. The soothblowing pattern and frequency is used to control furnace slagging and fouling of the superheaters and to control the thermal behaviour of the boiler. Finally, fine-tuning of the steam temperatures is achieved by the attemperation water flows.

Since only four burner levels are needed to maintain full load the operators may choose which burners are operated. Operation with the lower four burner levels in operation generally results in lower NO_x emissions and a higher burnout compared to the upper four burner levels in operation. A limiting factor is the thermal behaviour of the boiler, since the steam temperatures are sometimes difficult to maintain with the lower burners in service.

In general, a reduction of NO_x emissions by rearranging the air distribution leads to an increase of unburned carbon losses. At the Maasvlakte power plant an additional problem is encountered regarding the heat balance in the furnace (Rozendaal et al., 1993). The unusually large design of the forced circulation boilers in combination with the absence of slagging of the furnace walls result in a large heat transfer through the furnace walls so that the live and reheat steam temperatures are difficult to achieve and to maintain, especially, under transient conditions. Experience with the Maasvlakte units have shown that the NO_x emissions, the burnout and the thermal behaviour of the boiler are strongly related to each other. This relationship is known as the diabolical triangle. Adjustment of operating parameters, such as pulveriser arrangements, excess air level, burner tilt in order to improve one of these aspects, generally results in a negative effect on one of the other aspects. For instance, an increase of excess air level results in an improved burnout, but also leads to higher NO_x emissions and lower steam temperatures. Another example is the pulveriser arrangement. The desired steam temperatures are better to maintain by operation with the four upper burner levels, this, however, results in higher NO_x emissions and higher unburned carbon losses.

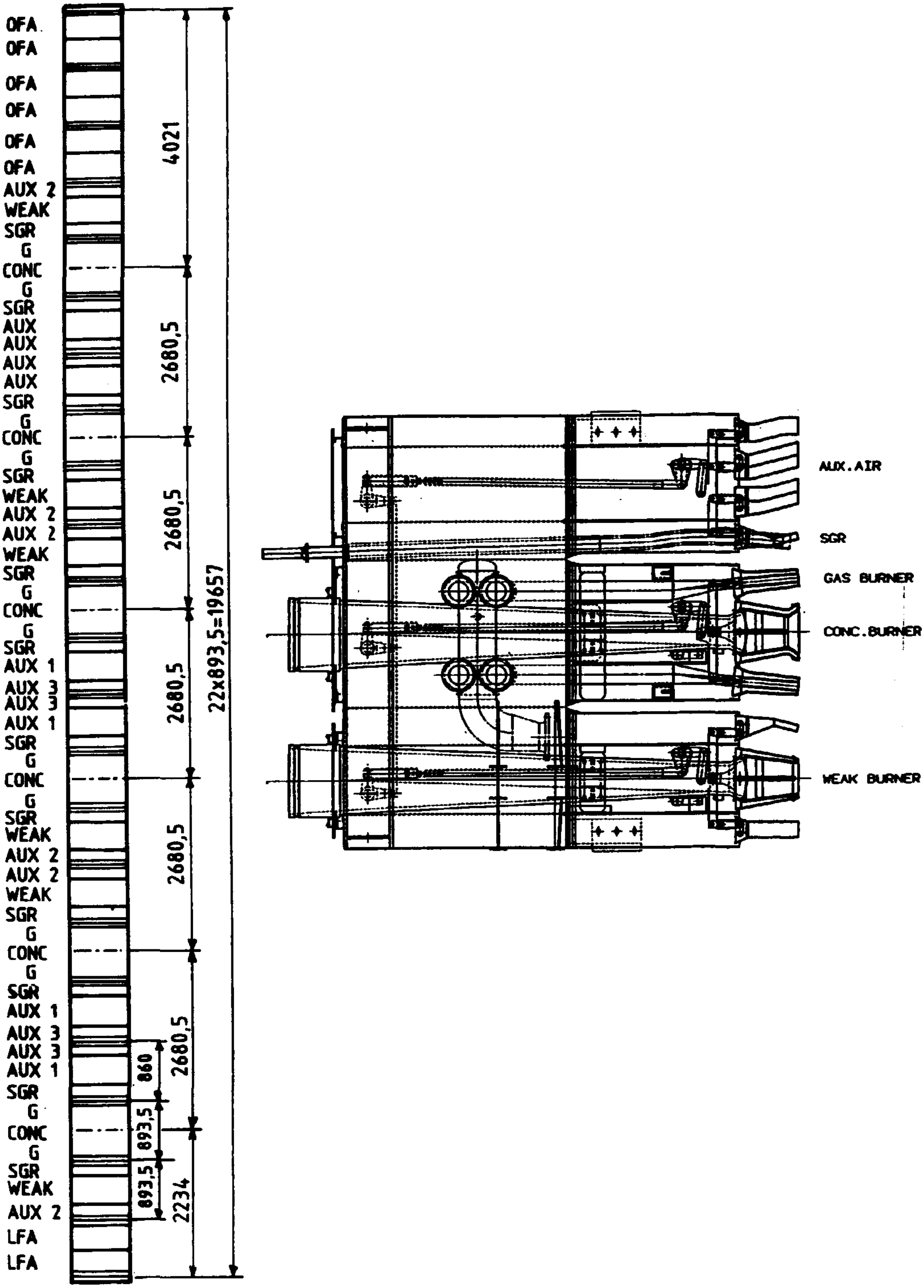


Figure 5.9 Details of the burners of Amer unit 9: (left) complete burner box (right) burner compartment

5.4.3 Amer power plant

Unit 9 of Amer power plant is a tangential-fired unit constructed by Royal Schelde in the Netherlands (license of Sulzer). The boiler is a two-pass supercritical once-through boiler with spiral-wounded tubes in the lower part of the furnace. The tangential-fired boiler is equipped with low NO_x Pollution Minimum burners (PM burner) designed by MHI (see **figure 3.6**) and (close coupled) overfire air ports. Deutsche Babcock designed the pulverisers (type MPS 235 with rotating classifier type SLS). Six pulverisers deliver pulverised coal (typically 75% smaller than 75μm) to six burner levels. Generally, five burner levels are needed to operate at full load.

Figure 5.9 gives an overview of a complete burner box. The PM burner consists of two separate burners both supplied with pulverised coal. The pulverised coal is transported from the outlet of the pulveriser to the burner. Just before the primary air/pulverised coal enters the burner this flow is divided in a fuel-rich and a fuel-lean flow by a divider. This divider separates the main flow in such a way that the fuel-rich burner is supplied with 70% of the pulverised coal and 50% of the primary air, and the fuel-lean burner with 30% pulverised coal and 50% primary air. Each burner level consists, furthermore, of several air compartments supplying the secondary air. The tertiary air is introduced into the furnace through the overfire air ports. **Figure 5.9** also illustrates a burner compartment. The fuel-rich burner is located between two separate gas recirculation (SGR) nozzles. Part of the flue gas is recirculated from the flue gas ducts after the air heaters and electrostatic precipitators via a flue gas heater to the burners. The auxiliary air ports are used to control the windbox-to-furnace pressure differential. Normally all auxiliary air ports are used to control the pressure differential. The operators, however, may choose to close or fully open one level of auxiliary air ports.

A simplified flow diagram of Amer unit 9 with the locations of the main monitoring equipment is given in **figure 5.10**. Flue gas samples are taken with a single point measurement system. The NO_x monitor downstream the FGD is from Du Pont. The O_2 monitors upstream the air heater and downstream the FGD are from Ametek.

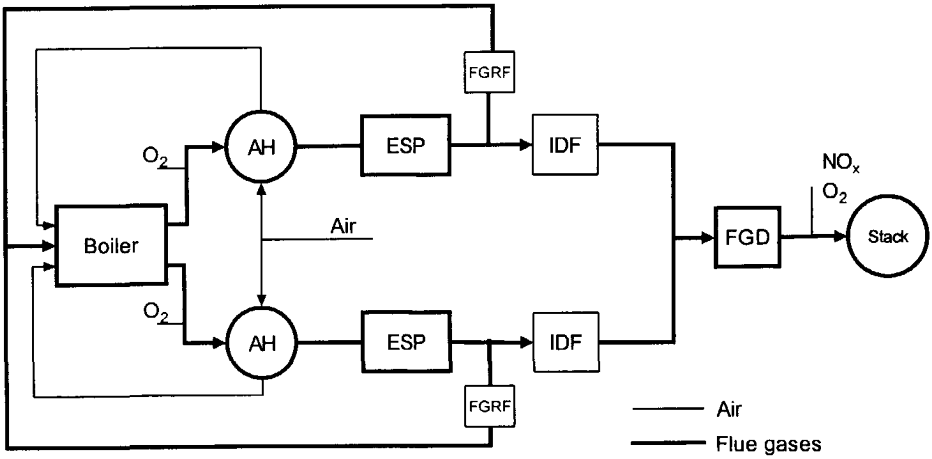


Figure 5.10 Simplified flow diagram of Amer unit 9

The impact of the different boiler settings on combustion performance is similar tot that of the units of Maasvlakte power plant. However, Amer unit 9 is equipped with flue gas recirculation. Flue gases are taken from the flue gas duct after the electrostatic precipitator and introduced into the bottom ash hopper and used as SGR (Separate Gas Recirculation) in the burners. The flue gases are recirculated through the bottom ash hopper only when the reheat steam temperature drops below 540 °C and is therefore a means to control the steam temperatures. The other part of the recirculated flue gases is passed through a gas heater located between the economiser and the air heater and is used for separating the pulverised coal and secondary air. The effectiveness of SGR for NO_x control is discussed in chapter 10.

5.4.4 Hemweg power plant

Hemweg unit 8 is an opposed-wall-fired supercritical Benson boiler manufactured by Stork boilers in the Netherlands. The unit is equipped with 36 HTNR burners equally distributed in the lower part of the front and back furnace wall. The type of burner is illustrated in **figure 3.5**. The furnace walls of this two-pass boiler are spiral wound. Above the main burners two rows of after air ports (AAP) have been installed to create air staging conditions favourable for low NO_x emissions. A schematic overview of the locations of the burners and the AAP's is given in **figure 5.11**.

The front and back wall of the furnace each contain two rows with six AAP's (totally 24 AAP's). The air supplied by each AAP is distributed over the core air and the swirling secondary air. The main task of the core air is to penetrate the centre of the furnace and to react with the combustion products from the primary combustion zone. The swirling secondary air is meant to oxidise the combustion reactants near the walls of the furnace. The air distribution over the upper and lower row of AAP's can also be varied. Generally, 70% of the overfire air enters the furnace through the upper row and 30% through the lower row of AAP's.

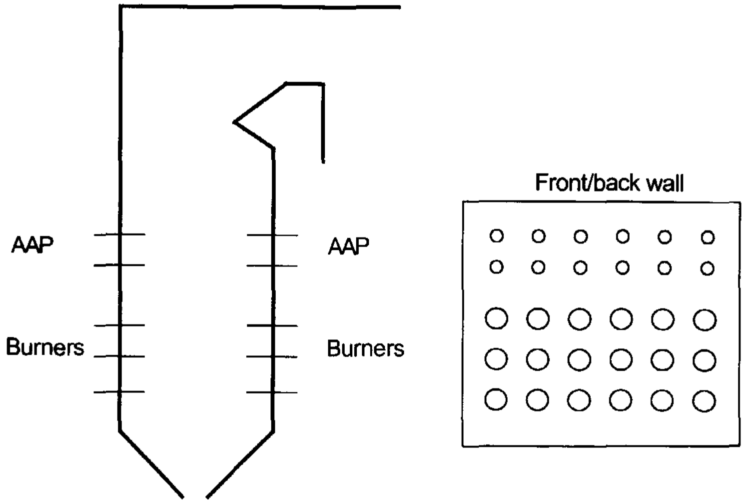


Figure 5.11 Location of burners and after air ports in the boiler of Hemweg unit 8

Various boiler settings may be used to optimise the combustion process. These include the overall stoichiometry, the stoichiometry in the burner zone, the settings of the AAP's, and the burner rows in service. Usually when the stoichiometry is increased the amount of overfire air is increased, since the burner zone stoichiometry is controlled separately. The impact of burner zone stoichiometry on NO_x emissions for three coals is illustrated in **figure 5.12** (Hoogendoorn et al., 1996). The effect on NO_x emissions is significant, whereas the effect on unburned carbon is almost negligible (not shown here). Low NO_x emissions can be achieved with a burner zone stoichiometry of about 0.8. This was also the burner zone stoichiometry used in the full-scale experiments (chapters 9 and 10).

In December 1996 it was noticed that the furnace wall suffered from corrosion (Huijbregts et al., 1998). Microscopic examination of the corrosion scales showed that the scale was typical for reducing atmospheres. It appeared that the flame shape played an important role in creating the corrosive atmosphere at the walls (flame impingement). One measure to reduce the flame impingement is to operate the centre burner rows at a lower capacity (-10%). In order to maintain capacity the other burner rows compensate the loss of capacity (+5%). The full-scale experiments presented in chapters 9 and 10 were all performed in this mode.

The oxygen concentration after the air heaters is measured with six Ametek in-stack monitors (three per flue gas duct). The O_2, NO and NO_2 concentration after the FGD is measured with an Ametek PDA monitor. A simplified flow diagram of Hemweg unit 8 together with the locations of the main flue gas measurements is shown in **figure 5.13**.

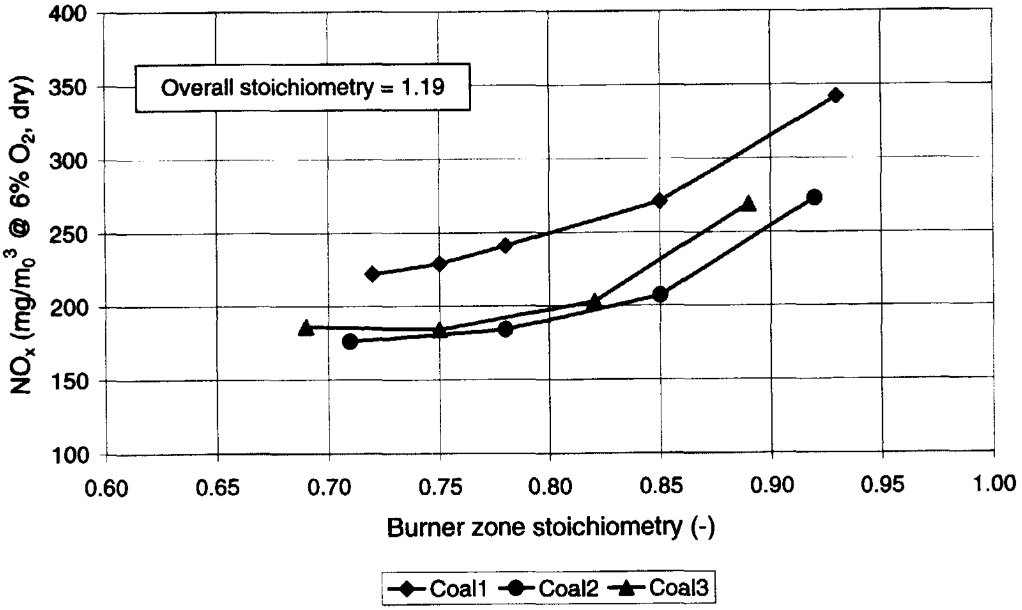


Figure 5.12 Impact of burner zone stoichiometry on NO_x emissions from Hemweg unit 8

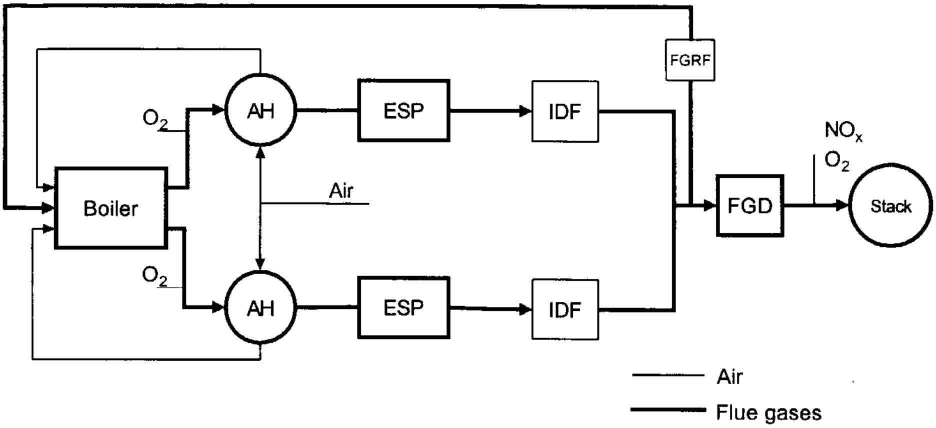


Figure 5.13 Simplified flow diagram of Hemweg unit 8

5.5 HEATED WIRE GRID REACTORS (HWG)

The coal(blend)s used in the Amer unit 9 experiments discussed in chapter 7 were characterised in the HWG reactor at DMT. The results of these HWG experiments are presented in chapter 8. The coals burned at Hemweg unit 8 were pyrolysed in the HTWM reactor at IC. These results are presented in chapter 9. This section contains a description of the HWG reactors.

The HWG reactor at DMT can be operated at pressures up to 10 MPa using gases such as H_2, CO or N_2 and up to 1.5 MPa pure steam. The maximum temperature of the platinum grid is 1500 °C. The coal particles are placed on the grid and are heated linearly with heating rates up to 1000 °C/s. The HWG reactor at DMT is illustrated in **figure 5.14**.

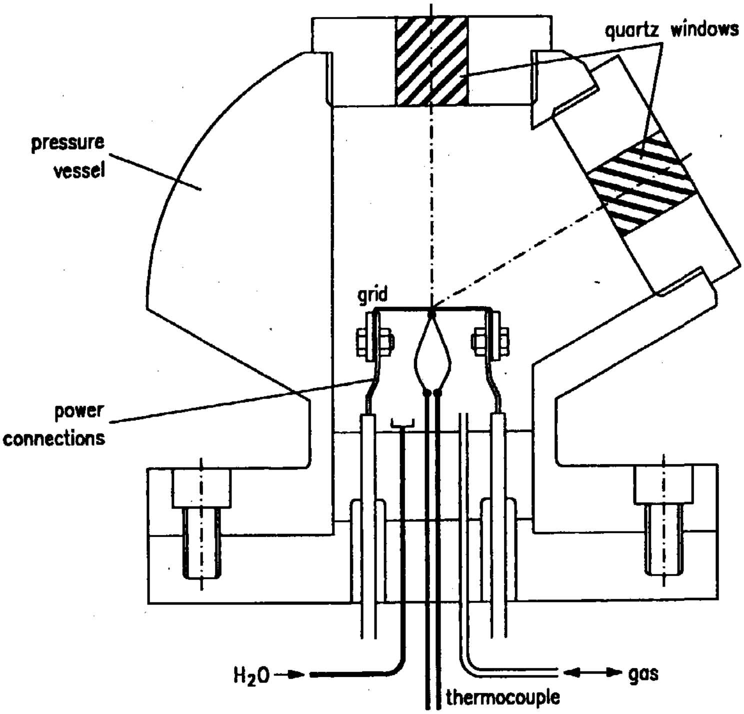


Figure 5.14 Schematic diagram of the heated wire grid reactor at DMT

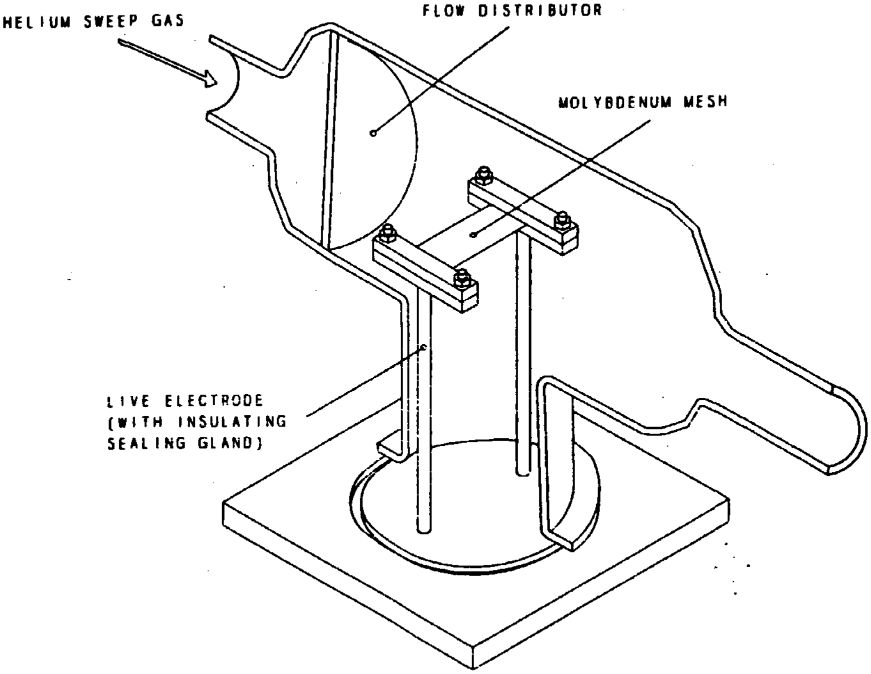


Figure 5.15 Schematic diagram of the high temperature wire mesh at IC

IC developed the HTWM reactor that can operate at a peak temperature of 2000 °C using a molybdenum mesh and with heating rates up to 50000 °C/s (Gibbins et al., 1995). Temperatures are measured using a two-colour infrared pyrometer calibrated against W3 thermocouples. A flow of helium across the wire-mesh sample holder prevents the redepositing of volatiles. This apparatus is limited to operation under reducing conditions by the properties of the mesh material. The HTWM reactor is shown in **figure 5.15**.

The coals are ground and sieved to 125–150 μm for compatibility with the molybdenum mesh (63 μm wires x106 μm aperture). The coal samples are dried overnight in a nitrogen-purged oven at 105 °C and then stored under nitrogen until required. Typically, 5 to 10 mg of the sample coal is used for each devolatilisation test. The residual char from the HTWM runs is recovered from the mesh. Sufficient char (typically 2 to 7 mg) is available for duplicate CHN measurements using a Carlo Erba 1106 microelemental analyser (Gibbins et al., 1995).

Table 5.3 lists the operating conditions of both HWG reactors.

Table 5.3 Conditions during the HWG experiments

	DMT	IC
Final temperature (°C)	1500	1600
Heating rate (°C/s)	103	104
Particle size fraction (μm)	53 – 105	125 – 150
Grid material	Platinum	Molybdenum

Chapter 6 COAL CHARACTERISATION IN 1 MW_{th} TEST RIG AND DROP TUBE FURNACE

6.1 INTRODUCTION

The effect of coal quality on NO_x emissions and burnout was studied with the 1 MW_{th} pulverised coal-fired test rig at KEMA. Within the framework of this study twenty world-traded coals were burned under unstaged and staged conditions. In the commissioning phase a burner parameter study was performed. On basis of these tests the operating parameters for the coal characterisation tests were selected. The tests described in this chapter were all performed with a swirl number of 0.6 and a gun position of 60 mm. In order to simulate in-furnace air staging conditions (overfire air), tests were performed with injection of part of the secondary air into the furnace at a distance of 1.35 m below the burner (corresponding to a residence time in the primary combustion zone of approximately 1.5 s). Additionally, most of the coals were characterised in a drop tube furnace (DTF) to determine the high temperature volatile yield and the partitioning of fuel nitrogen into volatile and char nitrogen.

6.2 EXPERIMENTAL

The proximate and ultimate coal analyses of the coals are presented in **table 6.1**. Because there was no grinding equipment available at KEMA, the raw coals were pulverised elsewhere. The fineness of the pulverised coal was checked every time the pulverised coal was delivered to KEMA.

The input conditions for the flames were relatively constant. The primary air temperature was 70 °C and the secondary air temperature was 275 °C. The thermal input including the secondary air preheat was approximately 0.95 MW_{th}. Generally, the coals were tested at three stoichiometric ratios (λ_{total} varied from 1.04 to 1.22). These tests are referred to as unstaged conditions. (In fact, this is not completely correct since the position of the gun was inside the internal recirculation zone as a result of which burner air staging was applied). At a stoichiometric ratio of about 1.2 two in-furnace air staging experiments were performed with in-furnace air staging with 15 and 30% of the total combustion air as overfire air. These tests are referred to as staged conditions. The test programme for each coal lasted a week. During each test char and fly ash samples were collected at various stages in the furnace. The flue gas composition and temperature were measured at the same locations for char sampling. A sample of the fly ash was taken form the bag house filter.

The results of the experiments have been described in more detail in (Rozendaal et al., 1992; 1993b; Benneker et al., 1994; Suijkerbuijk et al., 1995). This chapter focuses on the correlation of the NO_x emissions with coal parameters.

Table 6.1 Proximate and ultimate coal analyses of the coals tested in the 1 MW_{th} test rig

Coal	Proximate analysis				FR	D90	Ultimate analysis (wt.-%, daf)					Origin
	Moisture % ad	Ash % ad	VM % daf	LCV MJ/kg ad		µm	C	H	N	S	O[1]	
ATC	2.2	14.7	34.3	27.1	1.92	115	83.1	5.0	2.1	0.7	9.2	South Africa
Baileys	1.5	8.7	36.0	31.3	1.78	69	84.9	5.3	1.7	1.6	6.5	USA
CerrejonA	3.0	8.1	39.6	29.0	1.53	92	84.1	6.0	1.5	0.8	7.7	Colombia
CerrejonB	3.4	7.6	36.8	29.0	1.72	61	84.3	5.4	1.6	1.0	7.8	Colombia
Drayton	1.9	8.9	37.5	30.0	1.67	60	85.6	5.9	1.7	0.8	6.0	USA
Hobet	1.1	12.0	33.1	29.4	2.02	121	87.2	5.3	1.5	1.2	4.9	USA
Howick S.	2.8	11.4	37.4	27.9	1.67	100	82.9	5.4	1.7	0.7	9.4	Australia
Illawara	0.8	14.3	24.7	29.3	3.05	60	89.9	5.3	1.5	0.4	2.9	Australia
KPC	3.2	3.7	44.0	29.8	1.27	94	81.6	5.8	1.6	0.5	10.5	Indonesia
Koornfontein	2.9	14.0	31.3	26.6	2.19	78	85.1	4.5	2.0	0.7	7.8	South Africa
Mapco	1.2	8.6	35.1	31.2	1.85	104	87.8	5.5	1.6	0.9	4.2	USA
Middelburg	1.9	14.1	31.2	27.1	2.12	88	85.7	4.8	1.9	0.7	6.9	South Africa
Mingo Logan	1.2	10.3	34.9	29.4	1.87	53	85.1	5.3	1.6	1.1	7.0	USA
Prodeco	1.4	11.2	35.9	28.6	1.78	93	81.5	5.2	1.5	0.7	11.1	Colombia
Rietspruit A	2.4	16.6	26.9	26.7	2.72	57	85.3	4.7	2.0	0.9	7.2	South Africa
Rietspruit B	2.4	16.5	27.7	27.1	2.62	63	84.6	4.6	1.9	0.9	8.0	South Africa
United	1.6	13.7	38.2	28.3	1.62	69	85.8	6.0	1.4	0.9	5.9	USA
Ulan B	2.2	15.6	36.3	27.0	1.75	75	84.4	5.3	1.9	0.7	7.8	Australia
Vandijksdrift	1.7	14.9	30.4	27.3	2.29	94	85.8	4.6	2.0	0.4	2.9	South Africa
Whybro	2.0	11.3	38.3	28.6	1.61	87	85.0	5.6	1.8	0.8	6.8	Australia

[1] Oxygen by difference

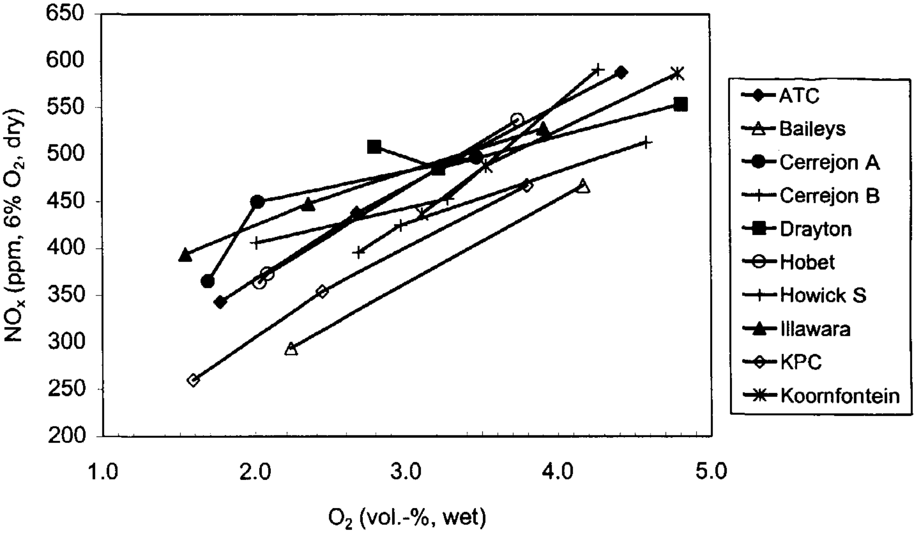


Figure 6.1a Impact of excess air on the NO_x emissions of ten coals in the 1 MW_{th} test rig

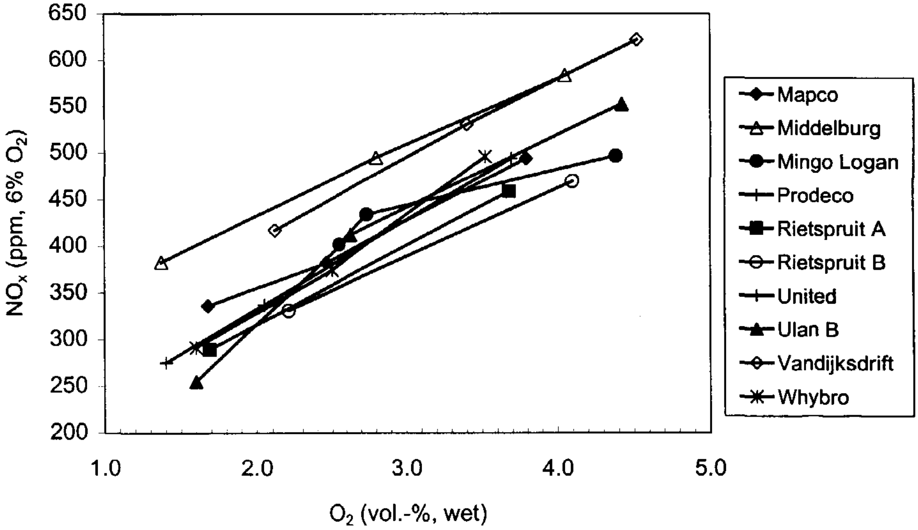


Figure 6.1b Impact of excess air on the NO_x emissions of ten coals in the 1 MW_{th} test rig (continued)

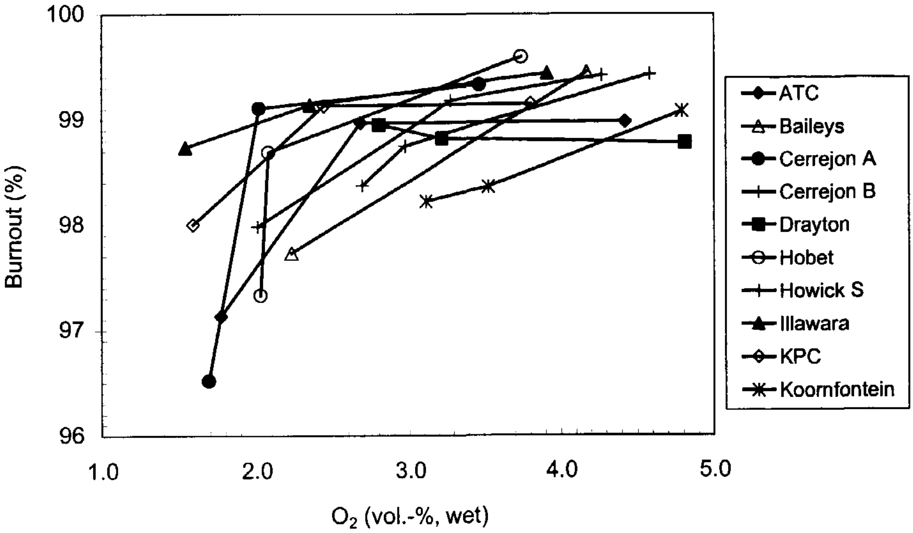


Figure 6.2a Impact of excess air on the burnout of ten coals in the 1 MW_{th} test rig

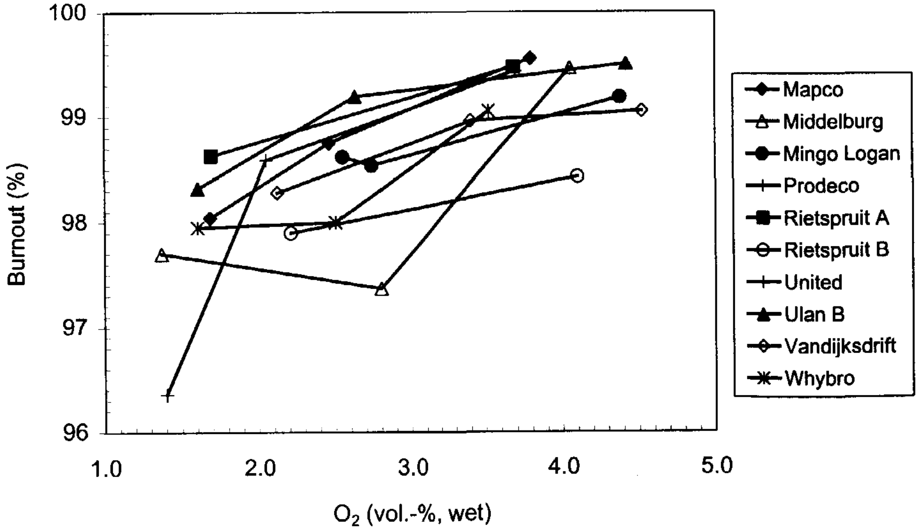


Figure 6.2b Impact of excess air on the burnout of ten coals in the 1 MW_{th} test rig (continued)

6.3 EXPERIMENTAL RESULTS

6.3.1 NO_x emissions and burnout in the 1 MW_{th} test rig

Figures 6.1a and **6.1b** show the impact of excess air on the NO_x emissions. Generally, it is observed that all coals behave similarly, although absolute NO_x values vary. NO_x emissions are high compared to the full-scale NO_x emissions discussed in the next chapters. The unstaged NO_x emissions of the test rig vary from 500 to 1300 mg/m_0^3 (normalised to 6% O_2), whereas the average full-scale NO_x emissions are in the order of 300 to 500 mg/m_0^3. The measurement error is estimated at 25 ppm. The average increase of NO_x emissions is 69 ppm with an increase of the oxygen concentration of 1 vol.-%.

The impact of excess air on burnout is illustrated in **figures 6.2a** and **6.2b**. The unburned carbon content in the fly ash is expressed as burnout by means of formula 3.35. It is observed that burnout increases with an increase of the excess air. For several coals the burnout is strongly reduced at low excess air ratios. The average increase in burnout is 0.49 % with an increase of the oxygen concentration of 1 vol.-%.

6.3.2 Drop tube furnace experiments

6.3.2.1 High temperature volatile matter

Sixteen (of the twenty) coals were pyrolysed in the DTF in an inert atmosphere to determine the high temperature volatile yield and to collect char samples prepared at temperatures of 1200 °C. The residence time in the DTF was estimated at a few seconds, which is long enough for pyrolysis to be completed. The particle size fraction of the coal samples was 53 - 106 μm.

The high temperature volatile matter (VM_{DTF}) was determined with the ash-tracer method according to formula 5.1. **Table 6.2** lists the results of the experiments in the DTF and the yield factor (sometimes referred to as the R factor) for each coal. The ash content in the char was determined with the proximate analysis. The collected char samples still contained some volatiles (VM_{char}) according the proximate analysis (also listed in **table 6.2**). This was also observed in experiments by others (Brink et al., 1990). The volatile matter content in the chars has been considered to be part of the fixed combustibles in the char and are therefore not included in the yield factor (similar to Brink et al. (1990)).

Table 6.2 The proximate volatile matter compared to the high temperature volatile matter

	VM (wt.-%, daf) (53 – 106 μm)	V_{DTF} (wt.-%, daf)	VM_{char} (wt.-%, daf)	yield factor
ATC	32.5	44.4	3.0	1.36
CerrejonA	40.0	46.8	2.0	1.17
CerrejonB	38.9	50.6	0.6	1.30
Drayton	39.3	53.7	2.1	1.36
Hobet	31.9	48.4	0.5	1.52
Howick S.	36.8	48.2	2.8	1.31
Illawara	23.0	31.5	1.1	1.37
KPC	43.3	56.2	0.6	1.30
Koornfontein	30.7	42.4	2.4	1.38
Mapco	34.0	45.2	2.4	1.33
Middelburg	30.8	41.2	3.1	1.34
Mingo Logan	35.5	51.3	0.4	1.45
United	37.6	57.3	2.1	1.52
Ulan B	36.1	49.8	1.0	1.38
Vandijksdrift	30.0	38.8	3.6	1.29
Whybro	37.3	50.4	2.2	1.35

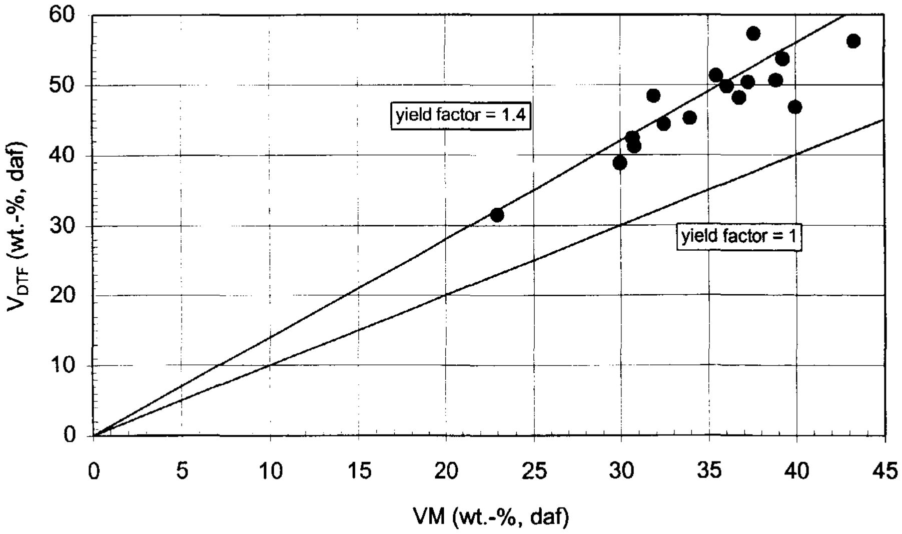


Figure 6.3 The high temperature volatile matter measured with the DTF (V_{DTF}) versus the proximate volatile matter (VM) of the size fraction 53 – 106 μm

The yield factor is defined as the ratio of the volatile yield measured with the DTF (V_{DTF}) to the proximate volatile yield of the particle size fraction 53 – 106 µm (VM), according to formula 2.5. The yield factor varies between 1.17 and 1.52. The average yield factor is approximately 1.4. **Figure 6.3** shows the relation between the proximate volatile matter yield and the volatile matter yield of the DTF. The South African coals all exhibit similar devolatilisation behaviour with an average yield factor of 1.34. Two of the four American coals used in this study have high yield factors of about 1.52.

6.3.2.2 Partitioning of fuel nitrogen into volatile and char nitrogen

The partitioning of fuel nitrogen into char and volatile nitrogen was determined by analysing the amount of nitrogen retained in the collected char samples. All experiments were executed twice. The fraction of nitrogen released with the volatiles, expressed as a percentage of the original amount of nitrogen in the coal, is calculated as:

$$\%N_V = \left(1 - \left(\frac{Ash_{coal}}{100 - Ash_{coal}} \cdot \frac{100 - Ash_{char}}{Ash_{char}}\right) \cdot \frac{N_{char,daf}}{N_{coal,daf}}\right) \cdot 100 \qquad (6.1)$$

with: $\%N_V$ percentage of total fuel nitrogen released with the volatiles

Ash_{coal} ash content in coal (wt.-%, db)

Ash_{char} ash content in char (wt.-%, db)

$N_{char,daf}$ nitrogen content in char (wt.-%, daf)

$N_{coal,daf}$ nitrogen content in coal (wt.-%, daf)

The results are listed in **table 6.3**. The fraction of nitrogen released with the volatiles versus the volatile yield is shown in **figure 6.4**.The results indicate that the nitrogen is slightly preferentially retained in the char for most of the coals at 1200 °C. The only exceptions are the South African coals ATC and Koornfontein and the Australian coal Ulan B.

The two Colombian coals El Cerrejon A and B have particularly high retention of nitrogen in the char as is shown in **table 6.3**. Man et al. (1994) and Brink et al. (1990) also found this anomalous behaviour for an unspecified Colombian bituminous coal.

Table 6.3 Partitioning of fuel nitrogen into volatile and char nitrogen (particle size fraction is 53 – 106 μm)

	N_{coal} wt.-%, daf	N_{char} wt.-%, daf	V_{DTF} wt.-%, daf	$\%N_V$ (%)	$\%N_V/V_{DTF}$
ATC	2.04	1.85	44.4	49.5	1.12
CerrejonA	1.68	2.03	46.8	35.6	0.76
CerrejonB	1.72	2.16	50.6	38.3	0.76
Drayton	1.87	2.09	53.7	48.2	0.90
Hobet	1.54	1.73	48.4	42.2	0.87
Howick S.	2.05	2.17	48.2	45.2	0.94
Illawara	1.69	1.71	31.5	30.7	0.97
KPC	1.61	1.97	56.2	46.4	0.83
Koornfontein	2.08	2.06	42.4	42.9	1.01
Mapco	1.61	1.66	45.2	43.4	0.96
Middelburg	1.97	2.01	41.2	39.8	0.97
Mingo Logan	1.75	1.90	51.3	47.4	0.92
United	1.63	1.75	57.3	54.2	0.95
Ulan B	1.97	1.95	49.8	50.5	1.01
Vandijksdrift	2.02	2.14	38.8	35.2	0.91
Whybro	1.84	2.01	50.4	45.8	0.91

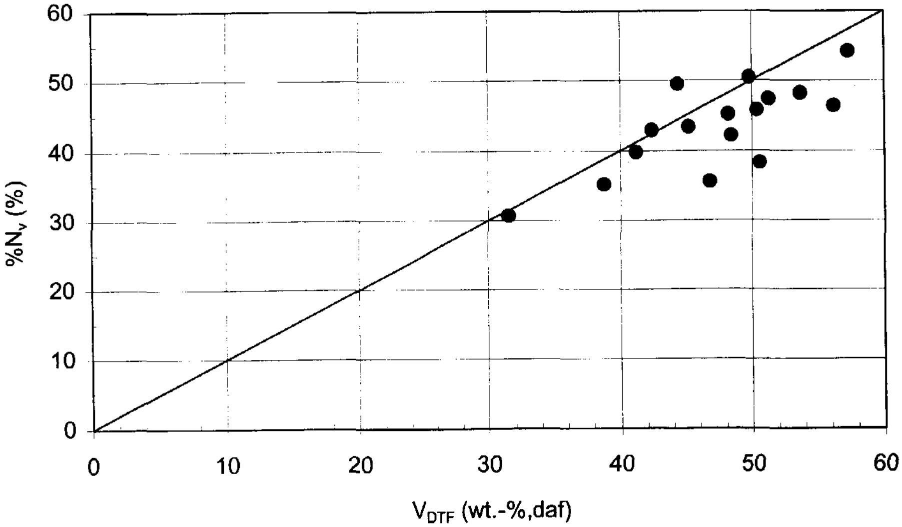


Figure 6.4 Fraction of nitrogen released with the volatiles ($\%N_V$ versus the high temperature volatile matter (V_{DTF})

6.4 CORRELATION OF NO_X EMISSIONS WITH COAL PARAMETERS

The NO_x emissions and burnout were correlated by means of linear regression analysis. Appendix A provides a short description of this statistical technique. The NO_x emissions and burnout values used in the regressions are interpolated values at an oxygen concentration of 3% in the flue gases. The input data set for the linear regression analysis is listed in **table 6.4**. In this data set also the NO_x emissions of the in-furnace air staging experiments are shown. The data set also contains the conversion ratio of fuel nitrogen to NO_x.

6.4.1 NO_x emissions as function of coal quality

The main results of the linear regression analysis are listed in **table 6.4**. An oxygen lean combustion zone in the centre of the flame (aerodynamically air staging) existed during the experiments, since the gun position was set at 60 mm. This was supported by the high CO and low O_2 concentrations measured in the near burner region, also in the unstaged experiments. High-volatile coals therefore, generally, resulted in lower NO_x emissions than low-volatile coals. With the staged combustion experiments, whereby 30% of the air is used as overfire air, the conditions are even more favourable for low NO_x emissions. However, the correlation coefficients given in **table 6.4** shows that no simple correlation exists between standard coal parameters and the NO_x emissions. For example, the correlation coefficients of the volatile matter and fuel ratio with the NO_x emissions of the unstaged experiments are only 0.17 and 0.15, respectively. A slightly better correlation is achieved with the high temperature volatile matter ($R^2 = 0.21$). The NO_x emissions of the staged experiments obtained a correlation coefficient of 0.29 and 0.35 with the proximate volatile matter and fuel ratio, respectively. The high temperature volatile matter resulted in a correlation coefficient of 0.45.

The conversion ratio (CR_{fuelN}) of fuel nitrogen to NO_x is calculated using the nitrogen and carbon content in the coal and the measured emissions of CO, CO_2 and NO_x. in the flue gases, according to (Shimizu, 1992):

$$CR_{fuelN} = \frac{[NO_x]}{([CO]+[CO_2])\left(\frac{N}{C}\right)_{coal}} \tag{6.2}$$

with: $[NO_x]$, [CO] and $[CO_2]$ concentrations of NO_x CO and CO_2 in the flue gases (as measured)
N/C ratio molar ratio of nitrogen and carbon in coal

The measured NO_x emissions originate partly from thermal NO, however, thermal NO is difficult to measure. Smart (1993) estimated the thermal NO for a similar burner at 100 ppm. The NO_x emissions with operation at natural gas equal 60 ppm. In the calculation of the conversion ratios it is assumed that the contribution of thermal NO is 100 ppm.

Table 6.4 Correlation of NO_x emissions and conversion ratios with coal parameters

Coals	NO_x	CR_{fuelN} 1)	NO_x	CR_{fuelN} 1)	V_{DTF}	$\%N_V$	VM	N	fuel ratio
	(ppm, 6% O_2)	-	(ppm, 6% O_2)	-	wt.-%, daf	%	wt.-%, daf	wt.-%, daf	-
Mode ▸	unstaged	unstaged	staged	staged					
ATC	460	17.1	338	8.9	44.4	49.5	34.3	2.06	1.92
Baileys	401	17.4	349	12.4	n.a.	n.a.	40.0	1.66	1.50
CerrejonA	475	19.9	417	15.5	46.8	35.6	39.6	1.49	1.53
CerrejonB	420	20.5	360	13.2	50.6	38.3	36.8	1.61	1.72
Drayton	479	18.8	400	12.3	53.7	48.2	37.5	1.67	1.67
Hobet	463	22.8	309	11.4	48.4	42.2	33.1	1.51	2.02
Howick S.	468	21.3	355	11.3	48.2	45.2	37.4	1.71	1.67
Illawara	498	24.1	483	20.5	31.5	30.7	24.7	1.52	3.05
KPC	396	17.4	287	10.1	56.2	46.4	44.0	1.60	1.27
Koornfontein	434	19.8	380	12.0	42.4	42.9	31.3	1.95	2.19
Mapco	431	19.8	328	11.7	45.2	43.4	35.1	1.60	1.85
Middelburg	507	20.8	361	11.0	41.2	39.8	31.2	1.88	2.21
Mingo Logan	434	19.8	308	10.7	51.3	47.4	34.9	1.64	1.87
Prodeco	428	20.3	250	8.2	n.a.	n.a.	41.0	1.46	1.44
Rietspruit A	389	14.9	335	9.7	n.a.	n.a.	33.2	1.95	2.01
Rietspruit B	363	15.1	291	8.0	n.a.	n.a.	34.1	1.92	1.93
United	448	21.1	n.a.	n.a.	57.3	54.2	38.2	1.43	1.62
Ulan B	419	18.4	343	10.4	49.8	50.5	36.3	1.87	1.75
Vandijksdrift	494	19.8	379	11.0	38.8	35.2	30.4	2.01	2.29
Whybro	436	17.5	285	8.5	50.4	45.8	38.3	1.79	1.61
R^2 NO_x unstaged	-	-	-	-	0.21	0.02	0.17	0.07	0.15
R^2 CR_{fuelN} unstaged	-	-	-	-	0.20	0.27	0.10	0.34	0.15
R^2 NO_x staged	-	-	-	-	0.45	0.44	0.29	0.01	0.35
R^2 CR_{fuelN} staged	-	-	-	-	0.32	0.57	0.17	0.23	0.27

1) Conversion ratios are calculated with formula 6.2. The as measured NO_x concentrations are used in the formula. Thermal NO_x is assumed *to be 100 ppm.*

Figure 6.5 shows the conversion ratio of fuel nitrogen to NO_x emissions for the staged and unstaged experiments as function of the proximate volatile matter content on a dry and ash-free basis. It is observed that, in both cases a weak trend exists of lower conversion ratios with higher volatile coals. This suggests that NO_x emissions are more dependent on the nitrogen formed in the burnout zone via char nitrogen and less from the nitrogen released with the volatiles.

6.4.2 Nitrogen partitioning and NO_x emissions

The conversion ratio of coal nitrogen to NO_x for both conditions is presented in **figure 6.6** as function of the percentage of nitrogen in the volatile fraction measured with the DTF. The regression lines and the coefficients of determination have been included. It is observed that the conversion ratio of nitrogen to NO_x is lower for the staged experiments than for the unstaged experiments. This indicates (as expected) that in the staged experiments less volatile nitrogen is converted to NO_x than in the unstaged experiments.

Two main conclusions can be drawn from the linear regression lines in **figure 6.6**. First, the conversion of volatile nitrogen to NO_x is lower than the conversion of char nitrogen for both the staged as the unstaged experiments. The second conclusion is that the conversion of volatile nitrogen to NO_x for the in-furnace air staging conditions (90/30) is much lower than the conversion of volatile nitrogen to NO_x with the unstaged conditions. It may be assumed that the conversion ratio of volatile nitrogen to NO_x is close to zero for the in-furnace air staging experiments. Extrapolation of this regression line indicates that if all coal nitrogen is released with the volatiles the conversion ratio of coal nitrogen is zero.

The char nitrogen conversion ratios can be calculated by assuming that for the in-furnace air staging conditions the volatile nitrogen conversion to NO_x is zero and that the thermal NO is 100 ppm. In **figure 6.7** the char nitrogen conversion ratios of 15, 20 and 25% are drawn and compared to the measured values. It is observed that the measured values all lie between the 15 and 25% char nitrogen conversion lines, except for the low-volatile coal Illawara. This coal experiences a char nitrogen conversion ratio of about 30%. It should be noted here that the char nitrogen conversion ratios are strongly dependent on the conditions at which the chars are produced. If the temperature is increased, generally more nitrogen is released with the volatiles. Consequently, the char nitrogen conversion ratio increases.

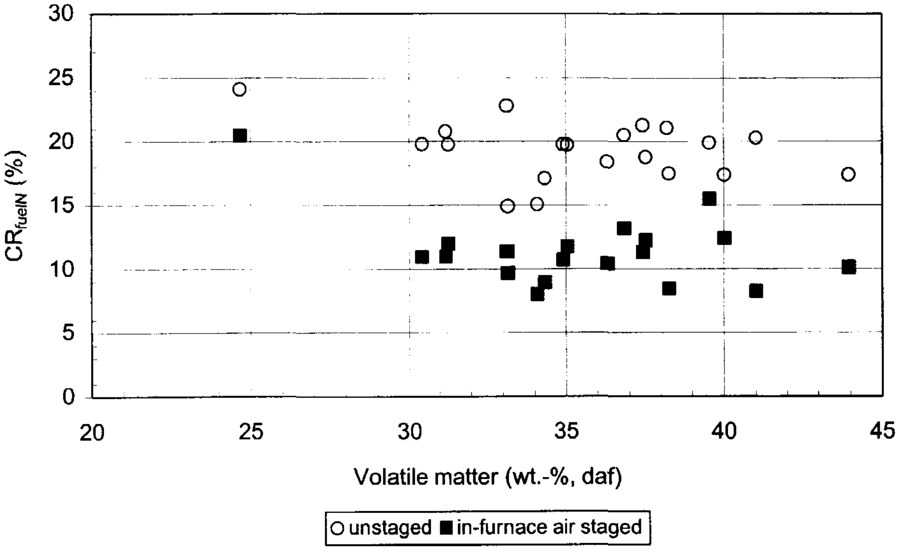


Figure 6.5 Conversion ratio of fuel nitrogen to NO_x as function of the proximate volatile matter (daf)

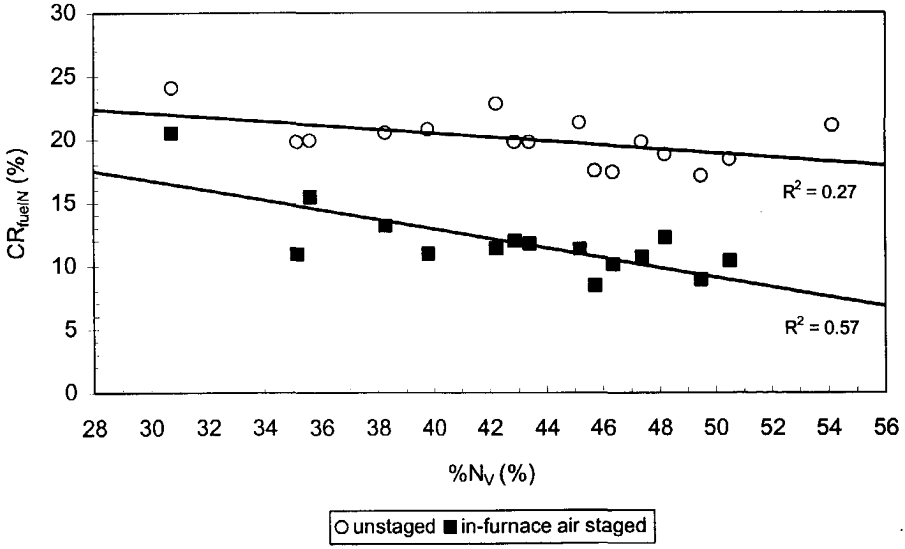


Figure 6.6 Conversion ratio of fuel nitrogen as function of the percentage of nitrogen released with the volatiles

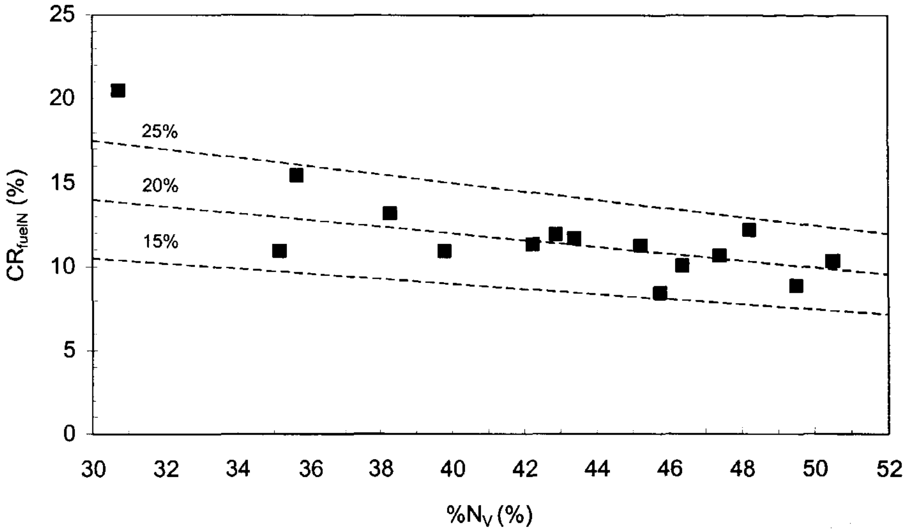


Figure 6.7 Measured char nitrogen conversion ratios to NO_x for the in-furnace air staged conditions compared to constant conversion lines (assuming that the conversion ratio of volatile nitrogen is zero and that the contribution of thermal NO is 100 ppm)

6.5 DISCUSSION

Unstaged conditions

The effect of coal properties on NO_x emissions of the AASB was investigated under both unstaged and staged combustion conditions. It should be noted that unstaged conditions refer to the condition that **no in-furnace air staging** was applied. However, burner staging was accomplished in both situations since the gun was positioned inside the internal recirculation zone (IRZ).

The correlation of the unstaged NO_x emissions with the standard coal characteristics was not very clear. A weak trend existed between the volatile matter content and the NO_x emissions, which indicated that burner staging is effective and also creates conditions favourable for low NO_x combustion. Because of the weak correlation between coal characteristics and NO_x it was expected that more advanced coal characteristics such as the high temperature volatile matter and data on the nitrogen partitioning into volatile and char nitrogen would result in a better correlation. The correlation improved, however, marginally.

The reasons for the difference in expectation and the observed behaviour may be twofold:

- the coal characteristics considered are not suited for NO_x prediction of the AASB
- the burner aerodynamics and hence NO_x emissions are sensitive to small fluctuations in process conditions.

The NO_x emissions under unstaged conditions are in the order of 700 to 1000 mg/m$_0^3$ (values interpolated at 3% O_2 in the flue gases) compared to the NO_x emissions experienced in full-scale boilers (200 to 500 mg/m$_0^3$) as is shown in the following chapters. In chapter 3 it was already deduced that in old units NO_x emissions increase with an increase of the volatile matter, while NO_x emissions decrease in modern low NO_x units. Somewhere in between an old high NO_x and a low NO_x unit there is a turning point where NO_x emissions are relatively insensitive to the volatile matter. The results suggest that this turning point appears around NO_x emissions in the order of 800 to 900 mg/m$_0^3$. The weak correlation of coal characteristics and NO_x emissions for the same burner type (2.5 MW_{th}) was also found by Morgan (1990), as is shown in **table 3.3** (staged in **table 3.3** refer to burner air staged, i.e. position of the gun inside the IRZ).

The behaviour of the burner depends on the particle trajectories as explained in chapter 5. Low NO_x emissions are achieved when the particles fully penetrate the IRZ. The extent of penetration is amongst others dependent particle size. Smaller particles are more easily entrained from the IRZ than large particles. Correlation of particle size with the NO_x emissions, however, did not result in a significant improvement of the correlation. Another complicating factor, observed by Morgan et al. (1989) with a similar burner, is that the oxygen availability is the same for all coals (assuming that the aerodynamic behaviour of the burner remains constant). Coals that release more volatiles are exposed to a relatively less amount of oxygen than coals releasing less volatiles. One would therefore expect higher NO_x emissions with coals with a low volatile content. However, the residence time required for the complete conversion of volatile nitrogen is longer for high-volatile coals than low-volatile coals. And, since these reactions have to be completed in the limited confines of the IRZ, this could result in penetration of the volatile nitrogen species in the oxygen rich shear layer between IRZ and secondary air flow. This mechanism compensates the expected low NO_x production of high-volatile coals. Since the particle size is believed to have a major impact on the particle trajectories it is not surprising that the explanation for the differences in coal behaviour is difficult to give.

Other variables that might result in fluctuations in process conditions, are thermal load and slagging of the furnace. Some coals caused slagging of the furnace, which resulted in a reduced heat transfer through the furnace walls. Consequently, the furnace temperature raised and NO_x emissions increased.

The various mechanisms mentioned above result in a burner behaviour that is difficult to explain. If the burner is operated in the burner air staged mode (gun positioned in the IRZ) high-volatile coals result in somewhat lower NO_x emissions compared to low-volatile coals. In actual low NO_x burners this effect is more pronounced. The behaviour of a low NO_x burner is approached when the burner is operated in the in-furnace air staged mode.

Staged conditions

Lower NO_x emissions were observed with the in-furnace air staging experiments compared to operation without overfire air. The main reason for this is that the primary burner zone is operated under reducing conditions. The effect of coal quality is more pronounced. The conversion ratio of fuel nitrogen showed a trend with the relative amount of nitrogen released with the volatiles. The more nitrogen is released with the volatiles the lower the conversion ratio.

A number of remarks has to be made. It is still uncertain if the conditions used for the determination of the high temperature volatile matter content are comparable to the actual conditions. In chapter 8 and 9 this will be discussed in more detail. Another point is that the average NO_x emissions in the staged experiments are still high compared to actual boilers. The NO_x emissions of the 1MW_{th} test rig under staged conditions vary between 500 and 900 mg/m_0^3, whereas the NO_x emissions from full-scale units vary between 200 and 500 mg/m_0^3. Since the balance between char and volatile nitrogen and the tendency to form NO_x from both precursors are very delicate it is doubted if the relations obtained with this burner can be extrapolated to full-scale burners.

The burnout was correlated with coal characteristics for both conditions. No simple correlation could be obtained. A weak trend existed between the burnout and volatile matter for the unstaged experiments. Low-volatile coals generally exhibited a lower burnout. It was apparent that the burnout was not reduced with the in-furnace air staging conditions, probably caused by the extended residence time in the primary combustion zone and the intense mixing of the tertiary air downstream the burner.

6.6 CONCLUSIONS

The correlation of coal characteristics with the NO_x emissions of twenty world-traded coals from a 1 MW_{th} test rig showed that under unstaged conditions (without overfire air, but with burner air staging) only a weak trend existed between coal characteristics and NO_x emissions. It was observed that an increase of the volatile matter content results in a minor decrease of NO_x emissions. The NO_x emissions under unstaged conditions were in the order of 700 to 1000 mg/m_0^3. It is suggested that operation of the AASB burner in the unstaged mode does not simulate a combustion process in a low NO_x boiler, where NO_x emissions as low as 200 to 300 mg/m_0^3 are possible.

The NO_x emissions from the staged experiments with an overfire air ratio of 30% correlated better with the coal characteristics, although NO_x emissions are still rather high (500 to 900 mg/m_0^3). The best correlation was obtained between the conversion ratio of fuel nitrogen to NO_x and the percentage of nitrogen released with the volatiles. The nitrogen release with the volatiles was measured with a drop tube furnace at 1200 °C. The conversion ratio of char nitrogen varied between 15 and 30%.

The drop tube furnace experiments showed that at 1200 °C the nitrogen is preferentially retained in the char. At a temperature of 1200 °C approximately 40% more volatile matter is released compared to the proximate volatile matter (yield factor is 1.4). The Colombian coal El Cerrejon observed the lowest yield factor of about 1.2.

Chapter 7 NO_x PREDICTIONS FOR TWO TANGENTIAL-FIRED UNITS

7.1 INTRODUCTION

In this chapter the experiments performed at two full-scale tangential pulverised coal-fired units, Maasvlakte unit 1 and Amer unit 9, are presented. The objective of both experimental programmes was to quantify the impact of coal quality on NO_x emissions and burnout to obtain prediction formulas based on standard coal characteristics. The prediction formulas can be used to judge coals or coal blends with respect to NO_x emissions and burnout before coals are procured or before coal blends are composed and delivered to the power plant.

Coal quality has a direct as well as an indirect impact on plant performance. NO_x emissions are influenced by coal characteristics, like the chemical composition and combustion reactivity, but are also governed by boiler settings. Generally, boiler settings, such as burner tilt, secondary air ports and overfire air ratio are adjusted as function of coal quality and load to control the steam temperatures or to realise a sufficient burnout. Maintaining steam temperatures at an acceptable level may conflict with the optimisation of other performance parameters. High-volatile coals, generally, result in low NO_x emissions (from a low NO_x unit), but can lead to marginal steam temperatures. By adjusting the boiler settings the desired steam temperatures can be achieved but the adjustments may be unfavourable for low NO_x emissions. The direct effect (volatile matter) results, in this example, to low NO_x emissions, whereas the adjustment of boiler settings (indirect effect) results in higher NO_x emissions. Sometimes boiler settings dominate the propensity of coal to form NO_x (Jones et al., 1995). To obtain useful predictions by correlating coal characteristics with regular day-to-day operating data of a power plant is therefore difficult (Rozendaal et al., 1995). Consequently, in the full-scale tests presented in this chapter the direct and indirect impact of coal quality on NO_x emissions and burnout has been studied separately.

At Maasvlakte power plant twelve coal blends were burned under comparable circumstances (hereafter referred to as baseline tests) with respect to boiler settings and unit load. The negative implications (for instance, too low steam temperatures) by keeping the boiler settings constant were taken for granted. With these baseline experiments the direct impact of coal quality on plant performance was studied. Subsequently, plant performance was also monitored with the same coal blends during normal operation in order to evaluate the direct and indirect effect of coal quality simultaneously. This was considered as the optimised case, since plant performance was optimised as a whole (efficiency, steam temperatures, NO_x emissions and unburned carbon).

7.2 EXPERIMENTAL APPROACH

The boiler settings were identical for all baseline tests, except for the excess air ratio, since the reproducibility of the excess air ratio (determined on basis of the oxygen concentration in the flue gases measured upstream the air heater) is sometimes poor. The baseline experiments were performed at three excess air ratios. As a result the relation between the excess air ratio and NO_x is known and the NO_x emissions from the coal blends can be compared at the same excess air ratio.

The standard settings were defined by which most of the coal blends could be burned without jeopardising the installation or the process (**table 7.1**). A description of the boilers and the boiler settings can be found in chapter 5. The baseline tests at Maasvlakte power plant would be terminated in case live or reheat steam temperatures would fall below 510 °C, the unburned carbon content in the fly ash would exceed 10% or the CO concentration in the flue gases would exceed 500 ppm. Similar constraints were put on the Amer baseline trials.

Table 7.1 Boiler settings during the baseline tests (an explanation of the boiler settings can be found in chapter 5)

	Maasvlakte 1	Amer 9
Output	520 MW_e	600 MW_e[1]
Load-following	no	no
Pulveriser arrangement	1-2-4-5[2]	20-30-40-50-60 10-20-30-50-60[3]
Classifier frequency	80 rpm	in control[4]
Outlet temp. pulv.	80 °C	in control
Burner biasing	no	no
Burner tilt	0°	0°
Tilt OFA ports	+ 10°	0°
Auxiliary air ports	NR10S003 100% open NR41S004 in control NR51S004 100% open	in control
Fuel air correction[5]	minimum	in control
Overfire air	100% open	100% open
Windbox-to-furnace pressure differential	14.5 mbar	10 mbar

[1] In a number of cases heat delivery for district heating was required. In those cases the live steam flow was kept constant (± 485 kg/s).

[2] This means for Maasvlakte power plant that the centre burner level was out of operation (see **figure 5.8**).

[3] Initially it was intended to perform all experiments with burner level 10 (the upper burner level) out of operation. However, due to burner plugging problems with one of the burners of burner level 40 the programme was adjusted. With the last five coal blends the experiments were performed with burner level 10 in operation instead of burner level 40.

[4] Normally 95-100 rpm.

[5] The fuel air dampers are normally coupled with the dampers controlling the auxiliary air. The operators may change this to some extent by changing the amount of fuel air.

Soothblowing of both boilers was completed before the baseline experiments were performed. Fouling or slagging of the furnace walls can influence the formation of NO_x, since the temperature in the furnace will increase as the heat absorption of the furnace walls is reduced (Brooks et al., 1986).

The first eight coal blends were burned at Amer 9 with burner level 10 out of operation (BOOP=10; Burner Out of OPeration). The remaining five coal blends were burned with burner level 40 out of operation (BOOP=40). An overview of the boiler of Amer unit 9 is shown in **figure 5.6**. The burner box is shown in more detail in **figure 5.9**. In general, operation with the upper burner level out of operation results in lower NO_x emissions. Sometimes the upper burner level is taken out of service, while maintaining a high airflow through these burners, to simulate overfire air. This is often referred to as BOOS (Burners Out Of Service). Reductions in NO_x emissions of 57% are reported with applying BOOS, comparable to reductions achieved with overfire air and low NO_x burners (Mazzi et al., 1997).

In general, the coal blends were burned for a week. The actual tests were performed at the end of this week. The baseline tests (variation of excess air ratio) were performed in one day. The fly ash samples were taken at the end of each test (after a stabilisation period of one and a half-hour). The optimised test was also performed in one day. Before each test series flue gas analysis monitors (such as NO_x and O_2 monitors) were calibrated.

7.3 COAL CHARACTERISTICS

The minimum and maximum values of the major coal characteristics of the coal blends investigated are given in **table 7.2**. The blends are referred to as MV1 – MV12 for the Maasvlakte tests and A1 to A13 for the Amer tests. A complete overview of the coal characteristics is given in appendix B.

Table 7.2 Range of some important coal characteristics of the coal blends fired at Maasvlakte and Amer power plant

		Maasvlakte 1	Amer 9
Lower Heating Value	MJ/kg (ar)	24.2 - 26.9	24.2 - 27.5
Moisture	wt.-% (ar)	7.5 - 13.9	6.9 - 13.9
Ash	wt.-% (dry)	8.5 - 15.5	5.9 - 16.8
Volatile matter	wt.-% (dry)	26.6 - 36.3	25.6 - 41.0
fuel ratio	-	1.5 - 2.3	1.3 - 2.2
Nitrogen	wt.-% (dry)	1.06 - 1.80	1.17 - 1.91

7.4 NO_x EMISSIONS

7.4.1 NO_x emissions as function of the excess air ratio (baseline tests)

The impact of excess air ratio (expressed as the oxygen concentration in the flue gases measured upstream the air heater) on NO_x emissions for the blends burned at the Maasvlakte unit is illustrated in **figure 7.1**. NO_x emissions are expressed as dry at standard conditions (1013 mbar, 0 °C) and normalised to 6% O_2.

A clear trend in NO_x emissions from Maasvlakte power plant versus excess air is observed. Although not all coal blends were burned at three excess air ratios the results suggest that NO_x emissions are, within the experimental envelope, linearly related to the oxygen concentration in the flue gases. This is supported by other investigations on tangential-fired boilers (Allen et al., 1995; Brooks et al., 1986; Savolainen et al., 1995). The relationships between NO_x emissions and the oxygen concentration for the individual blends are given in **table B.5** in appendix B. The slope of the relation between NO_x and O_2 ranges from 25 to 42, with an average of 35. This means that an increase of the oxygen concentration in the flue gases by 1% yields an increase of NO_x emissions of about 35 mg/m_0^3 (for the boiler settings given in **table 7.1**). No relation was found between the magnitude of the slope and coal characteristics (in particular, fuel ratio or volatile matter content).

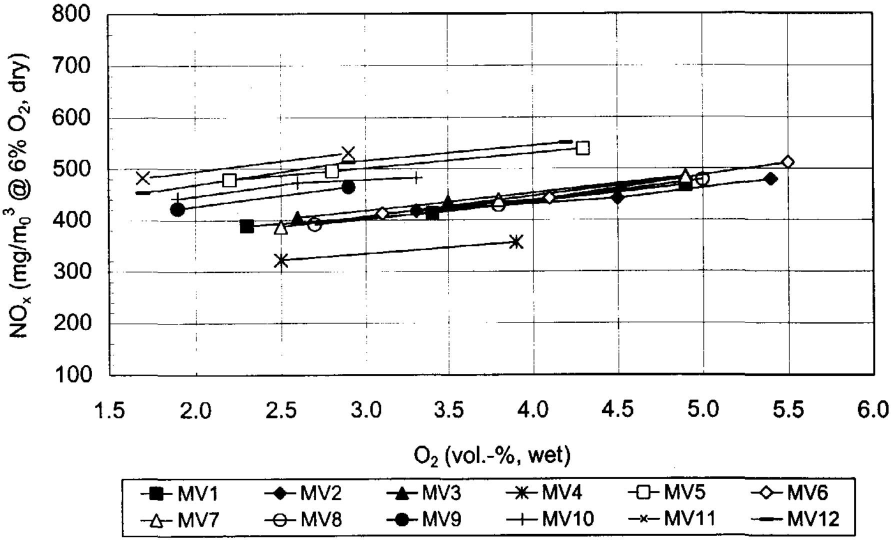


Figure 7.1 NO_x emissions as function of the oxygen concentration in the flue gases (Maasvlakte baseline tests)

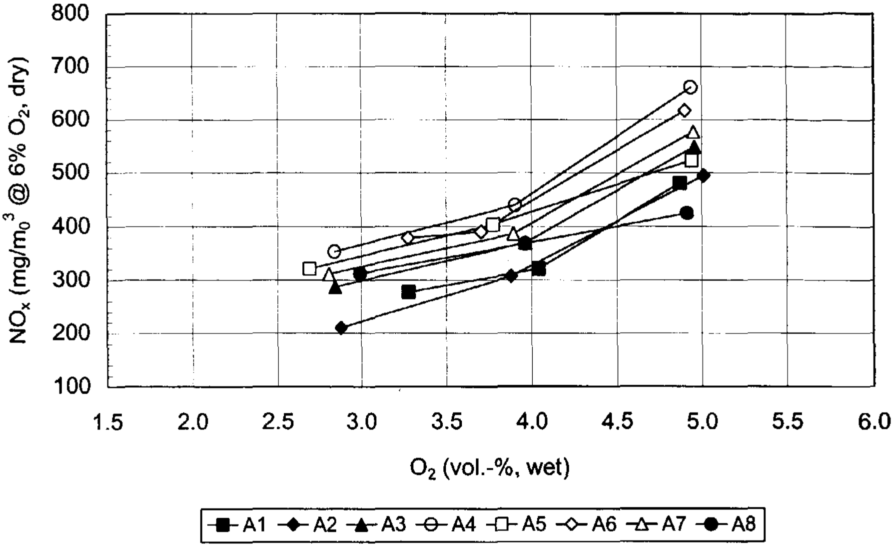


Figure 7.2 NO_x emissions as function of the oxygen concentration in the flue gases (Amer unit 9, BOOP=10)

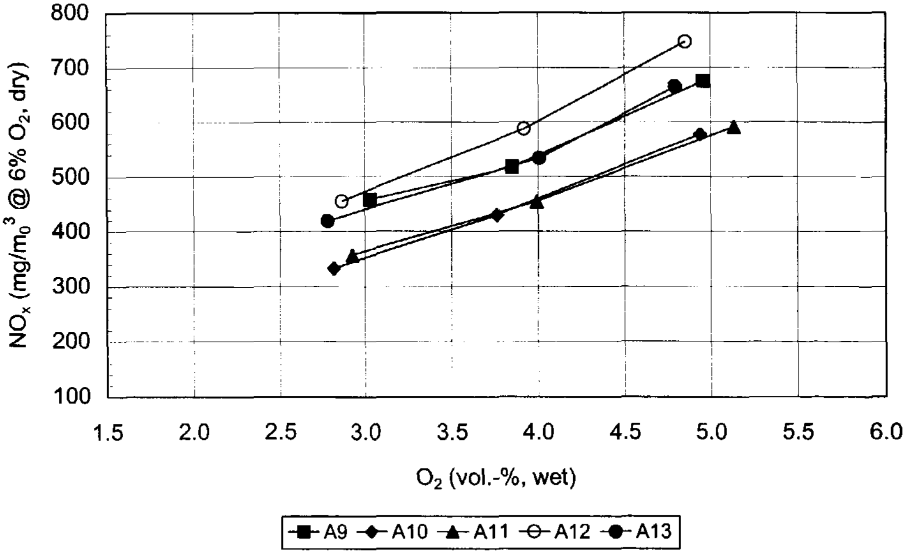


Figure 7.3 NO_x emissions as function of the oxygen concentration in the flue gases (Amer unit 9, BOOP = 40)

Figure 7.2 shows the NO_x emissions from the blends burned at Amer unit 9 with burner level 10 out of operation as function of the oxygen concentration in the flue gases. All blends were burned at three excess air ratios. This figure suggests that within the range investigated the NO_x emissions are not linearly related to the oxygen concentration in the flue gases. At higher excess air ratios NO_x emissions increase to a larger extent than at lower excess air ratios. The results of the experiments with burner level 40 out of operation (BOOP=40) are given in **figure 7.3**. It appears that also in this case NO_x emissions are not linearly related to the oxygen concentration in the flue gases.

In order to compare the NO_x emissions from the blends at the same excess air ratio the relationship between NO_x and O_2 was determined. Although **figure 7.2** indicates that no linear relationship exists between the NO_x emissions and the oxygen concentration in the flue gases over the range investigated, it is assumed that the relationship between NO_x and O_2 between the two lowest excess air ratios can be approximated by a straight line. This is also assumed for the relationship at the highest excess air ratios. Since the O_2 concentrations at which the NO_x emissions are known are relatively close to each other the error introduced with this assumption is relatively small. **Table B.6** in appendix B lists the slopes of the NO_x-O_2 relationships for the individual blends. The average dependency of NO_x with O_2 is listed in **table 7.3**.

7.4.2 Correlation of NO_x emissions and coal characteristics (baseline tests)

7.4.2.1 Regression analysis and model building

In the previous section the relation between the NO_x emissions and the excess air ratio was determined for all individual blends. In order to compare the NO_x emissions from the coal blends, without the effect of excess air ratio, the NO_x emissions from the coal blends were calculated at a specific oxygen concentration in the flue gases (interpolation at 3% O_2). The errors introduced by the interpolation are reduced, since most coal blends were burned with at an oxygen concentration in the flue gases of around 3%, as illustrated in **figure 7.1** and **7.2**. The NO_x emissions of each coal blend were calculated using the blend specific relations given in **table B.5 and B.6** in appendix B.

Table 7.3 Average slope of the NO_x-O_2 relationships (Amer unit 9)

	$2.8 < O_2 < 4.0$	$4.0 < O_2 < 5.1$
BOOP=10	73[1)]	160
BOOP=40	97	145

[1)] The results of blend A6 are neglected. During the experiments with the average excess air ratio the operation was not constant due to a variation of the windbox-to-furnace pressure differential, which resulted in lower NO_x emissions for the average O_2 concentration.

In the period that the experiments were performed at Amer power plant the impact of the excess air ratio on the heat release near the burners was not completely understood. During normal operation the unit was operated at relatively high excess air ratios. Experiments (Rozendaal et al., 1997b) showed, however, that a decrease of the excess air ratio resulted in a decreased heat release near the burners. Consequently, the risk of overheating the burners is reduced with a lower excess air ratio. At present the boiler is operated at lower excess air ratios corresponding to oxygen concentrations in the flue gases of around 3% measured upstream the air heater.

The relation between NO_x emissions and coal characteristics was analysed by means of linear regression analysis (described in appendix A). Scatter diagrams were plotted of NO_x emissions versus various coal characteristics. Furthermore, for each combination the coefficient of determination obtained with linear regression analysis was calculated (**table B.8** in appendix B).

The results listed in **table B.8** suggest that there is a strong statistical relationship between NO_x emissions and a number of coal characteristics, including moisture content, ash content, volatile matter content and fuel ratio. Commonly used coal parameters for the predictions of NO_x are volatile matter content (ar, db or daf), fuel ratio or nitrogen content (see chapter 3). Also in this experimental work it appears that these parameters have a relatively high coefficient of determination, except for the nitrogen content. Although, the moisture and ash content also suggest a strong relationship, they were not used as regressor variables, since no obvious explanation exists for the impact of moisture and ash content on NO_x emissions. The R^2 values and the regression coefficients of the linear regression analysis of the volatile matter content (ar, db, and daf) and fuel ratio are given in **table 7.4**. β_0 is the intercept and β_1 the slope of the straight-line model.

Table 7.4 The coefficient of determination (R^2) and the regression coefficients (β_0 and β_1) calculated with linear regression analysis of volatile matter and fuel ratio with NO_x

Plant	Combustion mode		VM_{ar}	VM_{db}	VM_{daf}	FR
Maasvlakte		R^2	0.66	0.79	0.68	0.64
		β_0	1075	1006	1085	63.6
		β_1	-22.1	-17.6	-17.9	210.7
Amer 9	BOOP=10	R^2	0.67	0.82	0.81	0.81
		β_0	754	704	800	-7
		β_1	-14.6	-11.8	-13.0	188.9
Amer 9	BOOP=40	R^2	0.70	0.79	0.72	0.69
		β_0	763	737	803	184
		β_1	-11.8	-9.7	-10.3	136.3

The best regressor from a statistical point of view is the volatile matter content on a dry basis, which in all three cases results in the highest coefficient of determination. Multiple linear regression analysis showed that additional regression variables did not improve the models. The simple linear regression analysis yields the following models:

Maasvlakte NO_x model (O_2 = 3%, wet)

$$NO_x = 1006 - 17.6 \cdot VM_{db} \tag{7.1}$$

Amer NO_x models (O_2 = 3%, wet)

BOOP = 10 $$NO_x = 704 - 11.8 \cdot VM_{db} \tag{7.2}$$

BOOP = 40 $$NO_x = 737 - 9.7 \cdot VM_{db} \tag{7.3}$$

7.4.2.2 Residual analysis, confidence and prediction interval

To determine if the models are an adequate fit to the data it is required to analyse the residuals (Montgomery et al., 1982). Residuals are the differences between the fitted and measured NO_x emissions (see appendix A). The residuals of the models in this thesis were analysed by means of a normal probability plot and plots of residuals against, for instance, predicted NO_x and the nitrogen content. It showed that the residuals were more or less normally distributed and that the model contained no outliers. The residual analyses are briefly discussed in section B.4 (appendix B).

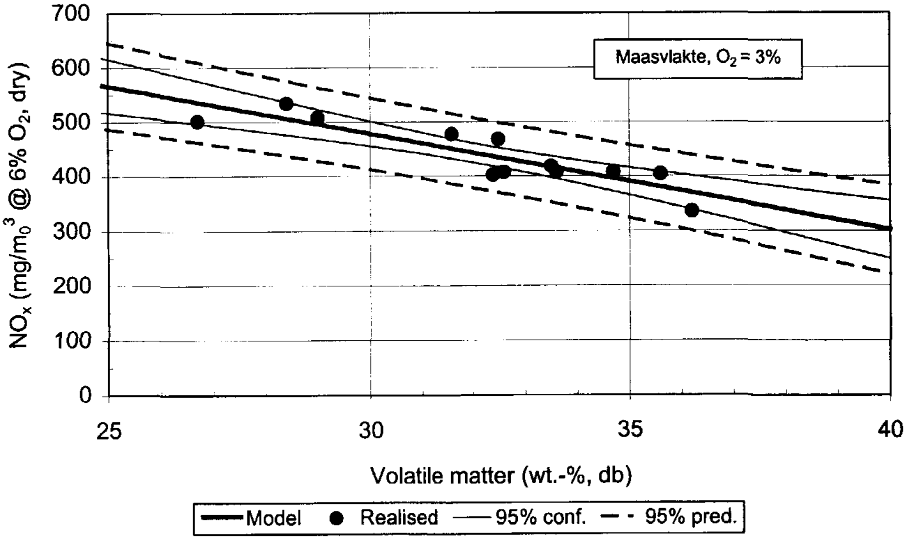


Figure 7.4 Maasvlakte NO_x model (O_2 = 3%) and the confidence and prediction intervals

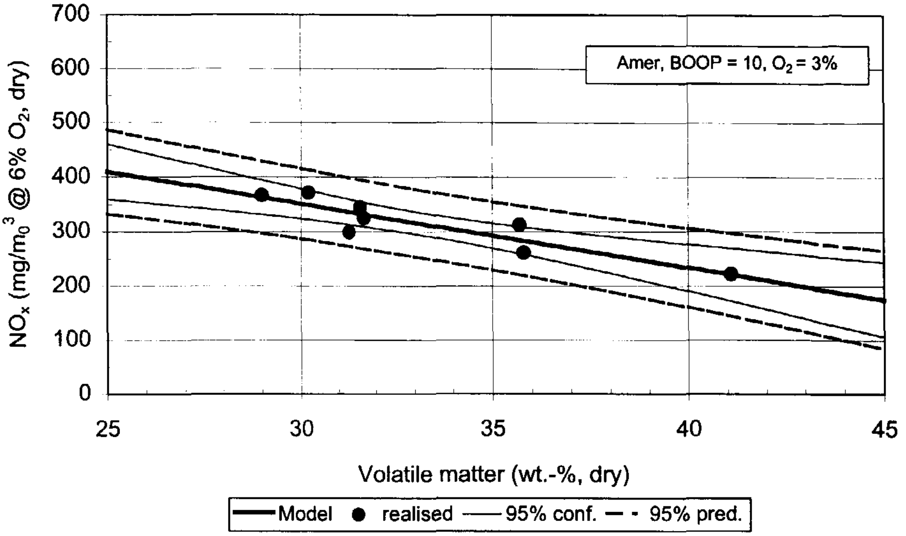


Figure 7.5 Amer NO_x model (BOOP = 10, O_2 = 3%) and the confidence and prediction intervals

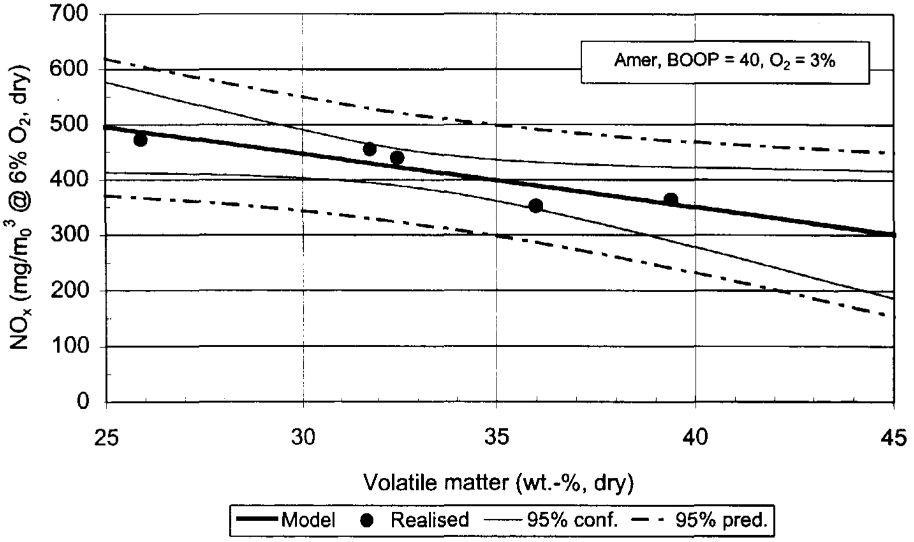


Figure 7.6 Amer NO_x model (BOOP = 40, O_2 = 3%) and the confidence and prediction intervals

Figure 7.4 shows the model for the Maasvlakte power plant determined with simple linear regression analysis as well as the observed values (scatter diagram). The 95% confidence interval on the mean response and the 95% prediction interval for new observations are also shown in this figure. The parameters for the calculation of the intervals are given in section B.4 (appendix B). **Figures 7.5** and **7.6** illustrate the NO_x prediction based on the baseline tests of Amer power plant.

The confidence and the prediction interval are smaller near the centre of the data than near the boundaries. The interpretation of both intervals is best explained with an example. Suppose an infinite number of coal (blends) with a volatile matter content of 32% (dry). With 95% confidence it can be predicted that for the Maasvlakte power plant the **mean** of the NO_x emissions obtained with these coals will lie between 425 and 461 mg/m_0^3 (confidence interval). In case only one coal (blend) is considered with a volatile matter content in 32% (dry) it can be predicted that with 95% confidence the NO_x emissions will lie between 378 and 507 mg/m_0^3. Note that the width of the confidence and prediction intervals increases with a decrease in the number of observations. The width of the intervals for the case "BOOP = 40" for Amer unit 9 is almost twice as large as the width of the Maasvlakte intervals. The confidence and prediction intervals reflect the measurement errors, but also the effects of other variables on NO_x emissions. Appendix C contains the analysis of measurement errors.

7.4.3 High excess air and the consequences for the Amer NO_x models

In Amer unit 9 the coal blends were also burned at high excess air ratios (much higher than with normal operation), corresponding to oxygen concentrations in the flue gases of about 4.9%. The NO_x emissions determined at these high oxygen levels were also correlated with the volatile matter content on a dry basis. The NO_x emissions used in the regression analysis are listed in **table B.6** (appendix B). **Table 7.5** arranges the results of the regression analysis.

Table 7.5 R^2 values and the coefficients (β_0 and β_1) from the linear regression analysis of volatile matter (db) with NO_x (4.9% O_2) in the flue gases (Amer measurements)

	Amer (BOOP = 10)	Amer (BOOP = 40)
R^2	0.61	0.93
β_0	1032.8	1158.7
β_1	-15.0	-15.4

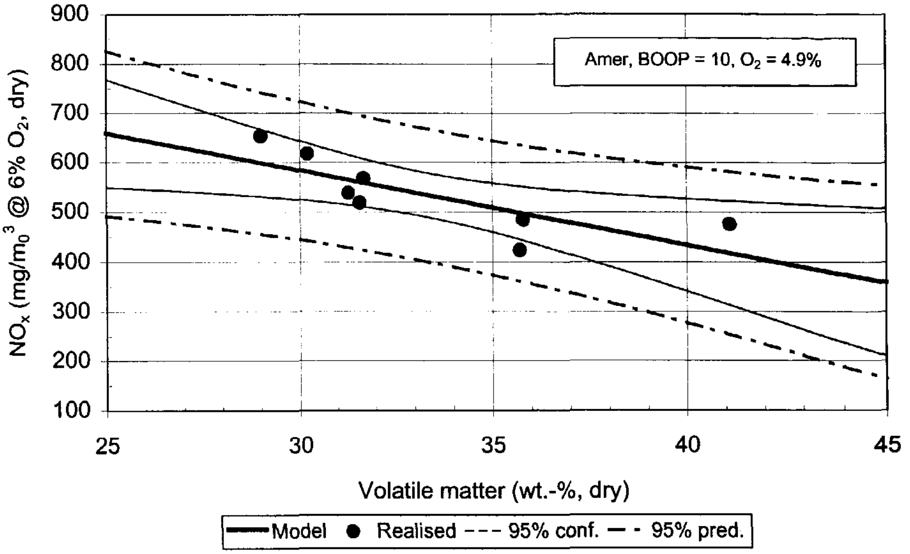


Figure 7.7 Amer NO_x prediction (BOOP = 10, O_2 = 4.9%) and the confidence and prediction intervals

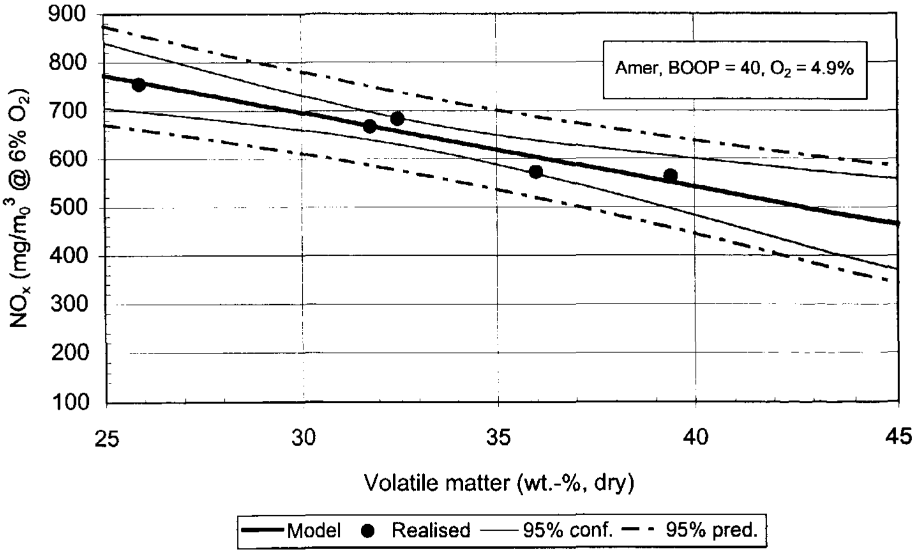


Figure 7.8 Amer NO_x prediction (BOOP = 40, O_2 = 4.9%) and the confidence and prediction intervals

The Amer models for the high excess air tests can be written as:

High excess air Amer NO_x models (O_2 = 4.9%, wet)

BOOP = 10 $$NO_x = 1033 - 15.0 \cdot VM_{db} \tag{7.4}$$

BOOP = 40 $$NO_x = 1159 - 15.4 \cdot VM_{db} \tag{7.5}$$

In **figures 7.7** and **7.8** the models are compared with the observed values. The confidence and prediction intervals are also given. The model for the case BOOP = 10 is probably not the best fit, as can be seen from **figure 7.7**. Neglecting the outlier would increase the coefficient of the model. The residual analysis (discussed in appendix B) also shows one data point that has a major impact on the model. The possible outlier belongs to a coal blend with a volatile matter content of 41.1% on a dry basis (blend A2). The different behaviour of this blend may be caused by the low ash content (5.0% ar), as a result of which the volatile matter content on a dry basis is somewhat higher compared to blends with higher ash contents. A better fit may therefore be possible if the volatile matter content on a dry and ash free basis is used.

7.4.4 Validation of the Amer model

With the objective to lower fuel costs, low-quality coals (e.g. coals with high ash or high moisture content) are burned in the Dutch coal-fired power stations. A number of full-scale test trials was carried out to investigate the effect of the combustion behaviour of low-quality coals on plant performance. In a specific case a test burn was performed with a subbituminous coal from the Powder River Basin (PRB) in the USA in the boiler of unit 9 of the Amer power plant (Rozendaal et al., 1997c). Subbituminous coals are characterised by a high moisture (28 wt.-%, ar) and volatile matter (43 wt.-%, dry) content. Consequently, it is practically impossible to burn this coal single in a boiler designed for bituminous coals. The high moisture content and, subsequently, the low calorific value makes that full load cannot be reached due to capacity limitations of the pulverisers. The drying capacity of the pulverisers is also too small to ensure sufficient drying of the coal. Moreover, the high volatile content can result in pulveriser fires, due to the high temperature of the primary air entering the pulveriser and the high volatile matter content. It was decided therefore, that the fraction of Powder River Basin coal in the blend would not exceed 40%. Calculations showed that with this blend ratio the pulveriser outlet temperature was sufficiently high to avoid dew point problems. The trial consisted of three tests. The first test was performed with a reference blend (PRB0). The other two test burns were performed with the reference blend containing 25 and 40% PRB-coal (on a mass basis). Hereafter referred to as PRB25 and PRB40, respectively. **Figure 7.9** shows the NO_x emissions measured with the PRB-blends (see also **table B.17** in appendix B). The tests were performed with similar boiler settings (BOOP = 10) used for the development of the models and the results of the PRB blends can be used to test the Amer NO_x model (BOOP = 10). **Table 7.6** lists the volatile matter content in the coal blends, the predicted NO_x emissions and the observed NO_x emissions. The comparison of the model prediction and the actual values is also shown in **figure 7.10**. The model predicts the NO_x emissions from the blends very well.

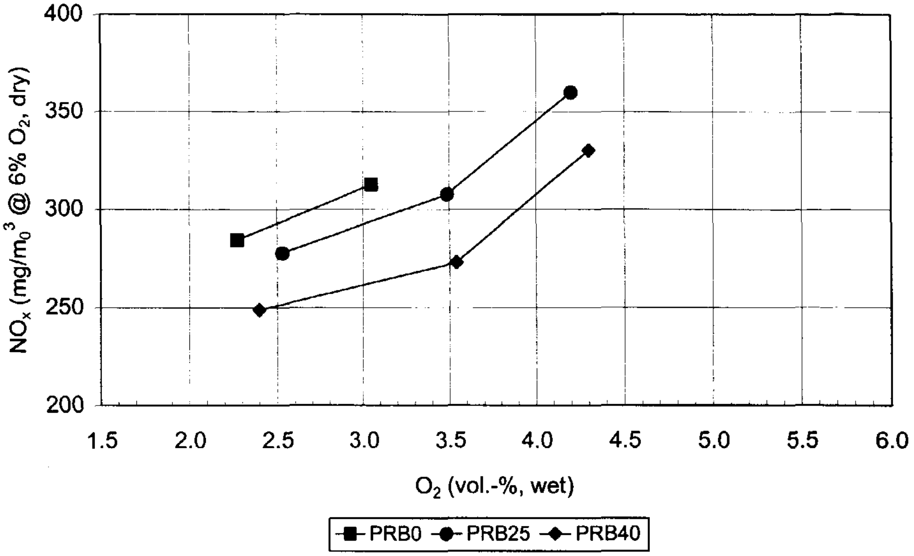


Figure 7.9 NO_x emissions measured at Amer power plant for the Powder River Basin blends (BOOP = 10)

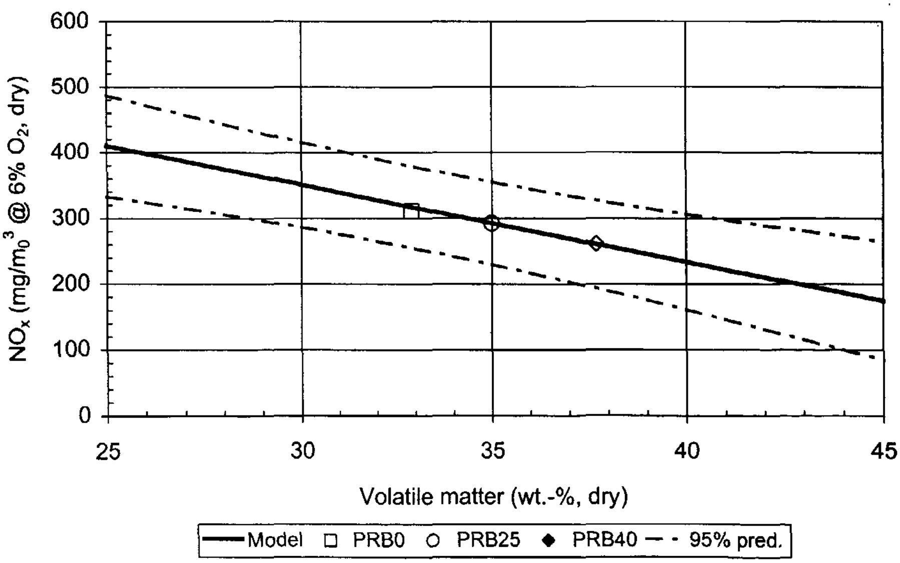


Figure 7.10 Predicted NO_x emissions (BOOP = 10) compared to the actual NO_x emissions from the PRB blends

Table 7.6 Predicted and observed NO_x emissions from the Powder River Basin blends (with model BOOP = 10, O_2 = 3% wet)

Blends	Volatile matter (wt.-%, dry)	Predicted NO_x emissions mg/m_0^3 (@ 6% O_2, dry)	Observed NO_x emissions mg/m_0^3 (@ 6% O_2, dry)
PRB0	32.9	316	311
PRB25	35.0	291	292
PRB40	37.7	259	261

It should be noted here that the relationship between the NO_x emissions and the oxygen concentration in the flue gases for these blends differ from the ones obtained with the coal blends used for the development of the model. This suggests that the NO_x emissions are not linearly related to the oxygen concentration but that a higher order relation exists, comparable to the impact of burner zone stoichiometry on the NO_x emissions from Hemweg 8, illustrated in **figure 5.12**. The increase of excess air at Amer unit 9 results in an increase of the burner zone stoichiometry. If the excess air is increased in sufficient amounts the burner zone stoichiometry will approach unity and a progressive increase of NO_x emissions is expected. **Figure 7.11** schematically shows the increase of NO_x emissions as function of the oxygen concentration in the flue gases (and hence burner zones stoichiometry). The error in calculating the NO_x emissions at 3% O_2 in the flue gases for the model, however, is relatively small since the NO_x emissions are measured with oxygen concentrations in the flue gases close to 3%.

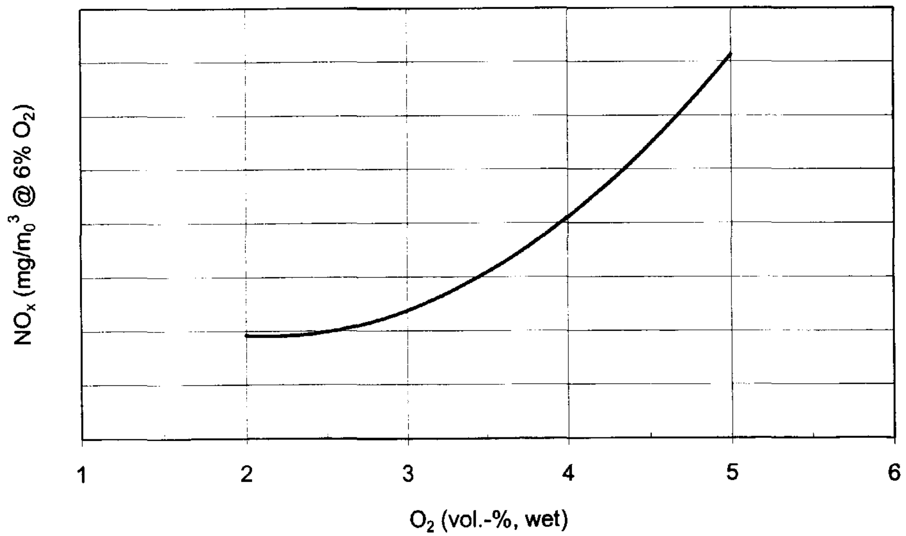


Figure 7.11 Tendency of NO_x emissions as function of the oxygen concentration in the flue gases (Amer unit 9)

7.4.5 Indirect coal quality effect on Maasvlakte NO$_x$ model

The coal blends used for the determination of the Maasvlakte NO$_x$ model were also burned under conditions optimising overall plant performance (the optimised case). The operation of both units of Maasvlakte power plant is suffering from a phenomenon referred to as the "diabolical triangle". This phenomenon represents the relation between the NO$_x$ emissions, the unburned carbon content in the fly ash and the thermal behaviour of the boiler, which often conflicts during power plant operation (discussed in chapter 5). One of the issues is that steam temperatures are difficult to achieve and to maintain at the desired values. **Figure 7.12** illustrates the impact of excess air on the live steam temperatures (design value is 540 °C) during the baseline tests. It is obvious that steam temperatures drop severely in case the excess air ratio is increased. The steam temperatures in a boiler with a fixed evaporation point (in the drum) such as the Maasvlakte units are influenced by many factors including boiler settings and coal characteristics. (Once-through boilers such as Amer unit 9 and Hemweg unit 8 do not suffer from this phenomenon). There exists a delicate balance between heat transfer by radiation and convection. A swing in the heat release profile can be caused by:

- lower flame temperatures with coals with a high moisture content
- higher flue gas flows with coals with a high moisture content
- reflection of radiation caused by deposits on the furnace walls
- variation in the rate of combustion of coal (high-volatile coals tend to burn faster).

Coals with high silica content often resulted in an improved thermal behaviour of the boiler (Rozendaal et al., 1993). It was suggested that the reflective properties of silica resulted in a reduced heat transfer through the furnace walls. Aumüller (1989) reported similar effects.

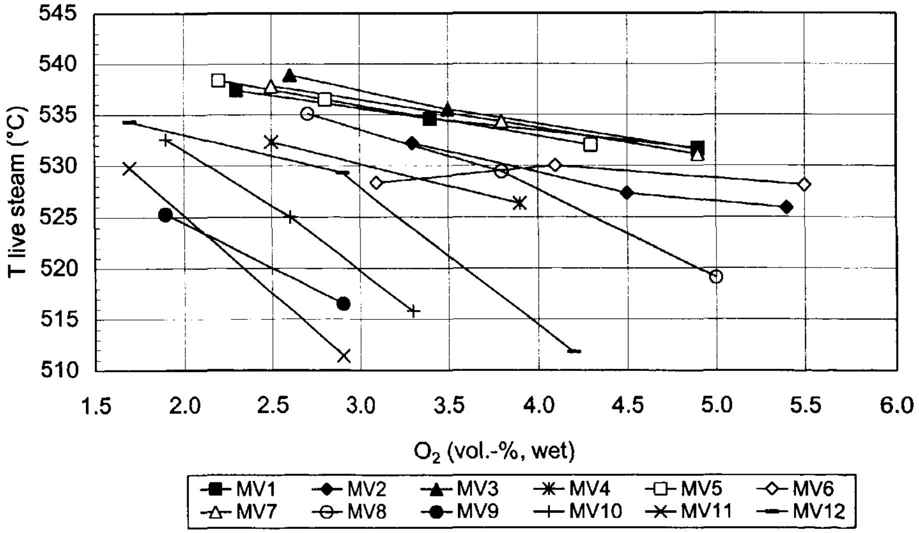


Figure 7.12 Live steam temperatures as function of coal quality and excess air during the Maasvlakte baseline experiments

It is evident that during normal operation the plant operators will primarily aim at maintaining steam temperatures, since temperature fluctuations reduce the remaining lifetime of the steam turbine and lower steam temperatures result in a lower efficiency. The second objective is to keep NO_x emissions and unburned carbon content in the fly ash at acceptable levels within the possibilities imposed by boiler controls and coal characteristics. This means that the baseline NO_x emissions used for the development of the NO_x model could be different from the NO_x emissions obtained during normal operation. Therefore, the NO_x emissions were also measured at those boiler settings at which plant performance was optimised as a whole (optimised case). Consequently, the boiler settings varied for the various coal blends. Correlation of these NO_x emissions with coal characteristics incorporates the direct effect of coal quality on NO_x emissions as well as the indirect effect via the boiler settings.

The results of the NO_x measurements, together with the major boiler settings are arranged in **table B.19** (in appendix B). The load of the unit was kept constant during the measurements. The relationships obtained by means of the regression analysis showed that again the volatile matter is a good predictor. **Table 7.7** lists the coefficients of determination and the regression coefficients of the regression analysis with the volatile matter content on different bases and with the fuel ratio. The table shows that also in this case the volatile matter content on a dry basis gives the best correlation with NO_x. The NO_x prediction model for the optimised case is given as:

Maasvlakte NO_x model (optimised case, O_2 = variable)

$$NO_x = 826 - 12.1 \cdot VM_{db} \tag{7.6}$$

The model and the observed values together with the confidence and prediction intervals are shown in **figure 7.13**. The residual analysis is discussed in section B.4.3 in appendix B. Comparison of the NO_x models of the base and the optimised case (shown in **figure 7.14**) indicates that the NO_x model describing the optimised case shows the same trend, but the impact of volatile matter content is somewhat less. Although from a statistical point of view the models are in fact not different, since the confidence intervals overlap.

Table 7.7 The coefficients of determination and the regression coefficients from the linear regression analysis of volatile matter and fuel ratio with NO_x (optimised case Maasvlakte)

Plant		VM_{ar}	VM_{db}	VM_{daf}	FR
Maasvlakte	R^2	0.74	0.75	0.69	0.66
	β_0	913	826	897	165
	β_1	-16.6	-12.1	-12.8	151.8

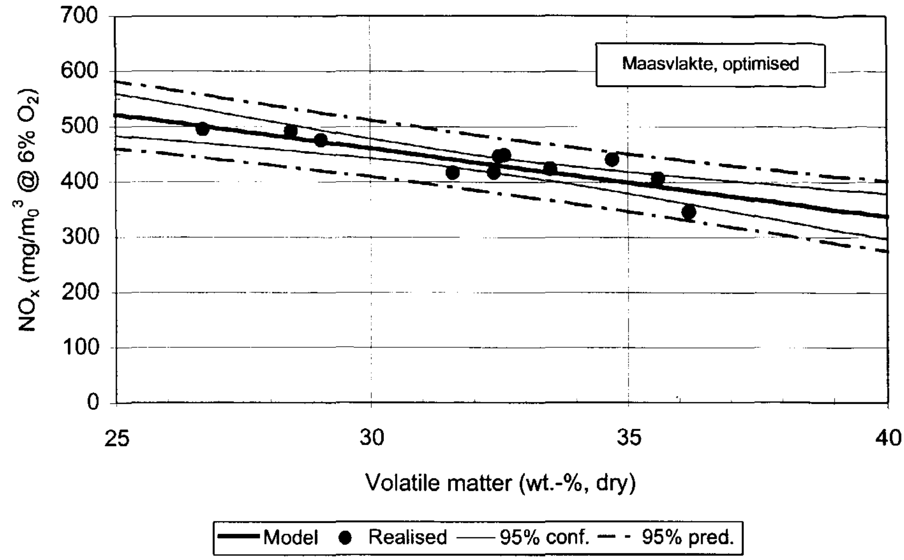


Figure 7.13 Comparison of the model and observed NO_x emissions (Maasvlakte optimised case)

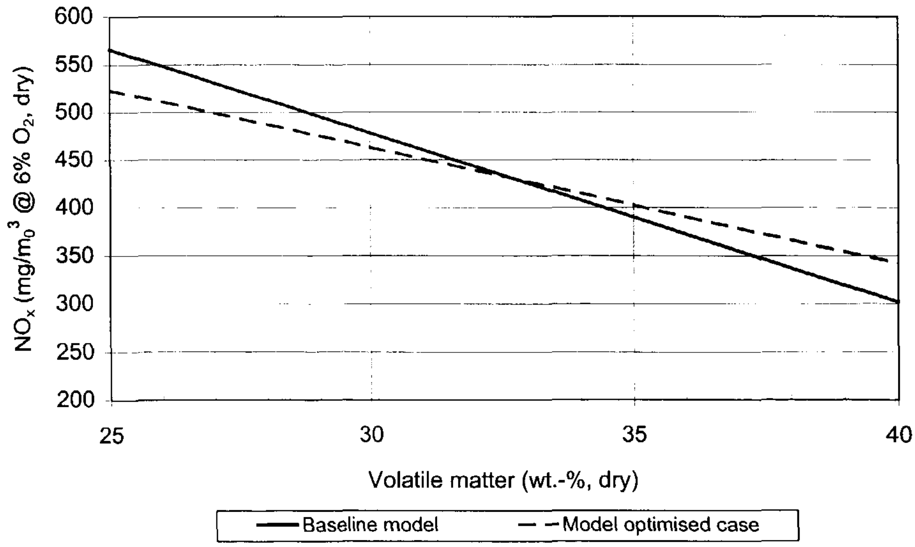


Figure 7.14 Comparison of the baseline and optimised case models of Maasvlakte power plant

The explanation for the reduced impact of volatile matter is that with the baseline tests the boiler settings were identical for all coal blends despite the sometimes high NO_x emissions in a number of cases. In the optimised case the operators try to keep NO_x emissions below 390 mg/m_0^3 or at least as low as possible, also with low-volatile coals by adjusting specific boiler settings. The opposite happens when a high-volatile coal is burned with relatively low NO_x emissions, the operators will then aim at achieving the desired steam temperatures and bringing the unburned carbon down at the expense of the NO_x emissions. The margin between the limit and the observed NO_x emissions will be used to optimise plant performance. This results in a decrease of the impact of coal quality as illustrated by both NO_x models.

The optimised measurements were also performed at Amer 9. Practically the same correlation was found for the optimised case as for the baseline tests. The reason that the NO_x models for both cases were almost identical is due to the fact that Amer 9 is a once-through boiler, which is less sensitive for steam temperature fluctuations and hence adjustment of the boiler settings is less needed.

7.5 UNBURNED CARBON AND BURNOUT

7.5.1 Unburned carbon as function of excess air ratio

The impact of excess air on the unburned carbon content in the fly ash for Maasvlakte power plant is given in **figure 7.15**. **Figures 7.16** and **7.17** show the unburned carbon content in the fly ash for the Amer power plant with burner level 10 out of operation and with burner level 40 out of operation, respectively.

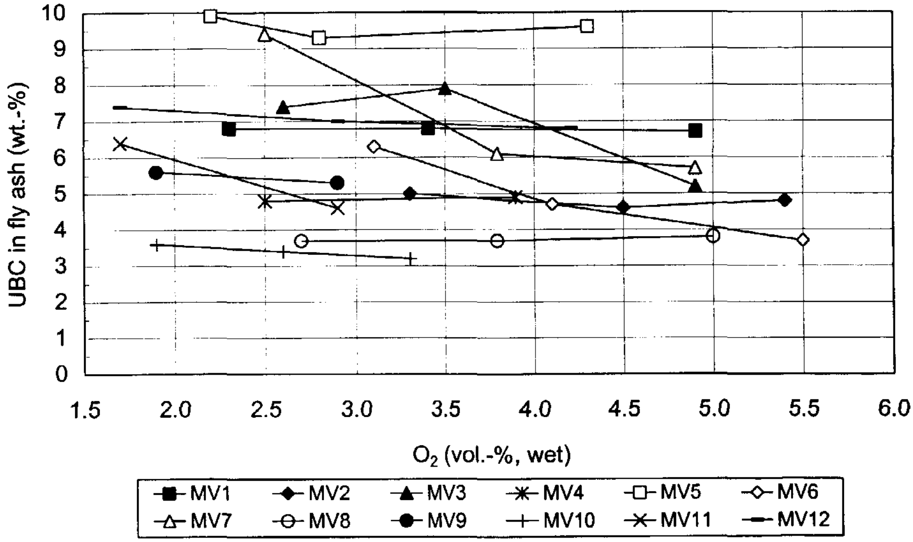


Figure 7.15 Unburned carbon as function of the excess air ratio (Maasvlakte baseline measurements)

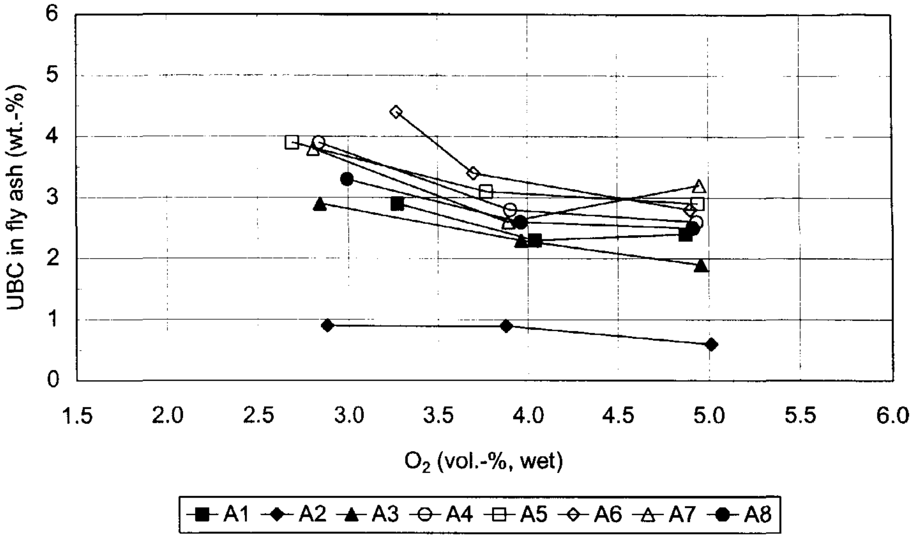


Figure 7.16 Unburned carbon as function of the excess air ratio (Amer baseline measurements, BOOP = 10)

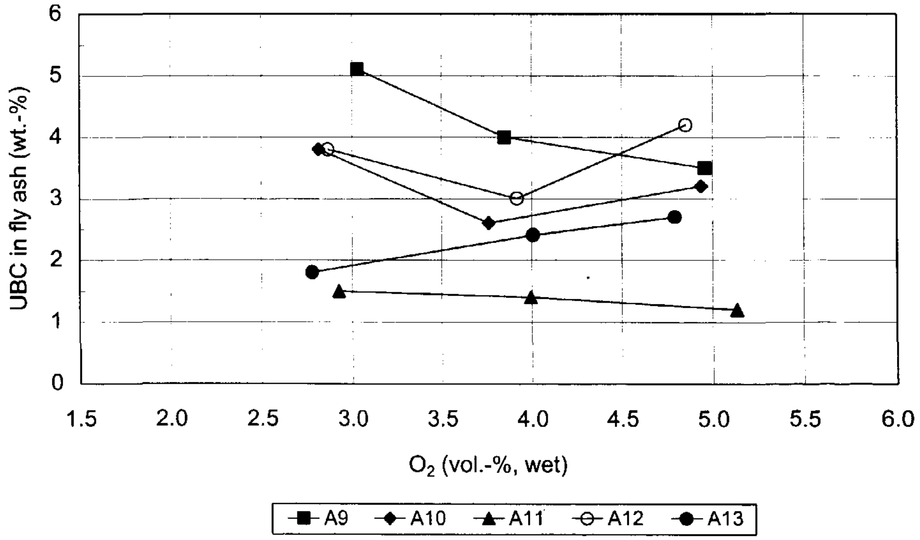


Figure 7.17 Unburned carbon as function of the excess air ratio (Amer baseline measurements, BOOP = 40)

The relationship between the excess air ratio and the unburned carbon content for the Maasvlakte measurements is not very clear. In general, a marginal decrease of the unburned carbon content is observed with increasing excess air ratios. However, some coal blends show a large non-linear effect with increasing excess air ratios, whereas the unburned carbon content in others remains constant over the range of excess air ratios investigated. **Figure 7.15** illustrates that with most blends it is difficult or even impossible to obtain an unburned carbon level below 5%.

The individual relations between unburned carbon and the excess air ratio show more similarities for the coal blends fired at the Amer power plant. Although in two particular cases there is a reverse trend between the unburned carbon content and the excess air ratio. The other blends show a decreasing or a constant unburned carbon with increasing excess air ratios. Each coal blend investigated was burned with unburned carbon values below 5%.

7.5.2 Burnout as function of excess air ratio

To compare the coal blends it is recommended to use the burnout instead of the unburned carbon content in the fly ash. Otherwise dilution effects of the ash obscure the results. The burnout can be calculated when the ash and moisture content in the original feed are known. It is assumed that the ash is inert and that the mass of ash in the feed coal equals the mass of the ash product. The relation between unburned carbon and burnout is given by equation 3.35.

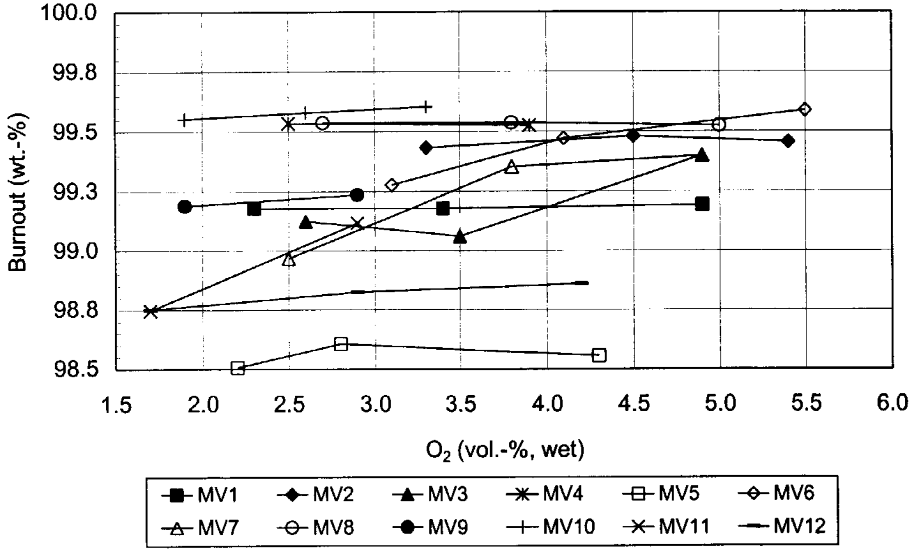


Figure 7.18 Burnout as function of the excess air ratio (Maasvlakte baseline measurements)

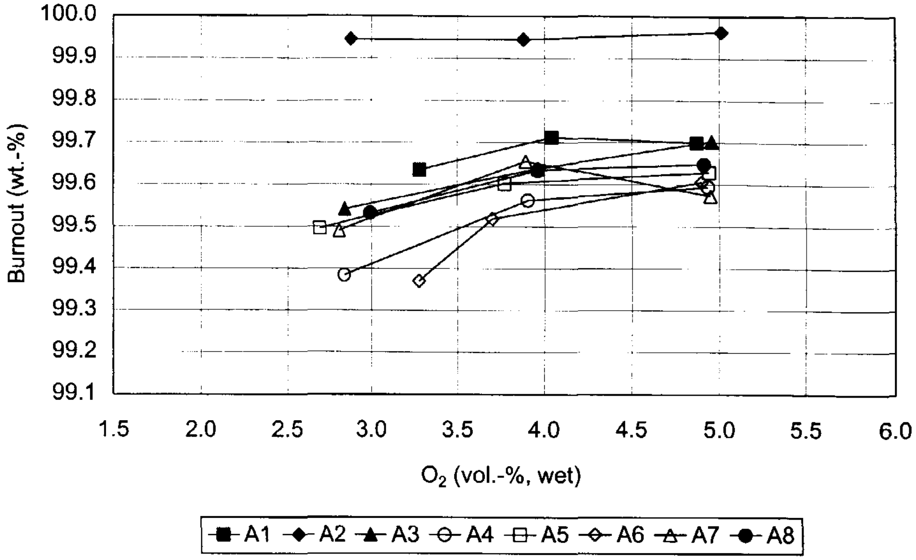


Figure 7.19 Burnout as function of the excess air ratio (Amer baseline measurements, BOOP = 10)

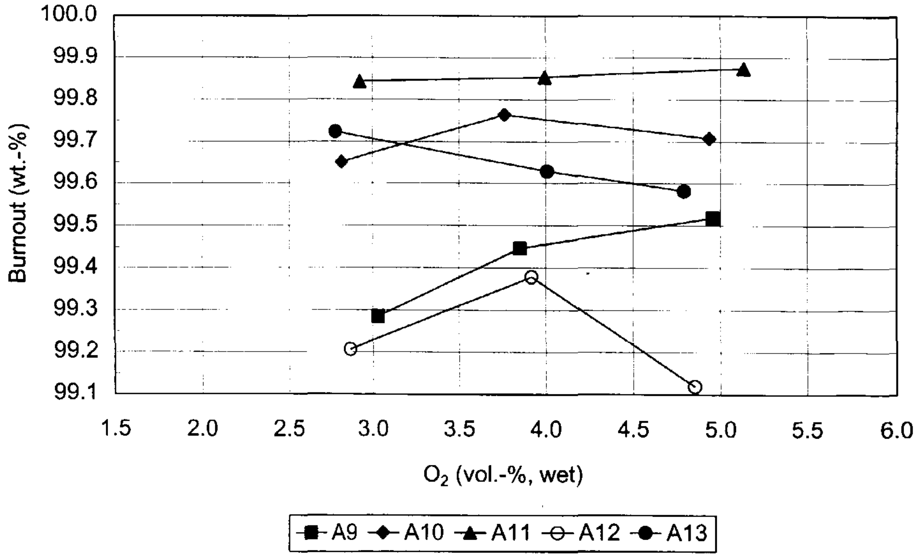


Figure 7.20 Burnout as function of the excess air ratio (Amer baseline measurements, BOOP = 40)

As is observed in **figure 7.18** the burnout of the coal blends burned at Maasvlakte power plant can be as high as 99.6% and as low as 98.5%. The burnout of the blends burned at Amer power plant is shown in **figure 7.19** and **7.20**. The burnout ranges from 99.3% to almost 100% for burner level 10 out of operation and from 99.1 to 99.9 with burner level 40 out of operation. Since the burnout results show an irregular trend with the excess air ratio, it was decided to use the average burnout in the regression analysis.

7.5.3 Burnout as function of coal quality

7.5.3.1 Regression analysis and model building

The burnout of the coal blends has been analysed by means of simple linear regression analysis. The average values of the burnout measured during the baseline experiments have been correlated with simple coal characteristics. **Table B.7** (appendix B) lists the burnout values for all coal blends used in the regression analysis. **Table B.9** (appendix B) contains the coefficients of determination obtained by the analysis for both units.

The volatile matter and fuel ratio appears to be the most dominant factors in controlling the burnout. **Table 7.8** contains the coefficients of determination and the regression coefficients of the models obtained.

Table 7.8 The coefficient of determination (R^2) and the regression coefficients (β_0 and β_1) from the simple linear regression analysis of volatile matter and fuel ratio with burnout

Plant	Combustion mode		VM_{ar}	VM_{db}	VM_{daf}	FR
Maasvlakte		R^2	0.63	0.61	0.59	0.63
		β_0	95.81	96.49	95.89	101.27
		β_1	0.119	0.085	0.092	-1.150
Amer 9	BOOP = 10	R^2	0.74	0.85	0.76	0.73
		β_0	98.34	98.52	98.31	100.47
		β_1	0.043	0.033	0.035	-0.498
Amer 9	BOOP = 40	R^2	0.91	0.96	0.97	0.97
		β_0	97.80	98.02	97.59	100.78
		β_1	0.060	0.047	0.053	-0.711

Taking into consideration that the NO_x models are based on the volatile matter on a dry basis and the fact that the coefficient of determination for the volatile matter on a dry basis is the best regressor on average it is decided to use this parameter as a first estimator. The following models can be derived:

Maasvlakte burnout model

$$Bu = 96.49 + 0.085 \cdot VM_{db} \qquad (7.7)$$

Amer burnout models

<u>BOOP = 10</u> $$Bu = 98.52 + 0.033 \cdot VM_{db} \qquad (7.8)$$

<u>BOOP = 40</u> $$Bu = 98.02 + 0.047 \cdot VM_{db} \qquad (7.9)$$

The Maasvlakte burnout correlation differs from the one already presented (Rozendaal et al., 1997a). The former model was based on the fuel ratio instead of the volatile matter content. Although the burnout values used in the regression analysis are an average value of two or three fly ash samples taken at different O_2 concentrations, it is supposed that the burnout model is less accurate at both low (O_2 < 3%) and high (O_2 > 5%) excess air ratios.

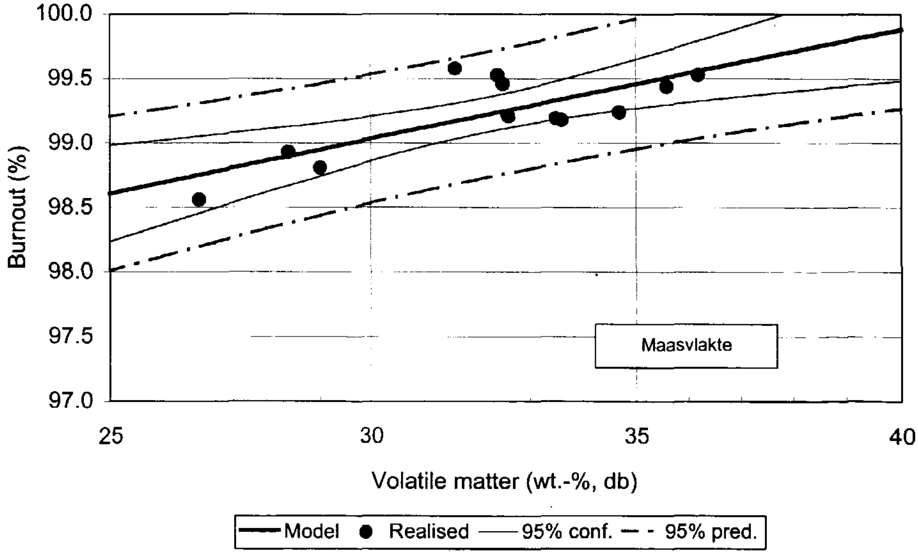


Figure 7.21 Maasvlakte burnout model (O_2 = 3%) and the confidence and prediction intervals

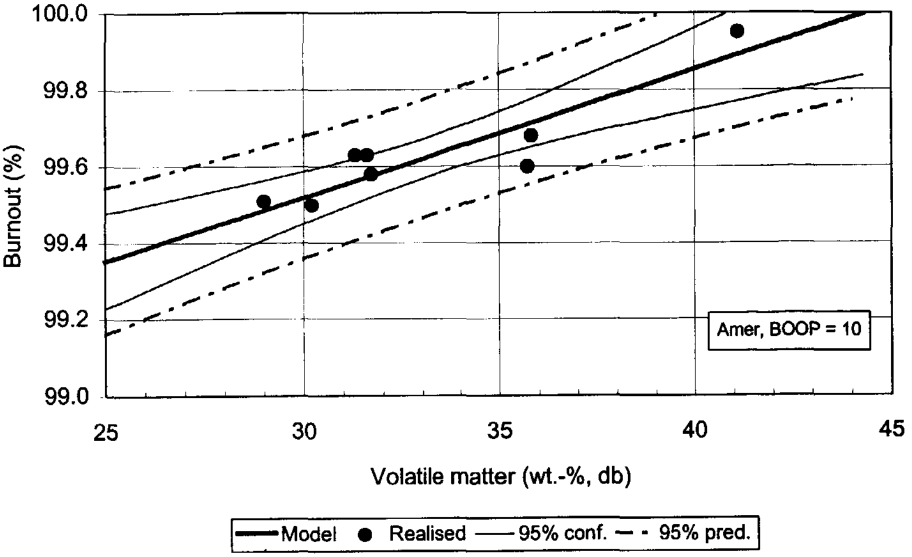


Figure 7.22 Amer burnout model (BOOP = 10) and the confidence and prediction intervals

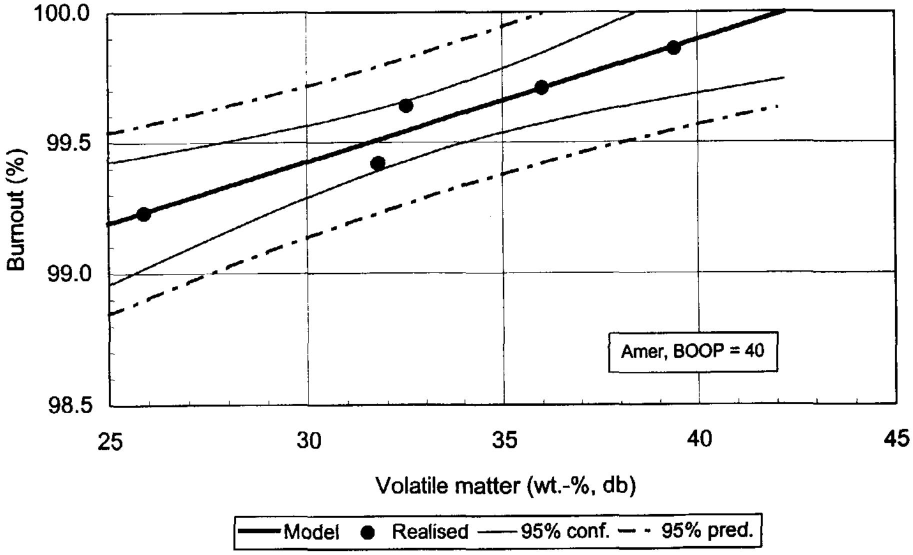


Figure 7.23 Amer burnout model (BOOP = 40) and the confidence and prediction intervals

7.5.3.2 Residual analysis, confidence and prediction interval

The residuals were considered to determine any model deficiencies. The residual analysis is given in section B.4.4 (appendix B). The residual plot of Maasvlakte showed that one data point near the centre of the data has a positive residual which is somewhat larger than average. This possible outlier belongs to blend MV10. From the particle size analysis given in section B.1 (appendix B) it can be observed that the pulverised coal is somewhat finer compared to the other coals. However, when the particle size was incorporated into the regression analysis the improvement of the accuracy of the model was marginal. The residual plot for the Amer case (BOOP = 10) showed that the model is strongly affected by one single data point (blend A5). Without this data point the relationship would be less progressive. Blend A5 was in fact a single coal from Colombia, which also observed a very good burnout at other Dutch power stations.

Figure 7.21 shows the burnout model of Maasvlakte power plant determined with simple linear regression analysis in combination with the observed values. The confidence interval on the mean response and the prediction interval for new (or future) observations are also given. The figure shows that the model fits the data points reasonably well. **Figures 7.22** and **7.23** show the burnout models of Amer power plant with burner level 10 and burner level 40 out of operation respectively. The models agree reasonably well with the data points.

7.5.4 Validation of the Amer burnout model

As with the NO_x model, the burnout model of Amer power plant can also be validated with the results of the test trials with the subbituminous coals. **Table B.18** (appendix B) arranges the burnout data of the tests with Powder River Basin blends (see also **figure 7.24**).

The observed burnout of the PRB-blends is compared to the model calculations in **figure 7.25** and **table 7.9**. Although the actual burnout values are within the 95% prediction interval of the model, it appears that the burnout is somewhat overpredicted, indicating that the model is not very accurate.

Table 7.9 Predicted and observed burnout of the Powder River Basin blends

Blends	Volatile matter (wt.-%, dry)	Predicted burnout (wt.-%)	Observed burnout (wt.-%)
PRB0	32.9	99.61	99.47
PRB25	35.0	99.68	99.60
PRB40	37.7	99.76	99.62

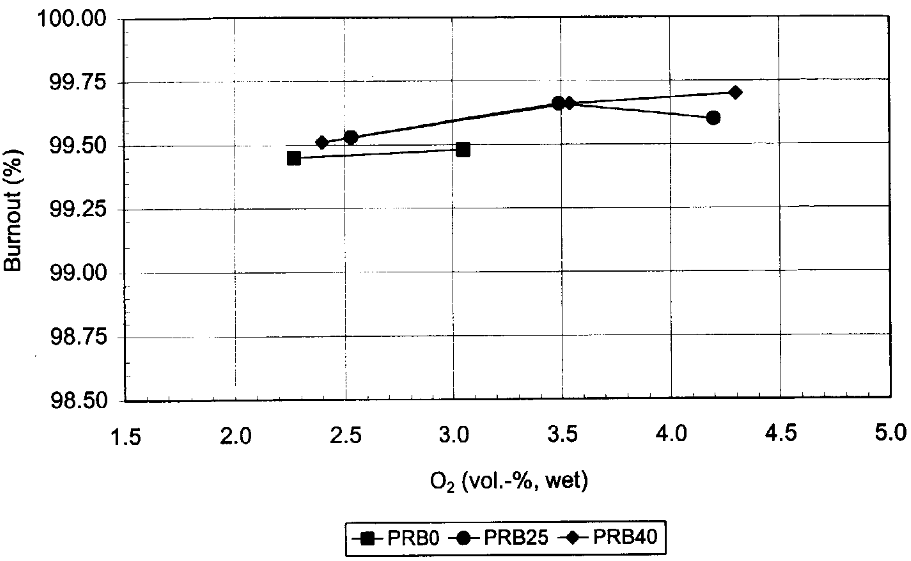


Figure 7.24 Burnout of the Powder River Basin blends (BOOP = 10) burned in Amer unit 9

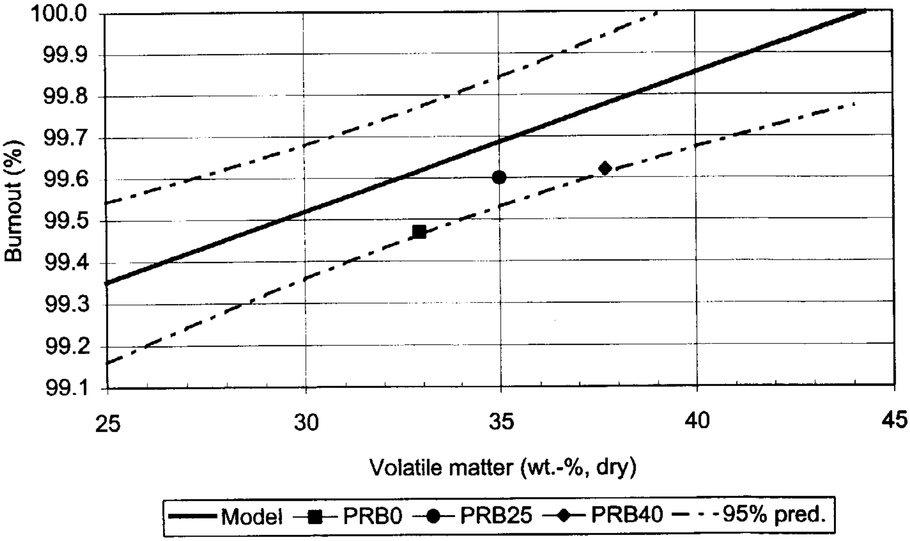


Figure 7.25 Observed burnout of the PRB blends (BOOP = 10) compared to the burnout model

7.6 INFLUENCE OF GRINDABILITY ON BURNOUT

From the period January 1996 till August 1996 performance data of both Maasvlakte units were analysed with respect to coal quality and burnout. In that specific period it was observed that the unburned carbon content in the fly ash was considerably lower than expected on basis of the coal characteristics. In that period a large number of blends was burned containing unknown coals not burned in the Netherlands before.

Usually, every day a fly ash sample is collected to determine the unburned carbon content. The period that a blend is burned may vary from a few days to more than a week. For each coal blend a specific number of fly ash samples was collected. The average value of the unburned carbon content in each blend was calculated and correlated with the coal characteristics and compared with the baseline burnout model of Maasvlakte which was discussed in section 7.5.3. The differences in boiler settings and load were left out of consideration.

The unburned carbon content in the fly ash has been converted to burnout. **Figures 7.26** and **7.27** show the burnout data of both Maasvlakte units compared to the model (equation 7.7). It is assumed that the burnout model developed for unit no. 1 of Maasvlakte power plant is also valid for unit no. 2, since both boilers are identical. (Although it is known that identical boilers may behave differently). The burnout has also been correlated with the volatile matter content on a dry basis (the regressor in the model). The coefficient of determination is in both cases low (0.16 for unit 1 and 0.11 for unit 2) indicating that the model is not adequate for these blends.

It appeared, however, that the Hardgrove grindability index (HGI) of a number of blends with an unexpected high burnout was rather high, indicating a relatively ease of grinding. Therefore the burnout data were also correlated using multiple linear regression analysis with the volatile matter content and HGI, giving coefficients of determination of 0.49 and 0.52, respectively. The regression equations derived are:

Maasvlakte unit 1
$$\mathrm{Bu} = 94.87 + 0.061 \cdot \mathrm{VM}_{db} + 0.044 \cdot \mathrm{HGI} \qquad (7.10)$$

Maasvlakte unit 2
$$\mathrm{Bu} = 95.88 + 0.046 \cdot \mathrm{VM}_{db} + 0.039 \cdot \mathrm{HGI} \qquad (7.11)$$

The predicted burnout on basis of these formulas is compared to the actual values in **figures 7.28** and **7.29**. Coals with a high HGI are easier to grind and may result in smaller particle size fractions, which will improve burnout. Although, the models have improved, still a lot of scatter is observed. This is partly caused by the fact that the boiler settings and load were not considered. Furthermore, above-mentioned models only yield a rough estimation of the burnout since many other factors, as already discussed in chapter 2, are involved.

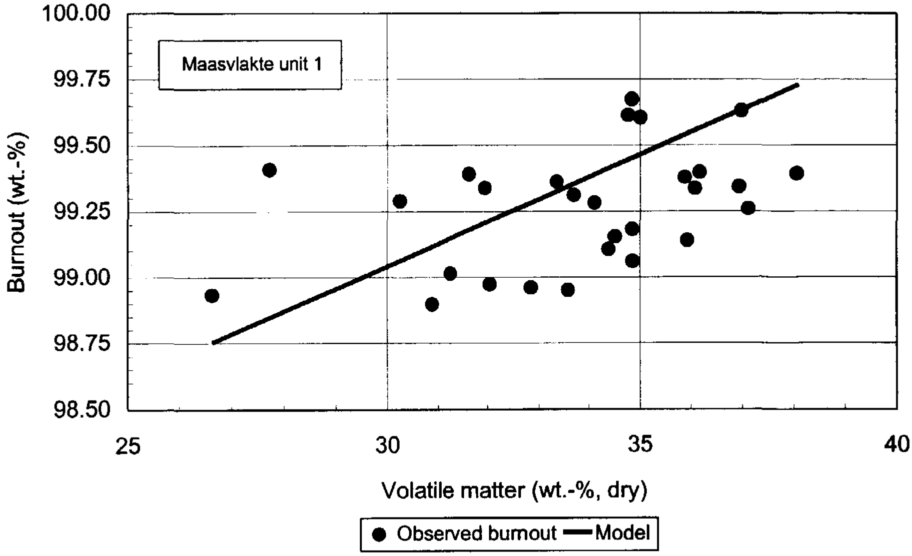


Figure 7.26 Burnout of the blends burned at unit 1 of Maasvlakte power plant compared to the baseline model in the period January 1996 - August 1996

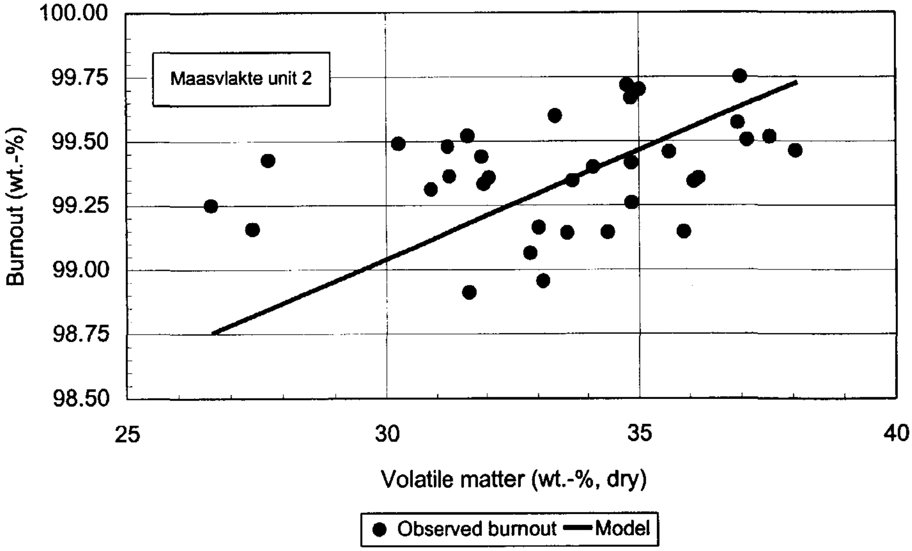


Figure 7.27 Burnout of the blends burned at unit 2 of Maasvlakte power plant compared to the baseline model in the period January 1996 - August 1996

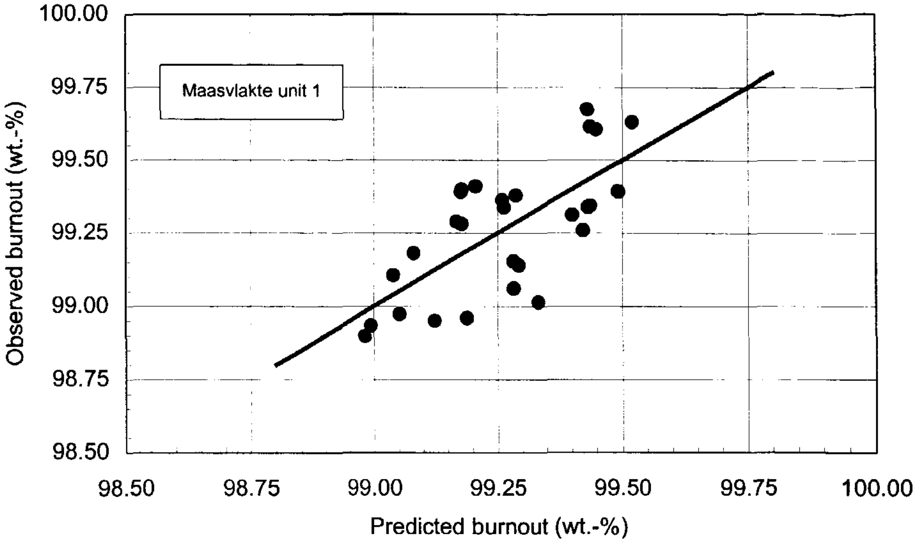


Figure 7.28 Burnout of the blends burned at unit 1 of Maasvlakte power plant compared to the alternative burnout model

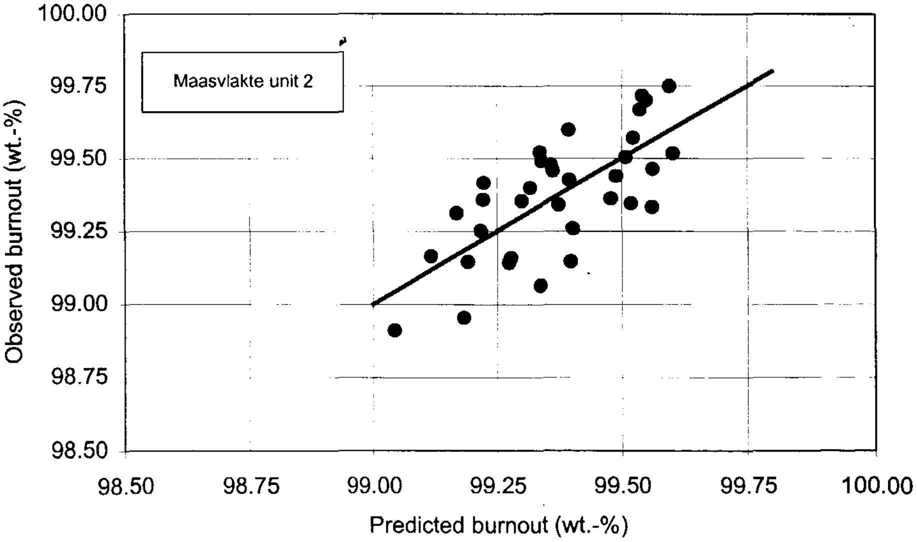


Figure 7.29 Burnout of the blends burned at unit 2 of Maasvlakte power plant compared to the alternative burnout model

7.7 DISCUSSION

7.7.1 NO_x prediction

The results presented in this chapter showed that NO_x emissions of coal blends composed from world-traded coals can be predicted reasonably well from simple coal characteristics. The models developed by means of linear regression analysis predict the NO_x emissions from the proximate volatile matter content. In reality the combustion process with the large variety of NO_x forming and reducing mechanisms involved is much more complicated than is described with the models. The models were developed with NO_x emissions measured under stable conditions, which were constant for all blends. Variation of the boiler settings and fluctuations of the unit load may result in NO_x emissions different from the predicted values. For example, the air distribution over the various auxiliary air ports and the overfire air ports is known to have a major impact on NO_x emissions. This was explicitly shown in a study on subbituminous coal-fired boilers (Dürselen, 1992). The measurements at the Amer power plant showed that NO_x emissions vary dependent on which burner levels are in operation. NO_x emissions are substantially lower (70-110 mg/m_0^3) with the upper burner level out of operation (BOOP=10) compared to operation with burner level 40 out of operation. The difference measured at Amer power plant is comparable with values measured at Maasvlakte power plant (KEMA, 1995) and with values mentioned in literature. For instance, a reduction of NO_x emissions of about 70 mg/m_0^3 was reported for a tangential-fired boiler in the United Kingdom that was retrofitted with low NO_x burners (Brooks et. al., 1986). The baseline NO_x emissions from this unit were in the order of 500 - 650 mg/m_0^3 with all (six) burners in operation. The reduction of 70 mg/m_0^3 was achieved by taking the upper burner level out of operation. Others reported a NO_x reduction of 15 to 30% due to the effect of BOOP (Himes et al., 1997).

The higher NO_x emissions with the upper burner level in operation are due to the reduced residence time in the main combustion zone. The impact of residence time on NO_x emissions is discussed in chapter 11.

The baseline tests at Maasvlakte and Amer power plant were performed, as mentioned before, under stable conditions and with identical boiler settings, apart from the excess air ratio and, specifically for the Amer power plant, the burner levels in operation. The best correlation with the NO_x emissions was observed for the (proximate) volatile matter content, although the fuel ratio also showed a good correlation. This is in agreement with other investigations which involved low NO_x combustion conditions (see chapter 3). This study also showed that the fuel nitrogen content was not a good predictor, which is supported by other studies (Kremer et al., 1990). However, the nitrogen contained in the coal is responsible for the vast amount of NO_x formed in low NO_x units, since volatiles themselves do not produce NO_x (except for the nitrogen containing species). As was already discussed in chapter 3, the volatile matter is closely related to the partitioning of nitrogen between volatile and char nitrogen (see **figure 3.4**). Although maybe not linearly related, an increase of the volatile release, results in an increase of the nitrogen released with the volatiles. Because of the substoichiometric main combustion zone volatile nitrogen is (partly) converted to N_2 instead of being oxidised to NO. It is apparent, however, that total nitrogen content is not a good predictor, whereas the volatile matter, which in fact indirectly affects NO_x emissions showed the best correlation. This is even more surprising, since, as was already discussed in chapter 2, the volatile matter is measured at conditions, which are far from the conditions experienced in actual flames. The results of the correlation of high temperature volatile matter and char nitrogen with NO_x emissions are discussed in the following chapters.

7.7.2 Burnout prediction

The burnout of coal is affected by many coal-related factors. In this study it was found that the volatile matter content might be used for predicting the burnout in the low NO_x units considered. Burnout is mainly governed by the reaction of fixed carbon with oxygen in the later stages of combustion. Factors, which are not considered in this study or did not show a statistical relevant impact are, for instance, the particle size, free swelling index, petrographic or maceral composition, char morphology and mineral matter distribution.

Analysis of day-to-day operational data of Maasvlakte power plant showed that the grindability might have an effect on burnout. This can only be explained that easier-to-grind coals result in a reduced particle size. More research is needed to confirm and quantify the impact of grindability on burnout.

7.7.3 Impact of blending

Since the experiments considered in this section were performed with full-scale boilers, as a result of which large amounts of coal were needed with specific characteristics, it was impossible to perform the experiments with single coals. The coal blends used in this study consisted mostly of three to five coals with varying characteristics. Nevertheless the coal blends were treated in this study as single coals. The impact of blending on power plant performance was studied in other programmes, which are discussed in chapter 10.

7.7.4 Error analysis

Appendix C contains an analysis of the measurement errors. It is shown that the regression models with the confidence intervals account for the measurement errors.

7.7.5 Practical implications

Simple prediction formulas for NO_x and burnout are very helpful in the decision to buy a specific coal or to compose a specific blend. Since the parameters used in the prediction formulas are generated by standardised analyses, which are moreover always included in a coal offer these formulas can be used to assess the suitability of a specific coal for the power plant.

The burnout behaviour of coal is even more difficult to predict on the basis of simple coal characteristics. For instance, the morphology of char plays a dominant role in burnout (Cloke et al., 1997). Swelling of coal particles, fractionation of the particles in the initial stages of combustion, but also the maceral type and particle size all influence the morphology of the char. Volatile matter may therefore only be used as a first indication for burnout.

In chapter 11 the overall results are discussed. The models are compared and interpreted by means of the combustion conditions prevailing in the boilers considered.

7.8 CONCLUSIONS

The NO_x emissions of a coal (blend) burned in a utility boiler can be predicted sufficiently accurate using simple coal characteristics. The volatile matter content on a dry basis determined with the proximate analysis proved to be the best predictor for the NO_x emissions. This was shown in two separate studies on two tangential low NO_x pulverised coal-fired boilers designed to burn a broad range of world-traded coals. The total nitrogen content in the coal is of minor importance and did not improve the accuracy of the prediction.

Although the prediction accuracy was less than with the NO_x emissions, the volatile matter content on a dry basis appeared to be the best predictor for the burnout. The relation between burnout and volatile matter content is a very simplified relation in which other important aspects of coal and char are not considered.

Chapter 8 CHAR NITROGEN AND NO_x EMISSIONS FROM AMER UNIT 9

8.1 INTRODUCTION

In chapter 6 the NO_x emissions from a pilot-scale facility were correlated with the coal characteristics determined with the proximate and ultimate analysis as well as with char nitrogen. The chars were produced in a DTF at 1200 °C. NO_x emissions from Maasvlakte unit 2 and Amer unit 9 were correlated with the standard coal analysis as was shown in chapter 7. It was observed that for both full-scale data sets the proximate volatile matter content showed the best correlation with NO_x emissions.

Since it is known that the main source of nitrogen responsible for the NO_x emissions from modern low NO_x units originates from the coal, the proximate volatile matter content is only a substitute for the actual NO_x determining factor. The nitrogen content in the char is believed to be the dominant factor in low NO_x units. In this chapter the impact of char nitrogen on the NO_x emissions from the tangential-fired boiler of Amer unit 9 is discussed. Since no standardised method is available to produce representative chars for the determination of the char nitrogen content a drop tube furnace (DTF) of KEMA was used as well as a heated wire grid reactor (HWG) of DMT.

8.2 OBJECTIVES AND APPROACH

8.2.1 Objectives

The main objective of this investigation was to determine if the char nitrogen content correlates with the NO_x emissions from Amer unit 9. Another objective was to determine to what extent the experimental conditions and type of equipment affect the partitioning of fuel nitrogen into volatile and char nitrogen.

8.2.2 Experimental approach

Pulverised coal samples were collected from a limited number of pulverised coal transport lines during the combustion experiments at Amer unit 9 with thirteen coal blends (described in chapter 7). The samples were sieved to obtain the fraction between 53 and 105 μm.

The pulverised coal samples were pyrolysed in the DTF of KEMA. Since the DTF is not capable of achieving high enough temperatures comparable to the temperatures in actual boilers, chars were also produced in a HWG reactor. The ash-tracer technique is often employed to measure the volatile yield with DTF experiments. This may lead to large errors when coal with a low ash content is used (see chapter 5). The HWG reactor is a captive sample technique, where a sample of coal is held between two layers of mesh. The volatile yield is then determined by weighing the mesh and the sample before and after treatment.

The main reason for selecting the HWG reactor of DMT (Essen, Germany) was that the platinum mesh used in this reactor was fine enough to hold the particle size fraction of 53 – 105 µm. The pulverised coal was too fine to obtain a sample with particles larger than 105 µm.

8.3 EXPERIMENTAL

8.3.1 Coal characteristics

The proximate analysis of the pulverised coal samples and the nitrogen content are listed in **table 8.1**. It should be noted that the coal characteristics listed in the table are somewhat different from the coal characteristics used in chapter 7 (appendix B). The proximate analysis displayed here was performed on the fraction 53-105 µm, whereas the proximate analysis given in chapter 7 was performed on the raw coal.

Table 8.1 Analysis of the pulverised coal samples (53 – 105 µm) used in the DTF and HWG experiments

Blend	Moisture (wt.-% ad)	Ash (wt.-%, db)	VM (wt.-%, daf)	N_{coal} (wt.-%, daf)
A1	3.4	8.7	38.0	1.82
A2	4.4	3.0	42.1	1.40
A3	3.0	10.4	34.7	1.96
A4	2.3	11.0	32.9	1.96
A5	1.9	9.3	35.1	1.80
A6	1.8	10.9	32.9	1.95
A7	2.3	10.2	34.7	1.94
A8	2.1	7.6	39.4	1.66
A9	2.3	10.1	36.4	1.71
A10	5.2	6.4	39.8	1.58
A11	4.8	7.8	40.0	1.60
A12	2.6	14.5	29.9	2.05
A13	3.7	11.1	35.1	1.88

8.3.2 DTF experiments

The experimental conditions during the DTF experiments are listed in **table 8.2**. A description of the DTF is given in chapter 5. All experiments were executed once. The volatile matter, nitrogen, moisture and ash content were determined of the pulverised coal samples. The char samples were analysed on nitrogen and ash content.

Table 8.2 Experimental conditions DTF experiments

Parameter	Value
Feed rate pulverised coal	12 g/h
Size fraction	53 – 105 μm
Wall temperature	1200 °C
Temperature carrier gas (nitrogen)	1200 °C
Heating rate	10^4 °C/s
Residence time	> 2 s

8.3.3 HWG experiments

The experimental conditions of the HWG experiments are listed in **table 8.3**. A description of the HWG reactor is given in chapter 5. The experimental conditions were determined by means of a parameter study, in which the temperature (1200, 1350 and 1500 °C) and the hold time (1, 5 and 10 seconds) were varied. It was observed that the nitrogen release was highest at a temperature of 1500 °C. Above 1350 °C no additional weight loss was observed. The impact of hold time was less pronounced.

The actual experiments were performed in triplicate. The values for volatile matter (V_{HWG}) presented in section 8.4 are the averages of three observations. The values for the nitrogen content in the char ($N_{char, HWG}$) are averaged over nine observations (each char sample was analysed in triplicate).

Table 8.3 Experimental conditions HWG experiments

Parameter	Value
Size fraction	53 - 105 μm
Temperature	1500 °C
Hold time	1 s
Heating rate	10^3 °C/s
Sweep gas	nitrogen

8.4 PYROLYSIS EXPERIMENTS

8.4.1 Results of the pyrolysis experiments in the DTF and HWG

Table 8.4 lists the results of the pyrolysis experiments in the DTF and HWG. The volatile yield is corrected for the moisture content in the coal samples (given in **table 8.1**). The char nitrogen content is expressed as the weight percentage of the original coal sample (53 – 105 μm). Subtracting the char nitrogen content on a coal basis (cb) from the total nitrogen content in the coal sample yields the nitrogen content in the volatiles on a coal basis. The percentage of nitrogen retained in the char ($\%N_{retained}$) is also listed. This is defined as the ratio of the char nitrogen content (on a coal basis) and the nitrogen content in the pulverised coal fraction (53 – 105 μm).

Table 8.4 Results of the DTF and HWG experiments

Blend	VM wt.-%, daf 53 – 105 μm	V_{DTF} wt.-%, daf	V_{HWG} wt.-%, daf	$N_{char, DTF}$ wt.-%, daf cb	$N_{char, HWG}$ wt.-%, daf cb	$\%N_{retained}$ DTF	$\%N_{retained}$ HWG
A1	38.0	45.6	52.5	1.26	0.70	69.2	38.5
A2	42.1	54.8	57.8	0.95	0.60	67.9	42.9
A3	34.7	43.7	44.5	1.44	0.78	73.5	39.8
A4	32.9	42.5	42.2	1.45	0.96	74.0	49.0
A5	35.1	50.6	48.1	1.29	0.83	71.7	46.1
A6	32.9	47.2	46.5	1.26	0.78	64.6	40.0
A7	34.7	47.9	46.8	1.24	0.88	63.9	45.4
A8	39.4	53.8	51.1	1.06	0.71	63.9	42.8
A9	36.4	48.1	47.5	1.22	0.81	71.3	47.4
A10	39.8	51.2	52.7	1.05	0.77	66.5	48.7
A11	40.0	52.8	51.1	1.20	0.90	75.0	56.3
A12	29.9	38.4	42.9	1.55	1.01	75.6	49.3
A13	35.1	45.7	49.8	1.41	0.86	75.0	45.7

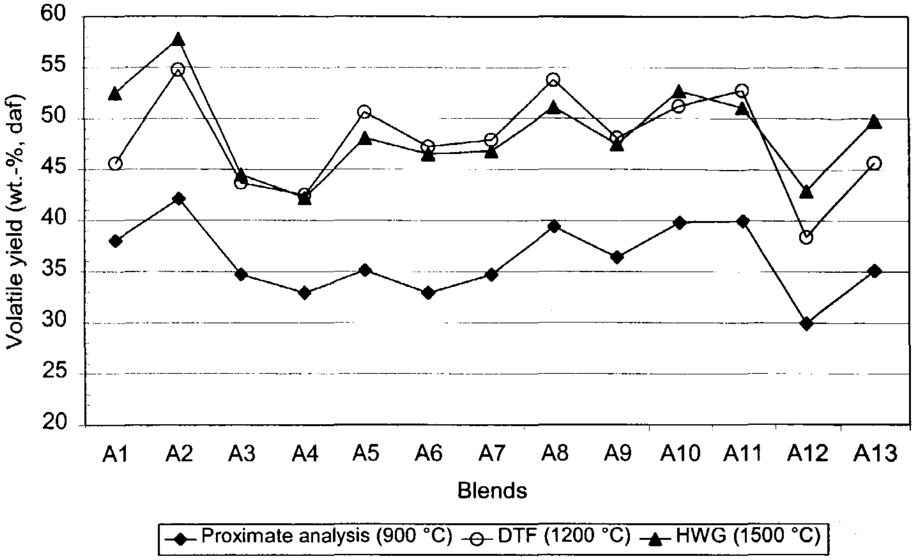


Figure 8.1 Comparison of proximate volatile matter (53 – 105 μm) and high temperature volatile yield determined with the DTF (1200 °C) and HWG (1500 °C)

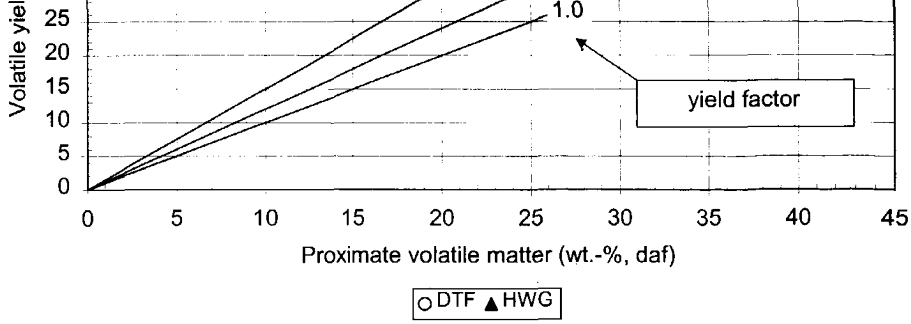


Figure 8.2 Plot of volatile matter determined with the DTF and HWG against the proximate volatile matter

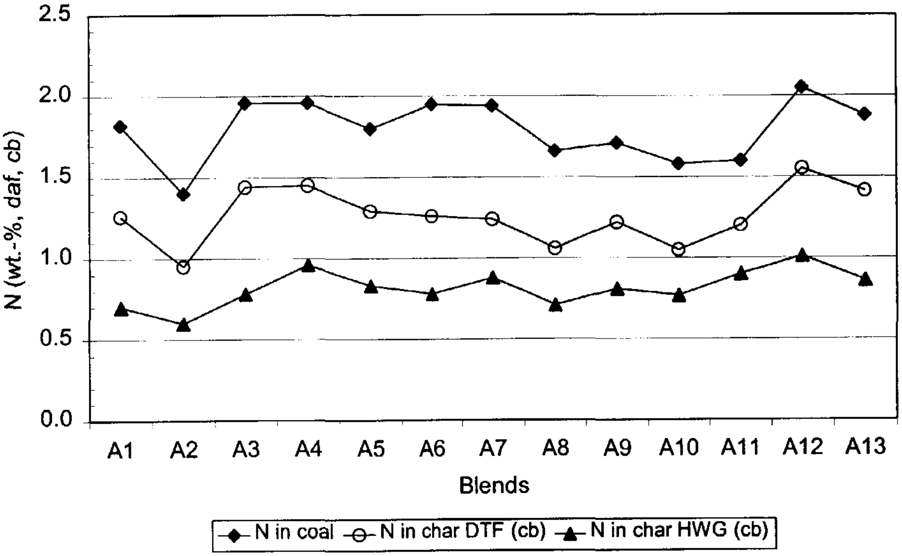


Figure 8.3 The nitrogen content in the coal (fraction 53 - 105 μm) and the nitrogen content in the chars (expressed on a coal basis) from the DTF and HWG experiments

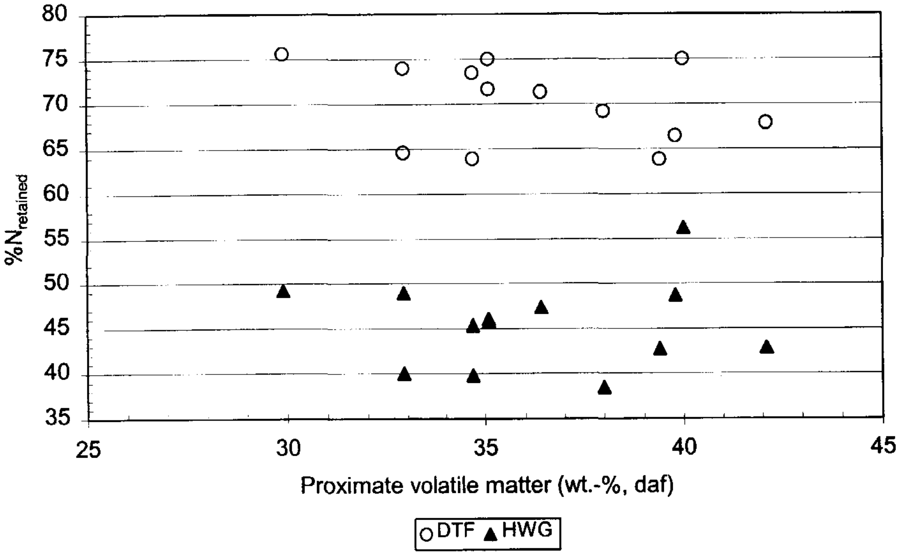


Figure 8.4 Plot of the percentage of nitrogen retained in the char against the proximate volatile matter

8.4.2 High temperature volatile matter

Figure 8.1 shows the amount of volatiles measured with the proximate analysis, at 1200 °C with the drop tube furnace and at 1500 °C with the heated wire grid reactor of DMT. It is observed that the volatile matter determined at higher temperatures clearly exceeds the volatile matter measured at standard conditions (900 °C). The volatile yields determined in the DTF at a temperature of 1200 °C and in the HWG at 1500 °C are more or less comparable. About 32% more volatiles are released at a temperature of 1200 °C (yield factor = 1.32) compared to the proximate volatile matter yield. This is 35% at a temperature of 1500 °C (yield factor = 1.35).

The volatile matter yields of the DTF and HWG experiments is compared to the volatile matter content from the proximate analysis once again in **figure 8.2**. The constant yield factor lines of 1, 1.2 and 1.5 are drawn in this figure. As is observed the yield factors vary between 1.2 and 1.5.

8.4.3 Nitrogen partitioning

The nitrogen content in the pulverised coal (fraction 53 – 105 μm) and the nitrogen content in the chars (on a coal basis) from the DTF and HWG experiments are shown in **figure 8.3**. The chars produced in the HWG reactor contain significantly less nitrogen then the chars produced in the DTF. Apparently the higher temperature used in the HWG reactor results in an additional release of nitrogen with the volatiles, despite the comparable volatile yields.

Obviously, the percentage of nitrogen retained in the char depends to a large extent on the pyrolysis temperature. The average percentage of nitrogen retained in the char is 70% for the chars produced at a temperature of 1200 °C in the DTF and 45% for the chars produced at a temperature of 1500 °C in the HWG. As observed in **figure 8.4** no relationship exists between the percentage of nitrogen retained in the char and the proximate volatile matter content in the coals. Plots of the percentage of nitrogen retained in the chars against the high temperature volatile matter yield determined with the DTF and HWG also show no dependency (not shown here). **Figure 8.5** illustrates the relationship between the nitrogen content in the coal and the percentage of nitrogen retained in the char. It is observed that there exists no obvious qualitative relationship between the nitrogen content in the coal and the percentage of nitrogen retained in the char.

Figure 8.6 illustrates the relationship between the percentage of nitrogen retained from the DTF experiments at 1200 °C and from the HWG experiments at 1500 °C. It is observed that no clear relationship exists between both parameters. This result suggests that the release of nitrogen is temperature dependent and that the temperature effect is coal dependent.

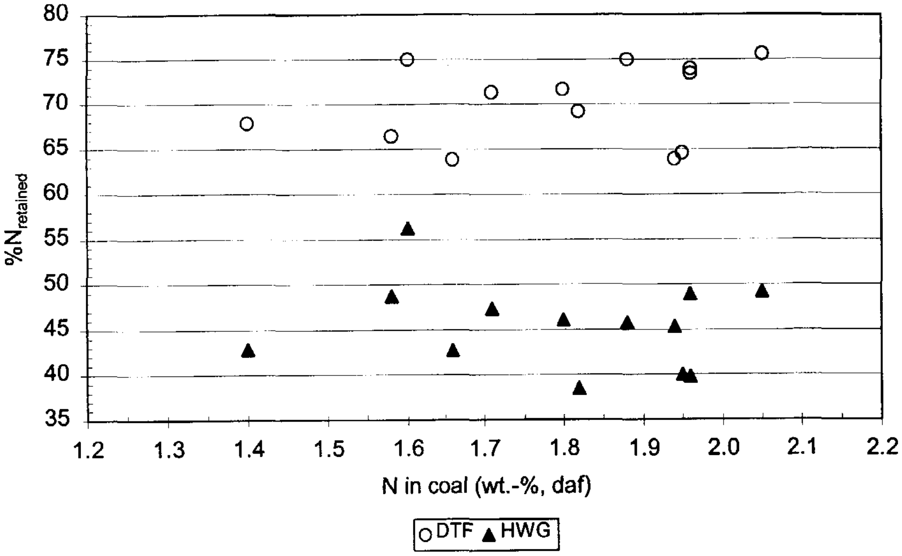


Figure 8.5 Plot of the percentage of nitrogen retained in the char and the coal nitrogen content (53 - 105 μm)

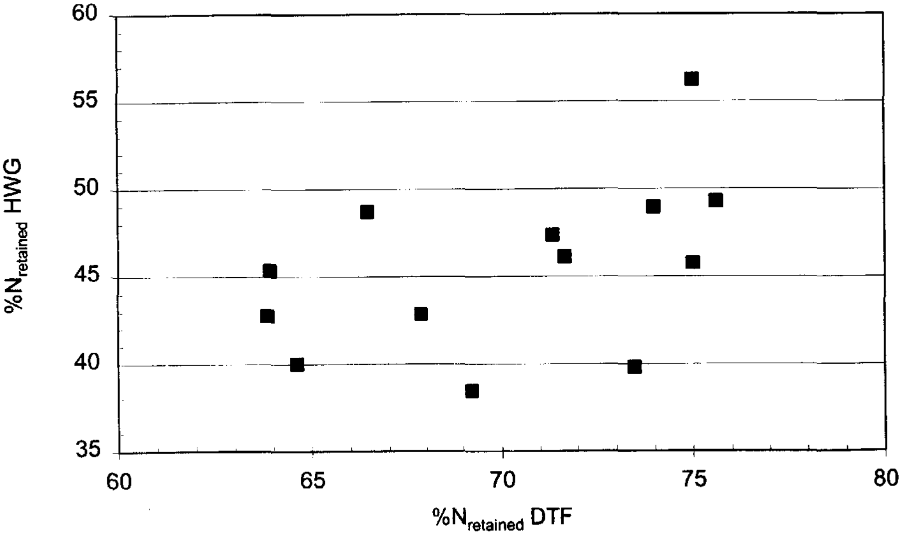


Figure 8.6 Comparison of the percentage of nitrogen retained in the chars of the DTF and HWG experiments

8.4.4 Discussion

The yield factors determined with the DTF and HWG are comparable to values mentioned in literature, which range from 1.1 to 1.8 (see chapter 2), although the experimental conditions and experimental techniques are different. At a temperature in the order of 1200 °C the maximum volatile yield is reached for bituminous coals (at sufficiently large residence times). In this study it was shown that an increase in pyrolysis temperature from 1200 °C to 1500 °C resulted in a marginal increase of volatile yield. However, it should be noted here that the pyrolysis techniques used in this study are quite different, which may also affect the volatile yield. For example, the heating rate in the HWG reactor is estimated at 10^3 °C/s, whereas the heating rate is ten times higher in the DTF.

The nitrogen release increases with temperature. This is consistent with observations by others (Pohl et al., 1976; Blair et al., 1976; Man et al., 1993). An explanation for this behaviour was already suggested by Pohl et al. (1976). In the early stages of pyrolysis the release of side chains and aliphatic links dominate the volatiles generated. Subsequently, the aromatic rings will decompose, releasing some nitrogen. Secondary condensation reactions, leading to char formation, will compete with the decomposition reactions leading to volatile evolution.

The condensation reactions can lead to the formation of multiple aromatic rings with internal carbon atoms. Nitrogen if incorporated in the products of condensation reactions will be either in a side chain or a peripheral atom in a multi-ring structure. Thus it is expected that condensation reactions will lead to the formation of relatively nitrogen-free chars (Pohl et al., 1976). In a recent overview on the role of nitrogen during char combustion by Thomas (1997) it was stressed that the partitioning of coal nitrogen into char and volatile nitrogen depends on pyrolysis temperature, heating rate, coal type and equipment used. It is suggested that coal pyrolysis at intermediate temperatures and for short residence times usually yields chars that are higher in nitrogen content than the parent coal. At higher temperatures the nitrogen content in the char is usually lower. The enrichment of nitrogen in the char is therefore a function of pyrolysis temperature and residence time, and reaches a maximum in the temperature range 700 – 1000 °C. This is consistent with the early stages of pyrolysis described with the speculative model of Pohl et al. (1976).

Thomas (1997) suggested the following explanation for the nitrogen release as function of temperature. Primary devolatilisation involves the release of tars which have similar nitrogen contents to that of the coal. The secondary devolatilisation involves the releases of gases such as methane and hydrogen, and this gives rise to an increase of the N/C ratio. As the pyrolysis temperature is increased further, this results in the release of HCN and NH_3, leading to a decrease of the N/C ratio in the remaining chars at higher temperatures. At relatively low pyrolysis temperatures (1000 °C) in an HWG reactor total volatile and nitrogen yields are approximately proportional. Pyrolysis at temperatures > 1400 °C results in the evolution of a significant amount of additional nitrogen (Gibbins et al., 1995a). Thomas (1997) concluded in his review that the release of this additional nitrogen during pyrolysis presents difficulties in selecting suitable test conditions for the prediction of char nitrogen contents under conditions pertaining to low NO_x combustion. The results presented in this chapter confirm this statement.

In addition, Thomas (1997) reviewed the role of coal nitrogen functionality in the partitioning of coal nitrogen into volatile and char nitrogen (see **figure 3.16**). He concluded that the type of nitrogen and the molecular structure of the precursor are not factors in determining the distribution of nitrogen functionalities in char. The residence time in the conversion of coal nitrogen to char nitrogen is believed to be a more important factor which needs to be examined in relation to the combustion and the structural characteristics of char particles in pulverised coal combustion.

8.5 CORRELATION WITH NO_X EMISSIONS FROM AMER UNIT 9

The high temperature volatile matter yield and the char nitrogen content in the coal blends have been correlated with the NO_x emissions from Amer unit 9. The NO_x measurements and the correlation with the standard proximate analysis are described in chapter 7. **Table 8.5** provides an overview of the data used for the correlation of NO_x emissions with coal characteristics.

The NO_x emissions shown in **table 8.5** are taken from **table B.6** (appendix B), and are part of the baseline experiments (oxygen concentration in the flue gases is 3%, wet) performed at Amer unit 9 under controlled conditions. The data are divided into two smaller data sets (BOOP = 10 and BOOP = 40) referring to the burner level that was out of operation during the measurements. The details of the full-scale experiments are explained in chapter 7.

Table 8.5 Data used for the correlation of coal characteristics with NO_x emissions from Amer unit 9

Blends	NO_x mg/m_0^3 ($6\%\ O_2$)	VM wt.-%, db	VM wt.-%, daf	V_{DTF} wt.-%, daf	V_{HWG} wt.-%, daf	N_{coal} wt.-%, daf	$N_{char,\ DTF}$ wt.-%, daf, cb	$N_{char,\ HWG}$ wt.-%, daf, cb
		whole coal		53-105 μm				
BOOP = 10								
A1	261	35.7	40.0	45.6	52.5	1.82	1.26	0.70
A2	222	41.1	43.6	54.8	57.8	1.40	0.95	0.60
A3	299	31.3	36.1	43.7	44.5	1.96	1.44	0.78
A4	367	29.0	33.4	42.5	42.2	1.96	1.45	0.96
A5	345	31.6	35.5	50.6	48.1	1.80	1.29	0.83
A6	371	30.2	34.4	47.2	46.5	1.95	1.26	0.78
A7	325	31.6	35.7	47.9	46.8	1.94	1.24	0.88
A8	313	35.7	40.5	53.8	51.1	1.66	1.06	0.71
BOOP = 40								
A9	455	31.8	36.0	48.1	47.5	1.71	1.22	0.81
A10	352	36.0	39.2	51.2	52.7	1.58	1.05	0.77
A11	364	39.4	43.4	52.8	51.1	1.60	1.20	0.90
A12	472	25.9	31.1	38.4	42.9	2.05	1.55	1.01
A13	440	32.5	37.4	45.7	49.8	1.88	1.41	0.86

Table 8.6 The coefficient of determination and the regression coefficients obtained from the simple linear regression analysis of selected coal parameters and NO_x emissions from Amer unit 9

	VM wt.-%, db	VM wt.-%, daf	V_{DTF} wt.-%, daf	V_{HWG} wt.-%, daf	N_{coal} wt.-%, daf	$N_{char, DTF}$ wt.-%, daf, cb	$N_{char, HWG}$ wt.-%, daf, cb
	whole coal		53 – 105 μm				
BOOP = 10							
R^2	0.82	0.81	0.18	0.69	0.54	0.35	0.66
β_0	705	801	550	735	-34	89	22
β_1	-11.8	-13.0	-49	-8.7	191.5	179.9	373.1
BOOP = 40							
R^2	0.79	0.72	0.70	0.76	0.72	0.66	0.25
β_0	736	802	801	1028	6	123	160
β_1	-9.6	-10.3	-8.1	-12.5	232.8	227.9	295.3

It is noted that the proximate volatile matter displayed in this table is the volatile matter content in the whole coal fraction that was also used in chapter 7 for the correlation of NO_x emissions and standard coal analysis data. All other variables are based on the 53 – 105 μm fraction.

NO_x emissions and coal characteristics have been correlated using linear regression analysis, following the approach outlined in chapter 7. **Table 8.6** summarises the results of the linear regression analysis. The regression coefficients β_0 and β_1 are the intercept and slope, respectively, of the linear regression model. As was the case in chapter 7 the volatile matter content on a dry basis appears to be the best predictor for the NO_x emissions. Neither the high temperature volatile matter (VM_{DTF} and VM_{HWG}) nor the char nitrogen content ($N_{char, DTF}$ and $N_{char, HWG}$) obtains a higher correlation coefficient than the proximate volatile matter. The weak correlation of char nitrogen is illustrated in **figure 8.7**. The lines in this illustration correspond to the best fits obtained from the linear regression analysis. Especially, the case with burner level 40 out of service (BOOP = 40) shows a weak correlation.

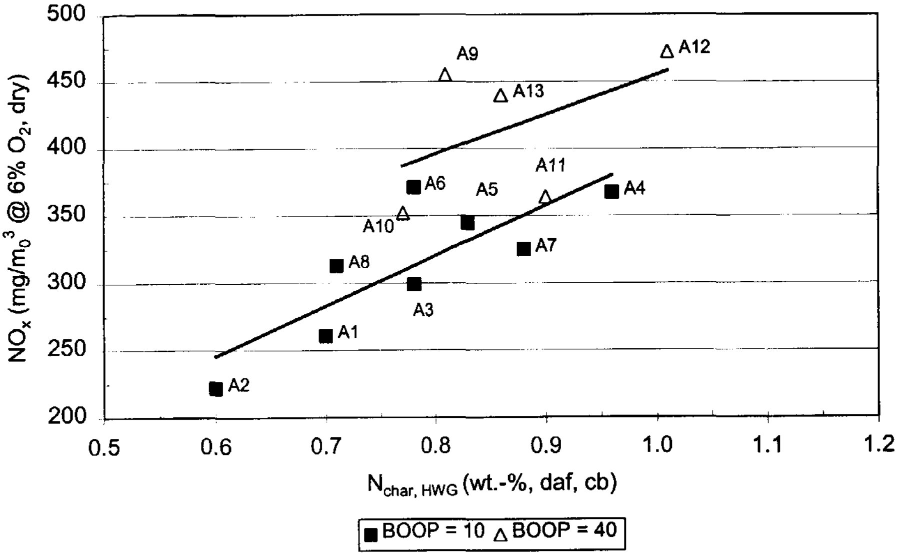


Figure 8.7 Correlation of char nitrogen (HWG, on a coal basis) and NO_x emissions from Amer unit 9

The difference between the observed and the expected behaviour may be due to a number of reasons:

- The experimental conditions used for the preparation of the chars are not representative for the conditions the pulverised coal experiences in the boiler of Amer unit 9. The difference in the percentage of nitrogen retained in the char between the DTF and HWG experiments indicate that the experimental conditions affect the results to a large extent (the average percentage of nitrogen retained was 70 and 45%, respectively). The nitrogen release in the HWG experiments, although much higher than the nitrogen release in the DTF experiments, may still be too low. Gibbins et al. (1995b) observed that the maximum release of nitrogen in a HWG reactor occurred at a temperature of 1600 °C, a hold time of 2 seconds and a heating rate of 10^4 °C/s.
- Indicative calculations (using equation 3.24) show that the conversion ratio of char nitrogen (HWG results) to NO_x, neglecting the contribution of thermal NO_x and NO_x formed from the volatile nitrogen, is in the order of 20%. Although, this is close to values mentioned in literature of 15 to 25% (Pohl et al., 1983), it has to be kept in mind that the conversion ratio of char nitrogen to NO_x strongly depends on the preparation of chars. The conversion ratio increases if char nitrogen is reduced by treatment at higher temperatures or higher heating rates. The residence time in the primary combustion zone plays a dominant role in the formation of NO_x. With the experiments with the upper burner level in operation, the residence time of the coal particles in

the substoichiometric primary combustion zone is substantially shorter compared to the other burner levels, since the overfire air ports are located directly above the upper burners. This may explain the weak correlation of NO_x emissions and char nitrogen for these experiments. The impact of residence time on NO_x emissions is discussed in chapter 11.

- The DTF and HWG experiments were performed on the 53 – 105 μm fraction. This size fraction contains approximately 25% of the mass fraction of the pulverised coal. It is unknown to what extent segregation may occur over the different size fractions. It can be observed that the volatile matter (daf) for this size fraction is somewhat lower than the volatile matter (daf) of the whole coal sample (compare **table 8.4** and **table 8.5**). The impact of particle size on the high temperature volatile matter and char nitrogen is not investigated in this study. Since in this study coal blends were used it is possible that segregation plays a more decisive role than with single coals.
- The number of observations is still limited. One small error in the measurements could already lead to erroneous conclusions.

8.6 CONCLUSIONS

The results presented in this chapter showed that the proximate volatile matter is substantially lower than the volatile matter measured under more severe conditions. Yield factors of 1.2 to 1.5 were achieved with a DTF operating at a temperature of 1200 °C and a heating rate of 10^4 °C/s as well as with a HWG reactor operating at a temperature of 1500 °C and a heating rate of 10^3 °C/s.

The results also showed that the chars produced in the HWG had released considerably more nitrogen than the chars produced in the DTF. This is a result of the difference in final temperature, which is confirmed by measurements found in literature.

The proximate volatile matter showed a better correlation with the NO_x emissions from Amer unit 9 than the high temperature volatile matter and the char nitrogen content. This is an unexpected result, since the proximate volatile matter is measured under conditions, which are mild, compared to the conditions in actual pulverised coal-fired boilers. A possible explanation for the weak correlation of char nitrogen content with the NO_x emissions from Amer unit 9 is that the conditions for char production are still different compared to the practical conditions. Furthermore, it is possible that volatile nitrogen still forms a major contribution to the NO_x emissions, especially with the upper burners in operation.

Chapter 9 CHAR NITROGEN AND NO$_X$ EMISSIONS FROM HEMWEG UNIT 8

9.1 INTRODUCTION

Unit 8 of Hemweg power plant has to meet a NO$_x$ emission limit of 300 mg/m$_0^3$ (6% O$_2$, dry). Coal characteristics and power plant operation play a decisive role in meeting the regulations. Full-scale combustion tests have been performed to determine the impact of coal quality on plant NO$_x$ emissions. From previous experiments it was known that standard coal analysis data alone could not accurately predict NO$_x$ emissions from Hemweg power plant (Hoogendoorn et al., 1998). A somewhat better correlation was found between the conversion ratio of coal nitrogen to NO$_x$ with the high temperature volatile matter yield determined in the drop tube furnace at KEMA (DTF) at 1200 °C and the volatile nitrogen content. However, the number of experiments was limited and it was felt that more experiments were needed to improve the prediction accuracy.

The previous chapter dealt with the impact of char nitrogen on NO$_x$ emissions from Amer unit 9. It was shown that the best correlation with NO$_x$ was achieved with the proximate volatile matter. The results suggested that the conditions for char production, which were produced in a DTF at 1200 °C and in a HWG at 1500 °C but at a lower heating rate (10^3 °C/s), were milder than the conditions prevailing in actual pulverised coal flames. This was very obvious for the DTF chars that had a significantly higher nitrogen content than the chars produced in the HWG.

Due to corrosion problems of the furnace walls probably as a result of flame impingement (Huijbregts et al., 1997) the burner settings and boiler operation were changed. Subsequently, a new test program with five coals and two coal blends was performed to determine the impact of coal quality on plant performance with these new burner settings. This chapter deals with the results of correlating the standard coal characteristics with the NO$_x$ emissions from Hemweg unit 8 as well as with the results achieved with correlating the char nitrogen content with the NO$_x$ emissions.

9.2 OBJECTIVES AND APPROACH

9.2.1 Objectives

The main objective of this investigation was to determine which coal parameter(s) is (are) the best predictor(s) for the NO$_x$ emissions. Coal characteristics involved are the standard proximate and ultimate analysis as well as the high temperature volatile matter yield and the char nitrogen content.

9.2.2 Approach

The NO_x emissions from unit 8 of Hemweg power plant were measured under standard operating conditions. A description of the unit can be found in chapter 5. Chars of the coals were produced in a heated wire grid reactor (HTWM, high temperature wire mesh) of the Mechanical Engineering Department, Imperial College (IC) to determine the char nitrogen content.

Since it was suggested that the conditions applied in the char nitrogen measurements, described in chapter 8, were not severe enough it was decided to perform the experiments in co-operation with IC. Dr. Gibbins and Dr. Man already had a long experience on the measurement of char nitrogen content with a heated wire grid reactor that was developed at IC. In the previous chapters a number of their papers on this subject has been cited. **Table 9.1** summarises the main differences between the conditions used in the heated wire grid experiments at DMT and IC. In earlier work by IC it was demonstrated that the conditions given in **table 9.1** resulted in the maximum release of nitrogen (Gibbins et al., 1995, DTI, 1998).

Table 9.1 Conditions during the heated wire grid experiments at DMT and IC

	DMT	IC
Final temperature	1500 °C	1600 °C
Particle size	53 – 105 μm	125 – 150 μm
Heating rate	10^3 °C/s	10^4 °C/s
Residence time	1 s	2 s

Table 9.2 Proximate analysis of the coals burned at Hemweg power plant

		Moisture (wt.-% ar)	Ash (wt.-%, ar)	VM (wt.-%, ar)	fuel ratio	N_{coal} (wt.-%, daf)
HW1	Venezuela	11.5	5.9	32.7	1.53	1.59
HW2	South Africa	7.0	14.0	22.6	2.49	2.06
HW3	Colombia	12.2	9.8	32.4	1.41	1.60
HW4	Colombia	13.8	6.1	32.7	1.45	1.72
HW5	blend	10.6	10.4	27.5	1.87	1.89
HW6	Colombia	12.2	3.7	35.5	1.37	1.52
HW7	blend	10.7	9.7	28.3	1.82	1.79

9.3 EXPERIMENTAL

9.3.1 Coal characteristics

The proximate analysis and the nitrogen content in the coals are listed in **table 9.2**.

9.3.2 Full-scale experiments Hemweg unit 8

The coals were burned at full load of the unit (620 MW_e) with all burners in service. The stoichiometry on the burners was set at 0.80. The NO_x emissions were measured at three excess air ratios. An increase of excess air in this boiler results in an increase of the overfire air since the stoichiometry at the burners was kept constant.

9.3.3 HTWM experiments

The coals were supplied from KEMA to IC. The pulverised coal fraction < 150 μm was analysed in a TGA. Subsequently, the coals were sieved to obtain a 125 – 150 μm fraction. This fraction was also analysed in the TGA and was used in the pyrolysis experiments in the HWG reactor. The HTWM experiments were performed in triplicate. CHN-analysis of the fraction < 150 μm, the fraction 125 – 150 μm and the chars were carried out in duplicate.

9.4 RESULTS

9.4.1 NO_X emissions Hemweg unit 8

Table 9.3 summarises the NO_x emissions measured at three excess air ratios. The NO_x emissions were measured in the flue gas duct downstream the FGD unit with the flue gas monitoring equipment of Hemweg unit 8. The NO_x emissions are normalised to 6% O_2.

Table 9.3 NO_x emissions (mg/m_0^3 @ 6% O_2, dry) measured downstream the FGD and O_2 concentration in the flue gases measured downstream the economiser (vol.-%, dry)

HW1		HW2		HW3		HW4		HW5		HW6		HW7	
O_2	NO_x	O_2	NO_x	O_2	NO_x	O_2	NO_x	O_2	NO_x	O_2	NO_x	O_2	NO_x
3.2	317	3.0	354	3.3	309	2.7	259	2.9	311	2.7	197	3.0	292
3.5	333	3.7	386	3.7	319	3.5	262	3.4	320	3.3	205	3.7	302
4.4	352	4.2	429	4.5	346	4.4	282	4.4	354	4.4	218	4.4	308

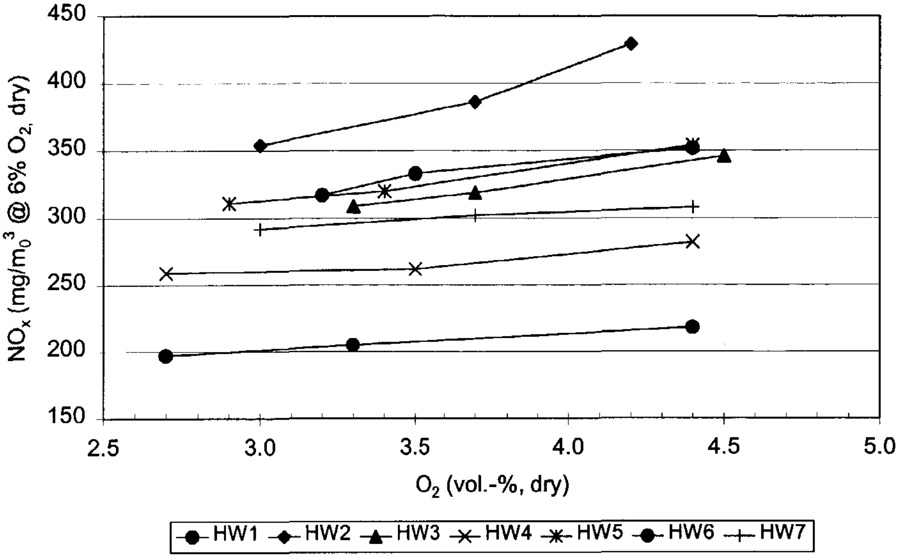


Figure 9.1 NO_x emissions from Hemweg unit 8 as function of the oxygen concentration measured downstream the economiser

Figure 9.1 illustrates the NO_x emissions of the coals as function of the oxygen concentration in the flue gases. The impact of excess air ratio is rather small since the stoichiometry at the burners remains constant when changing the excess air ratio.

The NO_x emissions of all coals were calculated at three fixed oxygen concentrations in the flue gases using linear regression analysis, comparable to the approach applied in chapter 7. **Table 9.4** lists the calculated NO_x emissions.

Table 9.4 Calculated NO_x emissions (mg/m$_0^3$ @ 6% O_2) for three oxygen concentrations (vol.-%, dry)

O_2	HW1	HW2	HW3	HW4	HW5	HW6	HW7
3.0	315	351	299	260	312	201	293
3.5	329	381	314	267	326	207	298
4.0	342	412	330	274	341	213	304

Table 9.5 Coal parameters determined at IC

Parameter	V_{TGA}	N_{coal}	Ash_{coal}	V_{TGA}	N_{coal}	V_{HTWM}	N_{char}
fraction	< 150 μm				125-150 μm		
basis	wt.-%, daf	wt.-%, daf	wt.-%, db	wt.-%, daf	wt.-%, daf	wt.-%, db	wt.-%, db
temp.	900 °C	-	-	900 °C	-	1600 °C	1600 °C
HW1	38.8	1.69	4.3	38.3	1.76	52.0	1.46
HW2	28.5	2.11	13.1	28.5	2.20	37.9	1.09
HW3	39.3	1.70	9.4	38.6	1.84	53.5	1.38
HW4	38.8	1.78	3.5	38.7	1.80	58.3	1.16
HW5	32.7	1.96	9.8	32.0	1.99	45.8	1.14
HW6	39.3	1.57	3.0	38.5	1.59	58.9	0.98
HW7	32.8	1.86	8.9	32.4	1.89	46.4	1.01

9.4.2 Pyrolysis experiments

The fraction < 150 μm and the fraction 125 – 150 μm were analysed in the TGA (900 °C) and the HTWM reactor. **Table 9.5** summarises the main results obtained with the experiments. The analysis of the individual samples showed a good reproducibility.

After pyrolysis in the HTWM reactor the nitrogen content in the chars was determined (**table 9.5**). The char nitrogen content was calculated on a dry ash-free coal basis according to:

$$N_{char,cb,125-150\mu m} = \frac{N_{char} \cdot (100 - V_{HTWM,db})}{(100 - Ash_{coal,db,125-150\mu m})} \tag{9.1}$$

The char nitrogen content on a coal basis is given in **table 9.6b.**

9.5 CORRELATION OF COAL PARAMETERS WITH NO_X EMISSIONS

9.5.1 Oxygen concentration of 3.5%

Starting point for the correlations are the NO_x emissions calculated at an oxygen concentration of 3.5 vol.-% (**table 9.4**). The NO_x emissions have been correlated with various parameters including relevant coal parameters measured with the proximate analysis and the coal parameters derived from the HTWM experiments. **Table 9.6a** and **9.6b** summarise the data used for the linear regression analysis as well as the coefficients of determination determined with the linear regression analysis.

Table 9.6a Data used for linear regression analysis

	NO_x	VM	FR	$V_{TGA, < 150\ \mu m}$	$V_{TGA, 125\text{-}150\ \mu m}$	V_{HTWM}
		900 °C	900 °C	900 °C	900 °	1600 °
	mg/m_0^3 @ 6% O_2	wt.-%, daf	-	wt.-%, daf	wt.-%, daf	wt.-%, daf
HW1	329	39.5	1.53	38.8	38.3	54.3
HW2	381	28.6	2.49	28.5	28.5	43.7
HW3	314	41.5	1.41	39.3	38.6	59.1
HW4	267	40.8	1.45	38.8	38.7	60.4
HW5	326	34.8	1.87	32.7	32.0	50.7
HW6	207	42.2	1.37	39.3	38.5	60.7
HW7	298	35.5	1.82	32.8	32.4	50.9
R^2		0.58	0.56	0.44	0.42	0.66

Table 9.6b Data used for linear regression analysis (continued)

	NO_x	N_{coal}	$N_{coal, < 150\ \mu m}$	$N_{coal, 125\text{-}150\ \mu m}$	$N_{char, cb, 125\text{-}150\ \mu m}$
	mg/m_0^3@ 6% O_2	wt.-%, daf	wt.-%, daf	wt.-%, daf	wt.-%, daf
HW1	329	1.59	1.69	1.76	0.73
HW2	381	2.06	2.11	2.20	0.78
HW3	314	1.60	1.70	1.84	0.71
HW4	267	1.72	1.78	1.80	0.50
HW5	326	1.89	1.96	1.99	0.69
HW6	207	1.52	1.57	1.59	0.42
HW7	298	1.79	1.86	1.89	0.59
R^2		0.51	0.60	0.76	0.92

A number of these correlations is shown in the **figures 9.2 – 9.7**. **Figure 9.2** shows the correlation of the proximate volatile matter content and the NO_x emissions. It is observed that the proximate volatile matter is not a good predictor for the NO_x emissions. The NO_x emissions vary between 201 and 329 mg/m_0^3 with the coals with a volatile matter content larger than 39%. The NO_x emissions as function of the fuel ratio are shown in **figure 9.3**. Again it can be observed that NO_x emissions are not very well correlated.

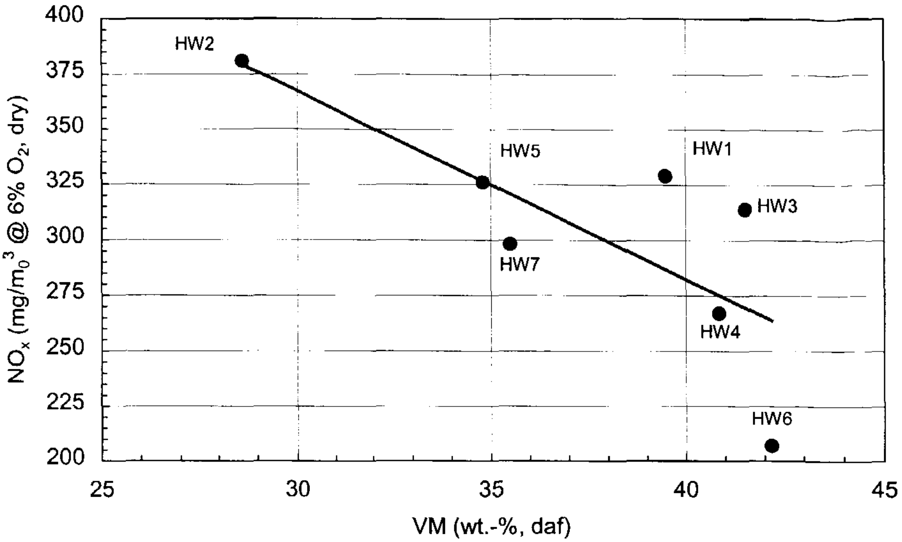


Figure 9.2 NO$_x$ emissions as function of the proximate volatile matter

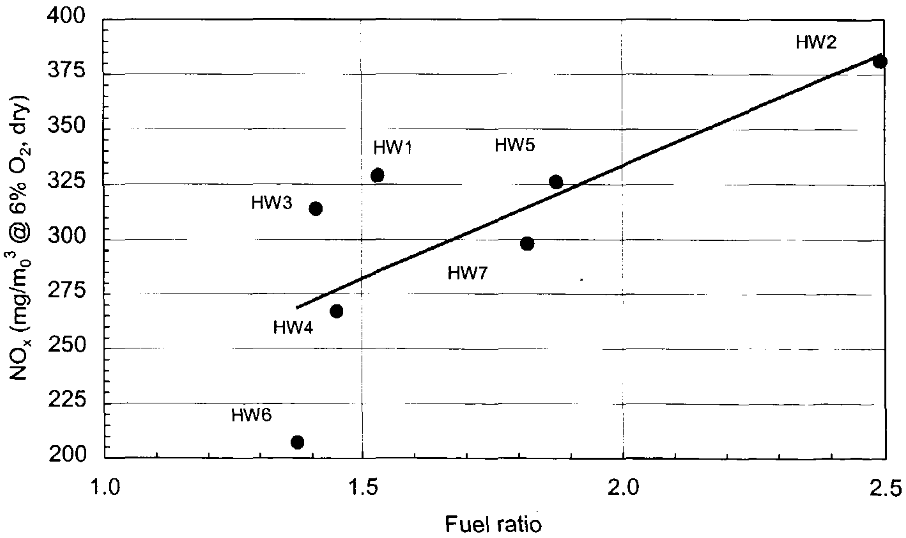


Figure 9.3 NO$_x$ emissions as function of the fuel ratio

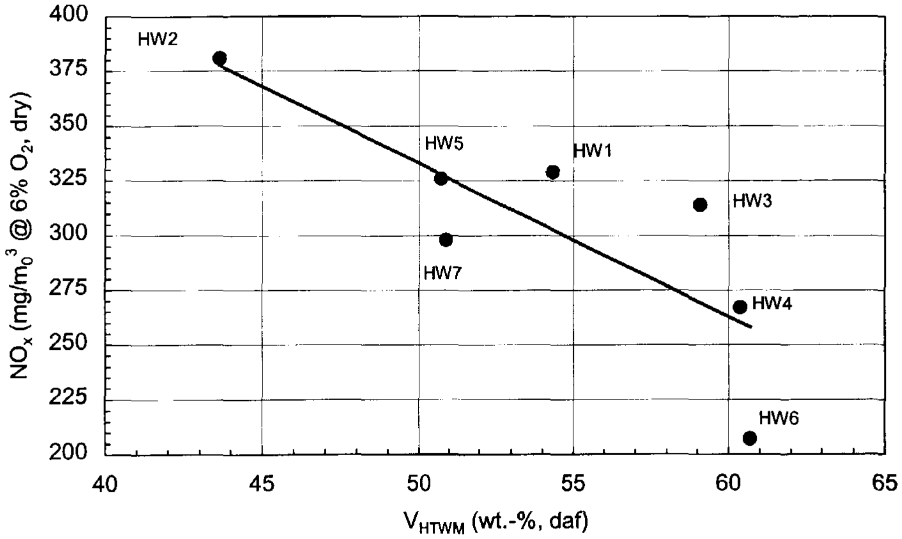


Figure 9.4 NO_x emissions as function of the volatile matter measured at 1600 °C with the HTWM reactor of IC

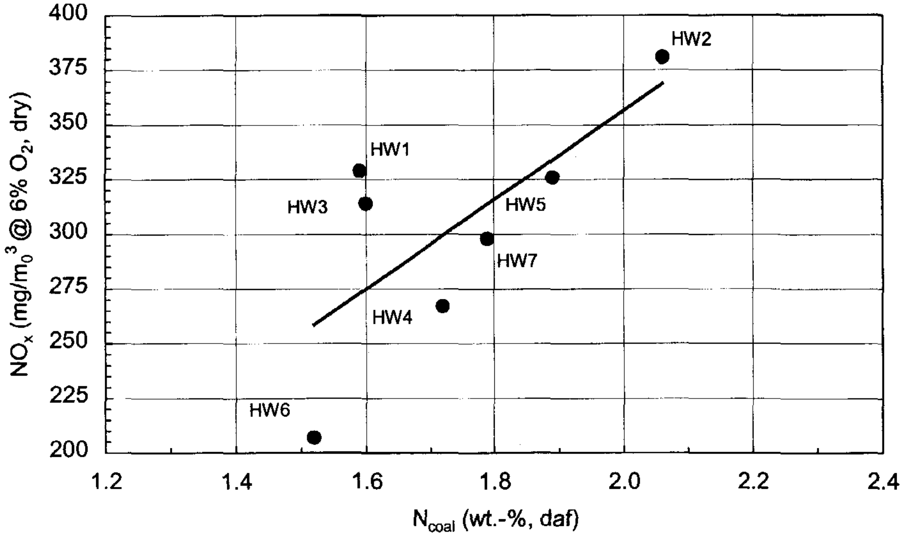


Figure 9.5 NO_x emissions as function of the nitrogen content in coal

Figure 9.4 shows the NO_x emissions as function of the volatile matter content measured with the HWG reactor of DMT. The correlation is slightly improved as is also expressed in the value of R^2 in **table 9.6a**. The small improvement is partly due to the difference in behaviour of the coals as a result of the more severe conditions during the HWG experiments. The high temperature volatile matter yield of coal HW1 from Venezuela is much less then the other higher volatile coals (HW3, HW4 and HW6). The results suggest that, although the coals are equally ranked according the proximate analysis, the Venezuelan coal is less volatile than the other coals. This anomalous behaviour is further discussed in **section 9.6 and 11.1**.

The correlation of the nitrogen content in the coal and the NO_x emissions is illustrated in **figure 9.5**. Especially the coals HW1 and HW3 show an anomalous behaviour. Although these coals do have relatively low nitrogen content compared to the other coals, the NO_x emissions are higher than the observed trend between the NO_x emissions and the nitrogen content in the other coals.

Figure 9.6 shows the correlation of the char nitrogen content and the NO_x emissions. It is observed that the correlation between coal characteristics and NO_x emissions has improved, which was already indicated with the R^2 values given in **table 9.6b**. The relatively high NO_x emissions with the coals HW1 and HW3, despite the relatively high volatile matter content is a result of the large nitrogen content in the char. The nitrogen retained in the char for these two coals is higher than for the other coals. The results indicate that the char nitrogen content affects the NO_x emissions from Hemweg unit 8 to a large extent.

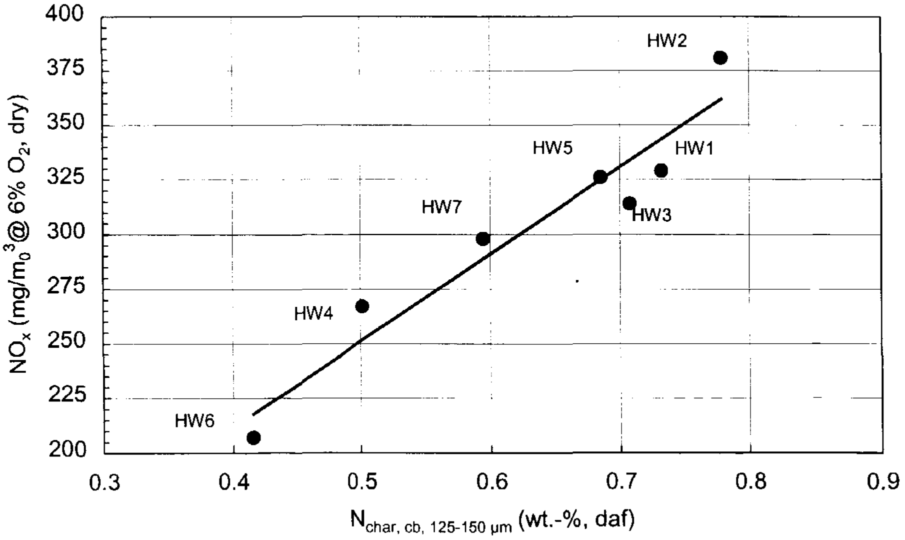


Figure 9.6 NO_x emissions as function of the nitrogen content in the char (on a coal basis)

Table 9.7 R^2 values of the correlations of selected coal parameters and the NO_x emissions at three excess air ratios

	VM 900 °C wt.-%, daf	V_{HTWM} 1600 °C wt.-%, daf	N_{coal} wt.-% daf	$N_{coal,\ 125\text{-}150\ \mu m}$ wt.-% daf	$N_{char,\ cb,\ 125\text{-}150\ \mu m}$ 1600 ° wt.-% daf
NO_x 3.0% O_2	0.55	0.64	0.48	0.73	0.91
NO_x 3.5% O_2	0.58	0.66	0.51	0.76	0.92
NO_x 4.0% O_2	0.60	0.66	0.52	0.78	0.91

9.5.2 Impact of excess air

In order to check the above findings, the NO_x emissions calculated at two other oxygen concentrations (**table 9.4**) have been correlated with the coal parameters as well. **Table 9.7** lists the coefficient of determinations from the linear regression analysis with selected coal parameters. The correlations for these excess air ratios are comparable to the ones obtained at the oxygen concentration of 3.5%. The char nitrogen content remains the best predictor. Because of the minor impact of excess air ratio this is not surprising.

9.6 DISCUSSION

The volatile yield determined with the HTWM reactor at a temperature of 1600 °C and a heating rate of 10^4 °C/s is plotted against the volatile yield determined with the TGA in **figure 9.7**. The lines of the constant yield factors of 1, 1.4 and 1.6 are also plotted in this figure. It is observed that these coals have yield factors close to 1.6, except for one coal. Generally, these yield factors are higher than those obtained with the coal blends of Amer 9 (chapter 10), which is probably partly due to the higher heating rate and temperature. Since the coals used in both experimental programs are different it is not possible to be conclusive.

The relation between the percentage of nitrogen retained in the char and the nitrogen content in the coal fraction 125 – 150 μm is illustrated in **figure 9.8**. As with the experiments with the Amer 9 coals described in chapter 8 no obvious correlation exists between the char nitrogen content and the nitrogen content in the coal. The percentage of nitrogen retained varies between 26 and 42%. This is substantially lower than the values obtained with the Amer unit 9 coals in chapter 8. In that case the percentage of nitrogen retained with the chars produced in the HWG of DMT varied between 38 and 56%. These values suggest that the higher heating rate and temperature during the HTWM experiments at IC result in an additional release of nitrogen at those conditions. However, it should be kept in mind that the coals in both experimental programs were different.

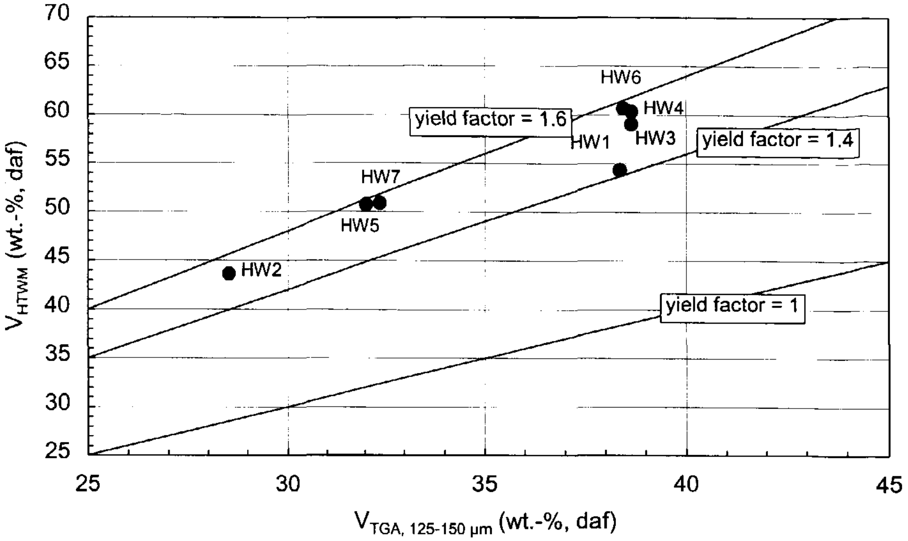


Figure 9.7 Plot of the volatile matter measured with the HTWM (1600 °C) versus the volatile matter determined with the TGA (900 °C)

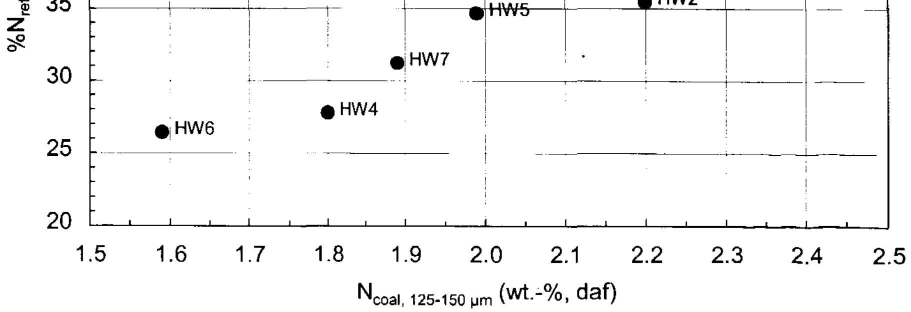


Figure 9.8 Plot of the percentage of coal nitrogen retained in the char versus the nitrogen content in the coal fraction 125 – 150 μm

The Colombian coal (HW3) and the Venezuelan coal (HW1) observe a larger nitrogen retention in the char than the other coals. The percentage of nitrogen retained in the char for the Colombian coal amounts to 39% and for the Venezuelan coal 42%, whereas the other coals range from 26 to 36%, with the highest value for the less volatile coal as expected. This anomalous behaviour of the Colombian coal as well as for the Venezuelan coal was also observed in other investigations involving Colombian coals (Man et al., 1994; Brink et al., 1990). In the DTF experiments of KEMA described in chapter 7 the Colombian coal El Cerrejon also observed a larger retention of nitrogen in the chars compared to the other coals. Although the chars have been produced with different equipment and under different test conditions, the results are consistent. The behaviour of the Venezuelan coal is comparable to the behaviour of the Colombian coal. This is understandable since both coals are mined from the same coal basin. The other Colombian coal (HW6) tested in this experimental program showed in contrast with the coals mentioned above a small retention of nitrogen in the char. This coal is from another coal basin, more to the south of Colombia. The low nitrogen retention of the char is caused to some extent by the large volatile release of this coal. However, a plot of the nitrogen retained in the char against the high temperature volatile matter shows that there is no obvious relationship between both parameters (**figure 9.9**).

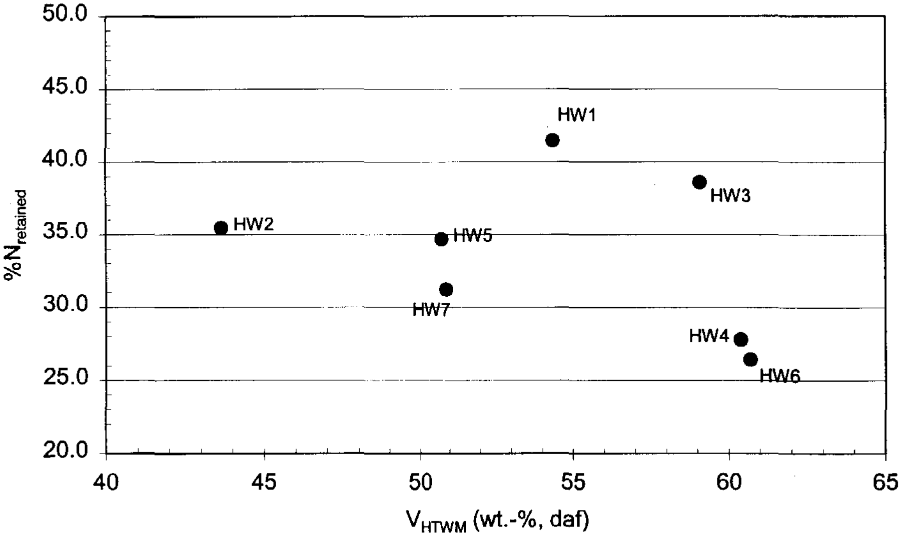


Figure 9.9 Plot of the percentage of nitrogen retained in the char versus the high temperature volatile matter

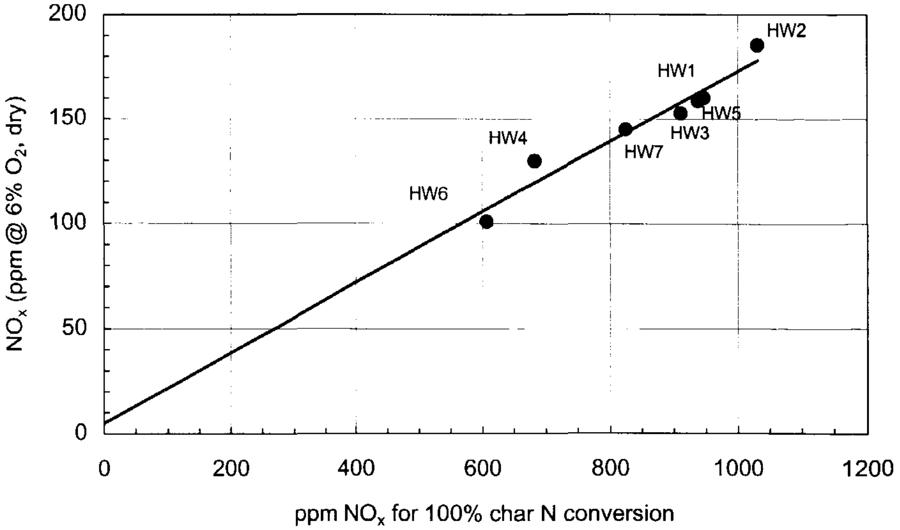


Figure 9.10 Correlation between measured NO_x emissions and 100% char nitrogen conversion

The char nitrogen conversion ratios can be calculated using the proximate and ultimate analysis and equation 3.22, with the assumption that the contribution of volatile nitrogen and thermal NO_x is negligible. The char nitrogen conversion ratios (for the 3.5% O_2 case) vary between 16.6 and 19.0%. Gibbins et al. (1998) observed a conversion ratio of char nitrogen to NO_x (for aerodynamically air staged burners) of 25% (assuming 100 ppm thermal NO_x and chars produced at a temperature of 1450 °C and a heating rate of 10^3 °C/s). Gibbins (1998) plotted the measured NO_x emissions against the NO_x that would be obtained from complete conversion of the char nitrogen (see, for instance, **figures 3.14** and **3.15**). **Figure 9.10** shows this type of plot for the Hemweg results (note that the NO_x emissions in this plot are in ppm). The intercept of the extrapolated line is almost zeroing, suggesting that there is no other source than char nitrogen that contributes to overall NO_x emissions. The char nitrogen conversion ratios show that the more nitrogen is retained in the char, the higher the NO_x emissions. This is especially true for low NO_x units since the largest contributor to the overall NO_x emissions is the nitrogen contained in the char. This emphasises the need to volatilise as much coal nitrogen as possible in the early stages of combustion. The results also show that char nitrogen conversion is more or less independent on coal characteristics, but that the partitioning of coal nitrogen into char and volatile nitrogen depends on coal characteristics. On the basis of these results it would be possible to develop a prediction formula that assesses the NO_x emissions as function of the char nitrogen content, as was done in chapter 7 for the Maasvlakte and Amer measurements. However, the number of coals used in this investigation is limited and the findings should be confirmed with additional measurements with other coals. Moreover, a prediction formula is only helpful if the char nitrogen content is measured on a regular basis.

9.7 CONCLUSIONS

The NO_x emissions from unit 8 of Hemweg power plant did not observe a straightforward relationship with the proximate volatile matter content and the nitrogen content in the coals.

The HTWM reactor of IC was used to produce chars for the determination of char nitrogen. It was observed that the NO_x emissions from Hemweg unit 8 correlated very well with the char nitrogen content. The conversion ratio of char nitrogen to NO_x was in the order of 16-19%. The percentage of nitrogen retained in the char varied between 26 and 42% and is dependent on coal quality.

This study involved seven coal(blend)s. More experiments with other coals are needed to confirm the results. Depending on the additional findings a prediction formula including the prediction intervals can be developed. Consequently, it should be decided whether the char nitrogen content will be measured on a regular basis for all coals of interest.

Chapter 10 IMPACT OF COAL BLENDING ON NO_X EMISSIONS AND BURNOUT

10.1 INTRODUCTION

This chapter deals with the results of coal blending experiments performed at three utility boilers to investigate the impact of blending on plant performance. These experiments were carried out at two tangential-fired units; unit 2 of Maasvlakte power plant and unit 9 of Amer power plant and at an opposed-wall-fired unit; unit 8 of Hemweg power plant. **Table 10.1** lists the main features of the blend trials.

It is apparent that coals from Colombia and South Africa were involved in all blend trials. However, the coals used in the experiments originate from different mines, except for the South African coal burned at Hemweg power plant where the two blending trials were performed with the same South African coal (referred to as SA2 in **table 10.1**). The experiments reported in this chapter were performed in the period from 1994 to 1998.

The quality of the coals, indicated by the fuel ratio (FR) and nitrogen content, shows that the coals involved are quite different. During the planning of the experiments it was expected that the coals would exhibit different NO_x emissions, allowing a possible interaction to be identified more easily. The experiments at Amer power plant were performed with a low-volatile blend of South African coals and a high-volatile blend of Colombian coals, instead of single coals. It was intended to perform an extended program at this plant in order to investigate also the effect of different blending strategies on plant performance. Approximately 75,000 tons of the individual coals were required for these experiments, which could only be obtained by blending sufficient amounts of comparable coals (with respect to characteristics and origin). Therefore, three South African coals were blended to obtain the low-volatile 'coal' and two Colombian coals to compose the high-volatile 'coal'. It was assumed that the interaction (if any) of the coals within those blends could be neglected. In the next sections the low- and high-volatile blend will be referred to low-and high-volatile coal, to avoid confusion with the actual blending experiments.

Many of the experiments were performed with blends consisting of equal amounts (50/50 by weight) of the composing coals. At Amer power plant also other blend ratios were tested, as is indicated in **table 10.1**. Generally, the blend trials were performed under controlled conditions, which means that the coals were tested at the same boiler settings and unit load, except for the excess air ratio. At Maasvlakte power plant, additional experiments were performed with the pulveriser arrangement (burners out of operation) and the speed of the rotating classifiers. At Amer power plant, additional experiments involved the variation of the amount of overfire air and replacement of the recirculated flue gases (SGR) with air.

Table 10.1 Full-scale blend trials

Plant	Coals	Code	Year	Coal characteristics		Blend ratio (wt/wt)	Boiler parameter variation	Blending method
				FR	N (wt.-%, daf)			
Maasvlakte unit no. 2	South African coal	SA1	1994	2.24	1.43	50/50	excess air	before grinding
	Colombian coal	Col1		1.50	1.47		BOOP	
Amer unit no. 9	South African blend	LV	1996	2.20	2.06	50/50	excess air	- before grinding
	Colombian blend	HV		1.30	1.49	40/60	overfire air	- in-furnace
						60/40	SGR	
Hemweg unit no. 8	South African coal	SA2	1998	2.49	2.06	50/50	excess air	before grinding
	Colombian coal	Col2		1.45	1.72			
	South African coal	SA2	1998	2.49	2.06	50/50	excess air	before grinding
	Colombian coal	Col3		1.82	1.79			

Generally, coals are blended on the stockyard prior to feeding the pulverisers (see chapter 4). However, instead of feeding a blend through all burners, single coals can be burned separately at various burner levels. The advantage of this last approach is that the individual pulverisers and burners can be tuned to the characteristics of the single coals, avoiding possible interactions during fuel preparation and the initial stages of combustion. A second advantage is that the residence time of the low-reactive coals in the furnace is increased when these are introduced at lower elevations. A major disadvantage is the increase of the logistics and planning activities, since several coals need to be handled and controlled separately instead of one uniform blend. At Amer power plant, a comparison was made of blending prior to feeding to the pulverisers ('normal' blending method) and the in-furnace blending method with respect to NO_x emissions and burnout.

10.2 OBJECTIVES

The overall objective of the full-scale test trials, described in this chapter, was to determine the impact of coal blending on plant performance, especially on NO_x emissions and burnout and to determine whether the impact is boiler-specific.

The tests performed at Maasvlakte power plant are considered as the baseline tests. The tests were performed in three weeks time, whereby each run lasted for a day. A multiple-point sample grid was installed downstream the FGD to secure a representative sampling of flue gases. **Table D.1** (appendix D) lists the features of the analysis devices.

The test program performed at Amer power plant contained several objectives. One objective was to demonstrate the NO_x reduction characteristics of the low NO_x combustion techniques applied for a range of coal qualities. The second objective was to determine the impact of coal blending on NO_x emissions and burnout. The third objective was to answer the question whether the blending of coals in the furnace (different coals on different burner levels) would result in an improved plant performance compared to blending coals before grinding.

The objective of the tests performed at Hemweg power plant was to determine the impact of coal blending in a low NO_x boiler equipped with low NO_x swirl burners, since both other units are tangential-fired.

The three programs are presented and discussed in a chronological order in three separate sections. At the end of this chapter a general discussion on the results is presented. A description of the power plants can be found in chapter 5.

10.3 MAASVLAKTE BLEND TRIALS

10.3.1 Experimental program

Two single coals and a blend with a blend ratio of 50/50 (wt/wt) were tested at Maasvlakte power plant. The coal characteristics are listed in **table 10.2**. The impact of excess air, burners in service and speed of the rotating classifier was investigated. The experimental program is given in **table 10.3**. An explanation of the various boiler settings is given in chapter 5.

Table 10.2 Coal characteristics (Maasvlakte blend trials)

	SA1	Col1	BLEND
Moisture (wt.-%, ar)	6.9	10.9	9.5
Ash (wt.-%, ar)	12.2	8.7	10.6
Volatile matter (wt.-%, ar)	25.0	32.2	28.5
Lower heating value (MJ/kg, ar)	25.79	25.75	25.66
Fuel ratio	2.24	1.50	1.80
N (wt.-%, daf)	1.4	1.5	1.5
Ash fusion temperatures (oxidising)			
Softening temperature (°C)	1255	1263	1269
Hemispherical temperature (°C)	1494	1388	1416
Fluid temperature (°C)	1508	1394	1422

Table 10.3 Boiler settings (Maasvlakte blend trials)

Coal ▸	SA1					BLEND					Col1				
Run ▸	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
O_2 (vol.-%)	3.4	4.2	3.1	3.5	3.2	3.5	4.0	3.1	3.6	3.7	3.6	4.0	3.1	3.6	3.4
Output (MW_e)	520	521	520	531	520	520	520	520	520	525	520	520	521	520	520
BOOP	4	4	4	4	1	4	4	4	4	1	4	4	4	4	1
NR40	0	i.c.	i.c.	i.c.	i.c.	0	i.c.	i.c.	i.c.	i.c.	i.c.	i.c.	i.c.	i.c.	i.c.
NR50	100	100	100	100	i.c.	100	100	100	100	i.c.	100	100	100	100	100
Tilt (deg.)	-3	5	1	0	-22	0	5	-6	2	10	0	8	-1	7	3
OFA tilt (deg.)	10	15	10	12	0	10	17	10	11	12	11	14	17	17	14
$\Delta p^{1)}$ (mbar)	14.6	14.7	14.3	15.0	11.8	14.1	13.9	13.5	14.7	14.7	14.6	14.6	14.6	14.5	14.4

1) Windbox-to-furnace pressure differential

Each run lasted six to eight hours. Plant performance data were recorded in the last four hours of each run. Flue gases samples for monitoring the NO, NO_x, CO and CO_2 concentrations were taken in the flue gas ducts downstream the FGD units a multiple-point sampling grid. The single coals (20,000 tons each) were delivered from EMO and stored on the stockyard of the plant. The blend (also 20,000 tons) was composed with the blending equipment of Maasvlakte power plant.

10.3.2 Maasvlakte results

10.3.2.1 General

An overview of the results of the Maasvlakte blend trials is listed in **table 10.4**. The values in this table are averaged over a period of four hours. Some of the boiler settings were adjusted throughout the program to control the steam temperatures (**table 10.3**).

The impact of excess air on NO_x emissions and burnout is illustrated in **figure 10.1** and **figure 10.2**, respectively. The NO_x emissions from the blend lie between the NO_x emissions of the single coals. The NO_x emissions from the blend appear to be somewhat lower than the average NO_x emissions from the single coals. However, due to the variation of the boiler settings it is difficult to interpret whether this is an effect of blending or an effect of boiler settings. The boiler settings for the blend during these runs (runs 1, 2 and 3) were not favourable for low NO_x emissions of the blend, since the windbox-to-furnace pressure differential was the lowest for the blend runs. A decrease of the pressure differential generally results in a decrease of the amount of overfire air and an increase of the stoichiometry in the primary combustion zone. Also the tilt of the burners and OFA ports were adjusted, as well as the position of the secondary air ports (NR40 and NR50) as a result of which the interpretation of the results is more complicated. In appendix C the error analysis is presented on the NO_x concentration measurements (**figure C.3**). Since the NO_x emissions of the single coals only differ by approximately 50 mg/m_0^3 and the measurement error in the NO_x concentration is about 5%, it is concluded that from a statistical point of view the NO_x emissions of the blend are not different from the weighted average of the NO_x emissions of the single coals.

The burnout values of the single coals and the blend are compared in **figure 10.2**. The burnout of the blend is, generally, better than the burnout of the single coals. The burnout of the Colombian coal measured at an oxygen concentration in the flue gases of approximately 3.5% is high compared to the burnout measured at the other excess air ratios. The fly ash samples were collected from a collection tank. Since this is the only run for the Colombian coal having a good burnout it is suggested that this fly ash was not representative for the bulk fly ash. It is possible that because of the residence time in the tank (approximately one hour depending on the ash load) and the typical construction of the fly ash sampling system, samples were taken of the wrong fly ash.

Table 10.4 Power plant performance data (Maasvlakte blend trials)

Coal ▸	SA1					BLEND					Col1				
Run ▸	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
O_2(vol.-%)[1]	3.4	4.2	3.1	3.5	3.2	3.5	4.0	3.1	3.6	3.7	3.6	4.0	3.1	3.6	3.4
NO_x[2]	440	468	440	462	514	421	417	401	427	425	398	407	392	396	452
CO (ppm)[3]	21	5	63	23	110	43	4	23	17	18	14	25	44	37	4
T live(°C)	541	531	534	537	538	536	533	535	530	536	533	531	544	538	538
T reheat(°C)	543	539	544	543	544	539	537	540	535	541	536	533	539	536	540
UBC(wt.-%)	6.5	4.7	6.7	6.2	5.3	7.8	6.2	7.5	7.6	8.7	6.0	10.1	11.0	12.2	7.2
Burnout(%)	99.0	99.3	98.9	99.0	99.2	99.1	99.3	99.1	99.1	99.0	99.2	98.5	98.4	98.2	99.0

1) Measured upstream the air heater (wet)

2) mg/m_0^3, dry, normalised to 6% O_2

3) dry, normalised to 6% O_2

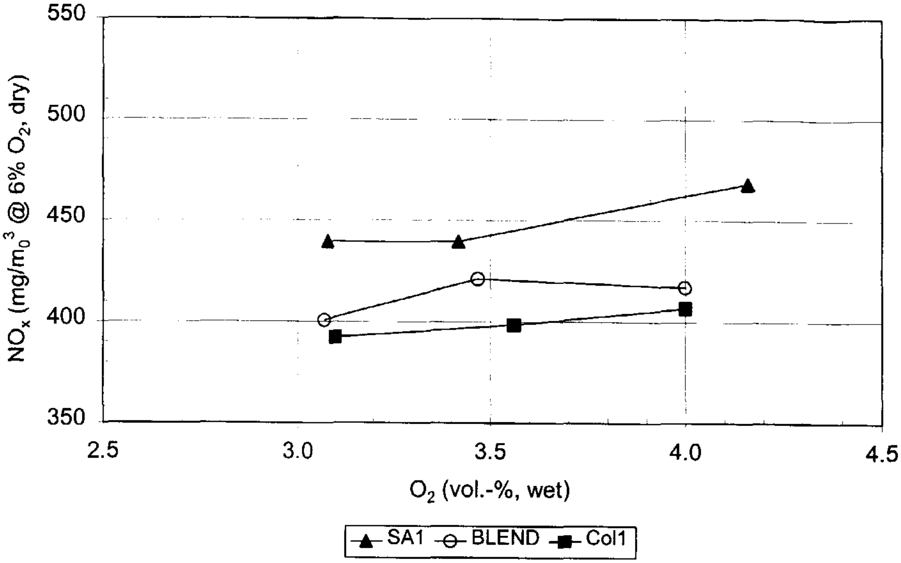


Figure 10.1 NO_x emissions of the single coals and the blend as function of the oxygen concentration in the flue gases (runs 1, 2 and 3)

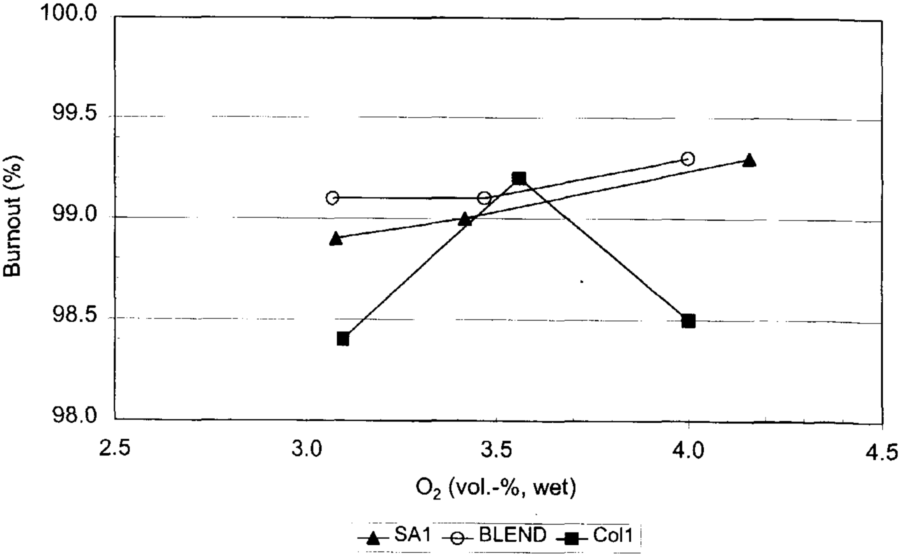


Figure 10.2 Burnout of the single coals and the blend as function of the oxygen concentration in the flue gases (runs 1, 2 and 3)

Table 10.5 Typical values of the particle size distributions

	SA1		BLEND		Col1	
Run	4	1	4	1	4	1
Speed (min^{-1})	75/80	80/85	75/80	80/85	75/80	80/85
D10 (μm)	6	6	7	7	8	8
D50 (μm)	39	39	45	45	55	52
D90 (μm)	140	132	143	141	154	148
% < 150 μm	92	93	91	92	89	91

10.3.2.2 Rotating classifiers

Pulverised coal samples were collected in four pulverised coal transport lines during the runs 1 and 4. **Table 10.5** lists the characteristic values of the particle size distributions as function of the speed of the rotating classifiers. The speed varied between 80 and 85 during run 1 and between 75 and 80 during run 4.

With a lower speed of the rotating classifier one would expect a coarser particle size distribution. The pulverised coal is somewhat coarser with the lower speed of the rotating classifier, but the effect is marginal. It is apparent that the particle size of the blend is approximately the average of the single coals.

The NO_x emissions from the blend with the lower speed of the rotating classifier is 427 mg/m$_0^3$ (**table 10.4**) which is approximately equal to the weighted average NO_x emissions of the single coals (429 mg/m$_0^3$). The burnout of the blend at the lower speed is better than is expected considering the burnout of the single coals. As mentioned before, it should be kept in mind that the boiler settings varied to some extent over the runs.

10.3.2.3 Pulverisers in operation

The impact of the pulveriser arrangement (or burner out of operation) is shown in **figures 10.3** and **10.4**. The NO_x emissions of the blend are with the upper burner level in operation (2345) low compared to the single coals. Again the boiler settings were varied for reasons of steam temperature control. The low-volatile coal was burned with a reduced windbox-to-furnace pressure differential, resulting in a higher stoichiometry in the primary burner zone and consequently in higher NO_x emissions. However, this accounts for the high NO_x emissions of the low-volatile coal, but this does not explain the result that the NO_x emissions of the blend are lower than the high-volatile coal. On basis of these experimental results it is not possible to be conclusive on the impact on NO_x emissions. The burnout of the blend is comparable to the burnout of the single coals.

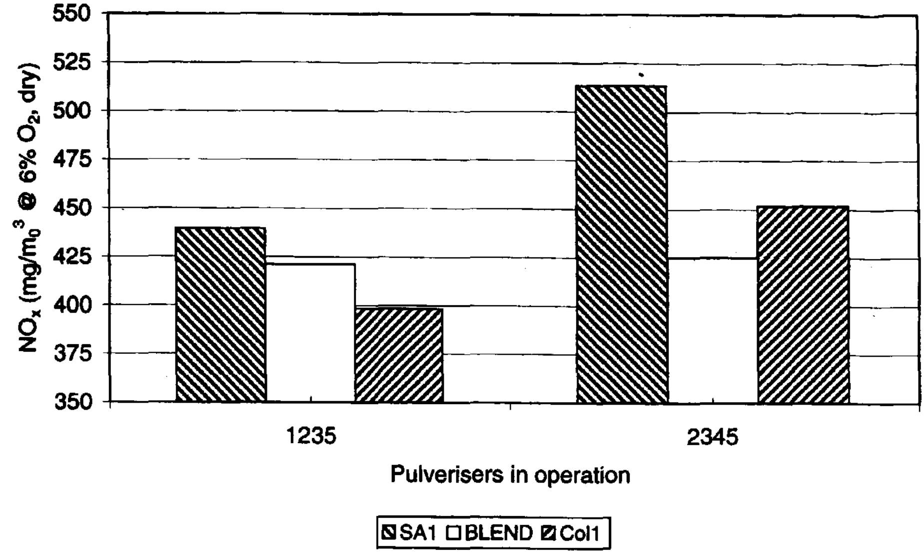


Figure 10.3 Impact of pulveriser arrangement on NO_x emissions (run 1 and 5)

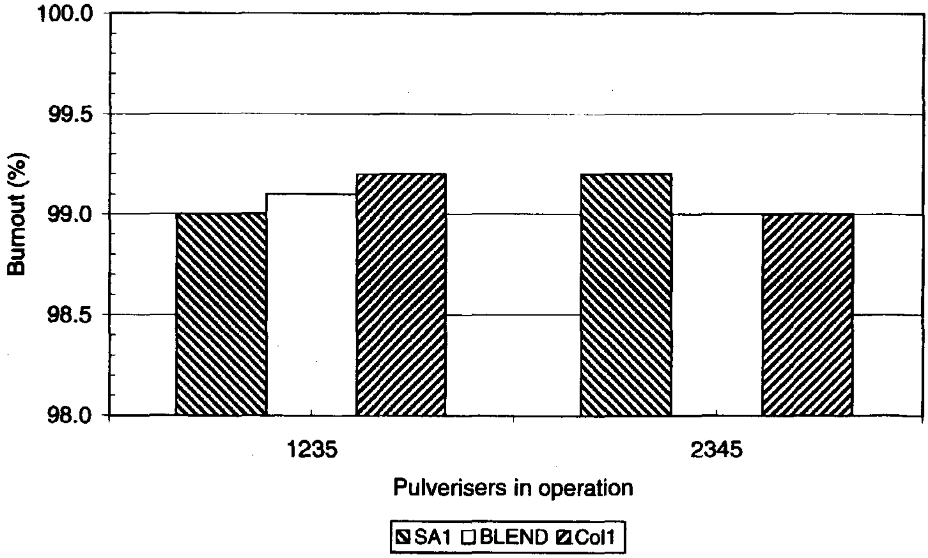


Figure 10.4 Impact of pulveriser arrangement on burnout (run 1 and 5)

10.3.3 Discussion

The blend was composed with the blending terminal at EMO and consisted of 50% of both coals by weight. Since large quantities of coal are involved and the accuracy of the weighing devices are reported to be ± 10 per cent it should be noted that the blend ratio could be 45/55 instead of 50/50. Taking this inaccuracy, together with the uncertainties due to the variation of the boiler settings and the potential error measurements into account, it could not be demonstrated that the NO_x emissions from the blend vary from the weighted average NO_x emissions of the single coals. With respect to the burnout it was shown that the burnout of the low-volatile coal during blend combustion did not deteriorate because of a preferential burning of the high-volatile coal.

10.4 AMER BLEND TRIALS

10.4.1 Experimental program

For the Amer blend trials a number of boiler settings was defined. These settings were not investigated for all coals and coal blends. The codes given to the different settings are listed in **table 10.6**. The tests performed with each series are summarised in **table 10.7**.

Table 10.6 Boiler settings Amer blend trials

Boilers settings (code)	O_2 in flue gases before air heater (vol.-%, wet) (orientation value)	Number of open OFA ports	SGR
A	4	all	on
B	3	all	on
C	5	all	on
D	4	all	on
E	4	4	on
F	4	3	on
G	4	2	on
H	4	all	on
I	4	all	off
J	3	all	off

Table 10.7 Amer blend trials

Series	Coal		Distribution	Day 1	Day 2	Day 3
1	PB	100%	all levels	A/B/C/E/F/G	H/I/J	-
2	SAB1 (LV)[1)]	100%	all levels	A/B/C	D/E/F/G	H/I/J
3	COLB1 (HV)[1)]	100%	all levels	A/B/C	D/E/G	H/I/J
4	SAB1-COLB1	50/50	see fig. 10.7	A/B/C	D/E/F/G	H/I/J
5	SAB1-COLB1	50/50	see fig. 10.7	A/B/C/E/F	-	-
6	SAB1-COLB1	40/60	see fig. 10.7	A/B/C/E/F/G	-	-
7	SAB1-COLB1	60/40	see fig. 10.7	A/B/C	D/E/F/G	-

[1)] LV and HV are the codes for the low-volatile and high-volatile coal in **figure 10.5**.

An overview of the blending configurations tested at unit 9 of Amer power plant is given in **figure 10.5**. Generally, the five lowest burner levels are used for full-load operation. However, due to problems with burner level 40, it was decided to perform these experiments with burner level 10 (upper burner level) instead of burner level 40. Seven series were performed in this program. The first series was performed with a reference coal from Poland. The second and third series were the baseline tests with the low-volatile and high-volatile coals, respectively. In run 4 a blend of the low- and high-volatile coals was burned at all burner levels in service. The blend consisted for 50% of the low-volatile coal and for 50% of the high-volatile coal (by weight). In the series 5, 6 and 7 tests were performed with different coals on the various burner levels. The method of blending in these series is different from normal operation. As is illustrated in **figure 10.5** the high-volatile coal was burned at the upper burner level(s), whereas the low-volatile coal was burned at the lower burner level(s).

The low-volatile coal consisted of three South African coals. These coals were delivered separately to the power plant and blended on site with the blending equipment of Amer power plant. Sufficient amounts of the blend were prepared for the complete test program. The high-volatile coal consisted of two Colombian coals. At EMO these coals were blended using the silos of the blending facility. For the blend trials (low- and high-volatile coals in the series 4 and 5) the high-volatile coal was blended with the low-volatile coal on the belt from the stockyard towards the coal feeding system. The low-volatile coal was reclaimed from the stockyard and the high-volatile coal was simultaneously unloaded from the boats.

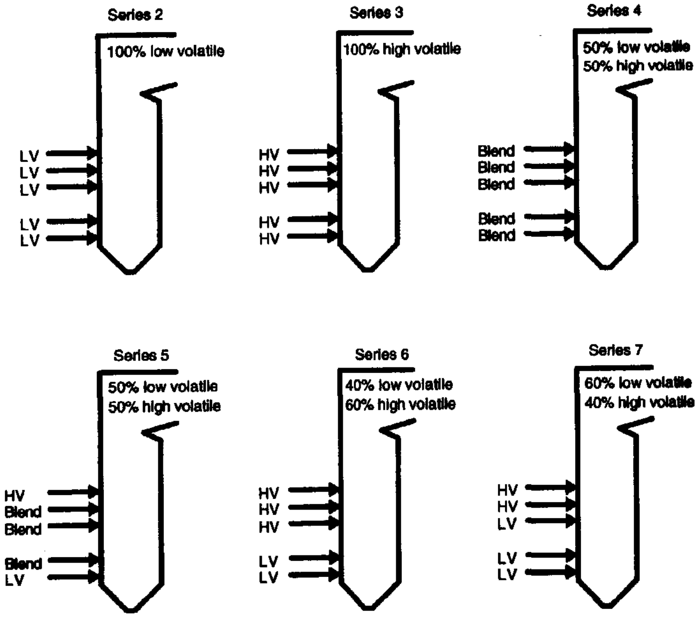


Figure 10.5 Overview of the blend tests (burner 40 out of operation)

Table 10.8 Coal characteristics (Amer blend trials)

Series Analysis	▸ ▾	1	2 (LV)	3 (HV)	4[1] BLEND	5[1]	6[1]	7[1]
Proximate analysis								
LHV	MJ/kg (ar)	24.87	24.92	25.31	24.51	24.17	24.33	24.92
Moisture	wt.-% (ar)	10.3	7.9	11.3	11.2	12.1	12.1	10.3
Ash	wt.-% (ar)	12.3	14.9	8.4	12.0	12.3	11.3	11.7
VM	wt.-% (ar)	30.0	24.1	34.9	28.2	27.7	28.5	27.2
FR		1.58	2.21	1.30	1.72	1.72	1.69	1.87
HGI	-	50	50	47	55	52	54	53
Ultimate analysis								
C	wt.-% (daf)	83.75	83.70	81.68	83.27	83.12	83.06	83.86
H	wt.-% (daf)	5.26	4.55	5.48	4.99	5.03	5.12	4.89
N	wt.-% (daf)	1.33	2.09	1.55	1.90	1.93	1.74	1.83
S	wt.-% (daf)	0.92	0.76	0.57	0.83	0.88	0.77	0.60
O	wt.-% (daf)	8.75	8.92	10.72	10.00	10.04	10.32	8.82
Ash fusion temperatures								
ST (ox)	°C	1252	1272	1387	1255	1257	1264	1338
HT (ox)	°C	1298	1287	1425	1290	1286	1305	1369
FT (ox)	°C	1334	1300	1478	1343	1345	1360	1401

[1] Calculated values based on the individual analysis of both coals and the blend ratios (see appendix D)

10.4.2 Amer results

The main results are listed in **table D.3** in appendix D. During the experiments samples were taken of the pulverised coal. The particle size distributions are given in **table D.4** in appendix D.

10.4.2.1 Excess air

Figure 10.6 shows the NO_x emissions as a function of the oxygen concentration in the flue gases (measured upstream the air heater) for the two coals and the blend of the high- and low-volatile coal. An increase of the combustion air results in a higher primary combustion zone stoichiometry without adjusting the amount of overfire air. As a consequence, NO_x emissions increase rapidly. The NO_x emissions of the blend (50% LV/50%HV) tend to be a little bit higher than the average NO_x emissions. But as is illustrated in the error analysis in appendix C the NO_x emissions of the blend are from a statistical point of view not different from the weighted average.

Figure 10.7 illustrates the impact of excess air on the burnout of the low- and high-volatile coals and the blend. It is observed that no clear trend exists between the oxygen concentration in the flue gases and the burnout. One would expect an improvement of the burnout at higher oxygen concentrations. This is only the case for the high-volatile coal. The burnout of the low-volatile coal is influenced by the poor milling behaviour of this coal. The speed of the rotating classifiers had to be reduced, especially for pulveriser 30, since the pulveriser started to rumble. The particle size distribution listed in appendix D, shows that the pulverised coal of this pulveriser is much coarser compared to the other pulverisers.

The burnout of the blend is slightly better than the weighted average burnout. The particle size distribution shows that the blend is somewhat coarser than the high-volatile coal, but is much finer than the low-volatile coal. This may explain the good burnout behaviour of the blend.

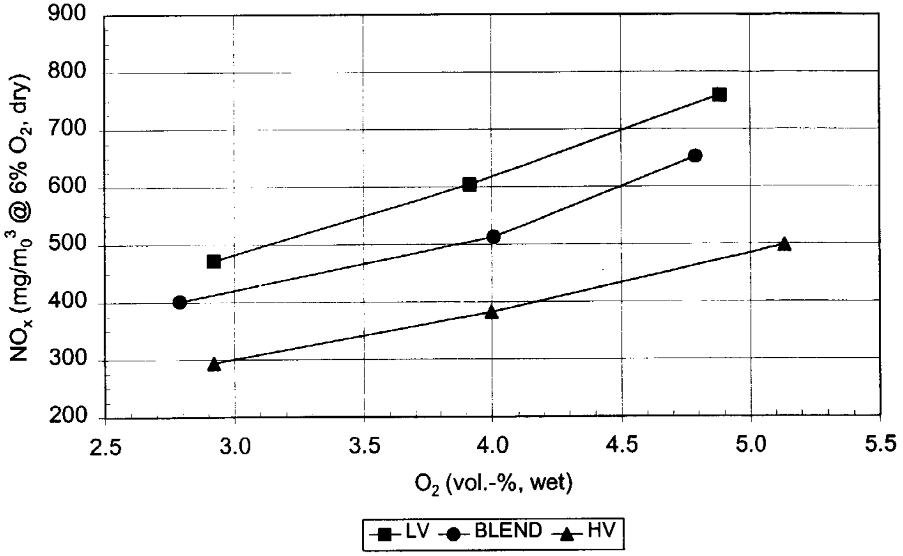


Figure 10.6 Influence of excess air ratio on the NO_x emissions of the low- and high-volatile coals and the blend (run A, B and C)

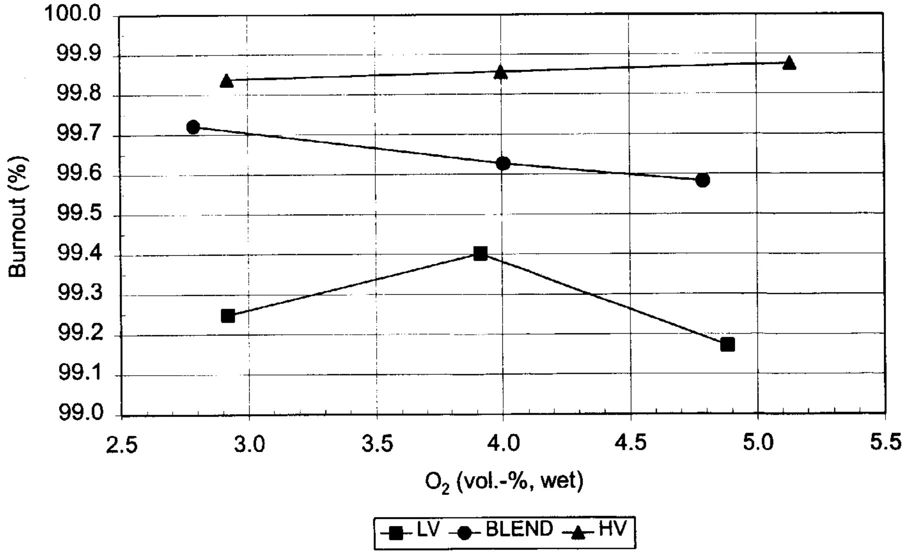


Figure 10.7 Influence of excess air ratio on the burnout of the low- and high-volatile coals and the blend (run A, B and C)

10.4.2.2 Overfire air

Air staging is one of the most frequently applied techniques to reduce NO_x emissions. This principle is very effective and almost all newly built power plants are equipped with OFA ports. In **figure 10.8** the impact of the overfire air on the burnout is shown. All experiments were carried out with oxygen concentrations in the flue gases of about 4% (wet).

Figure 10.9 shows, except for the high-volatile coal, a decrease of the burnout with an increase of the number of open overfire air ports. The burnout of the high-volatile coal is unaffected. This is probably caused by the already fairly high burnout (99.9%) with six overfire air ports opened. The high burnout under almost all circumstances is due to the good performance of the pulverisers and the large residence time in the furnace. With respect to the impact of blending it is observed that NO_x emissions are slightly higher than the average value. The burnout of the blend is slightly better.

10.4.2.3 Influence of separate gas recirculation

In order to test the effectiveness of flue gas recirculation by the separate gas recirculation (SGR) technique of MHI on NO_x reduction, tests have been performed with replacing the recirculated flue gases with secondary combustion air. **Figure 10.12** shows the impact of SGR on NO_x emissions. The experiments without SGR were performed at two excess air ratios. As is shown in **figure 10.12**, NO_x emissions are nearly the same with or without SGR. Also, the burnout is not affected by the replacement of the recirculated flue gases with air (**figure 10.13**). As a result the same conclusions as in the previous sections can be drawn on the impact of coal blending.

The efficiency, however, did improve by the replacement of SGR with air as a result of:

- lower temperature of the flue gases leaving the air heater (reduction of flue gas losses)
- reduction of attemperation water flow in the reheater (Δ = 7 kg/sec)
- lower auxiliary power of SGR fans (Δ = 50 kW_e).

The total unit efficiency increase was in the order of 0.3% (absolute).

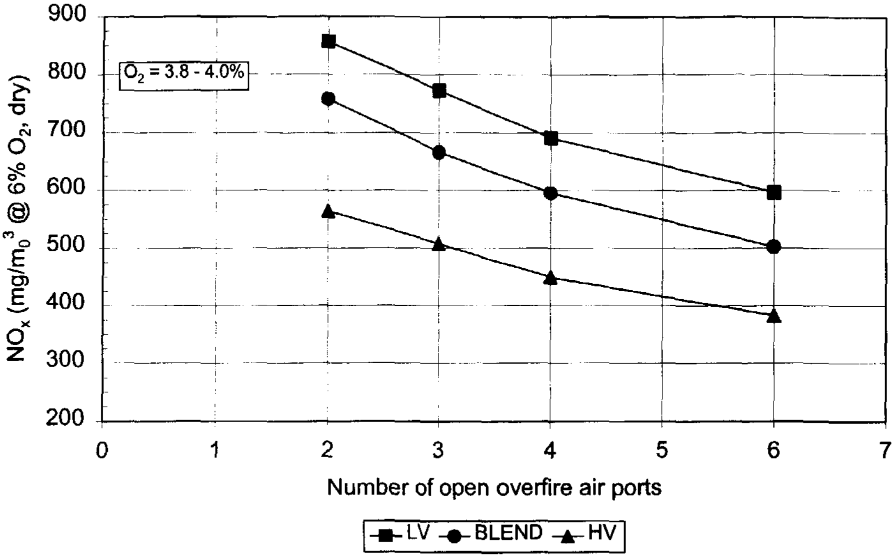


Figure 10.8 Impact of overfire air on NO$_x$ emissions (run D, E, F and G)

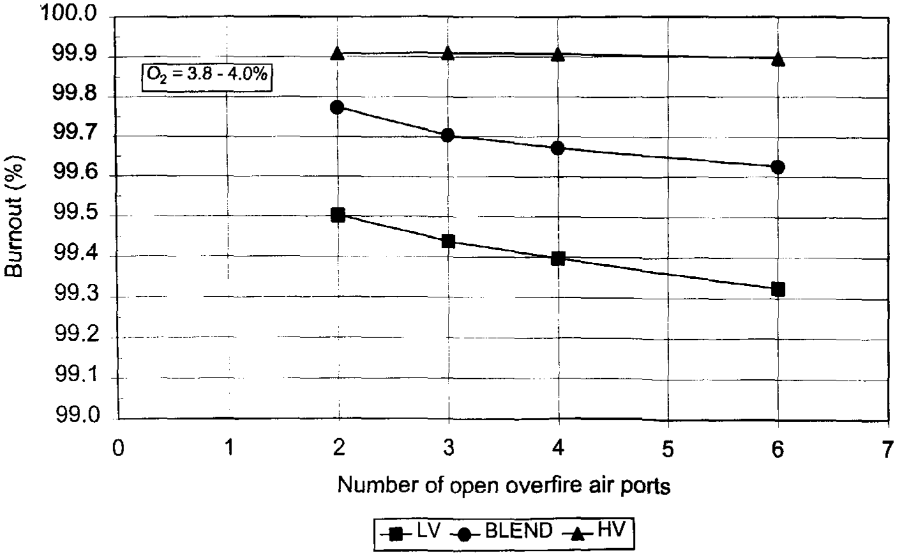


Figure 10.9 Impact of overfire air on burnout (run D, E, F and G)

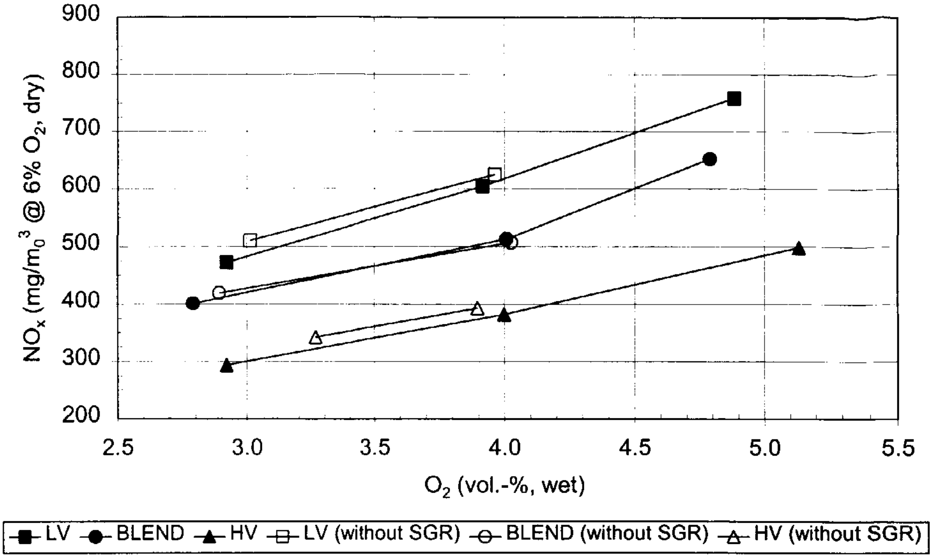


Figure 10.10 Impact of SGR on NO_x emissions (run A, B, C, H, I and J)

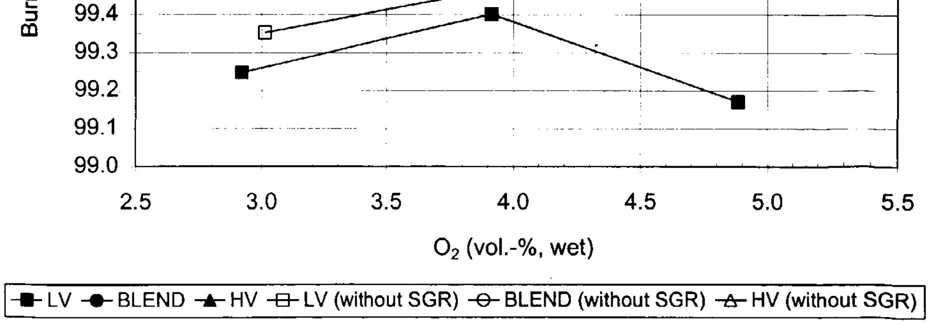


Figure 10.11 Impact of SGR on burnout (run A, B, C, H, I and J)

10.4.2.4 Coal blending method

The impact of the method of blending was investigated with variations in two operating parameters: excess air ratio and the amount of overfire air.

Figure 10.12 shows the NO_x emissions as a function of the excess air ratio. The NO_x emissions from the blend trials are between the NO_x emissions of the single coals. The results of series 4 (BLEND) were already presented in the previous sections. With respect to the other blend trials (high-volatile coal on the upper burner level(s)) it can be seen that the NO_x emissions are lower than the NO_x emissions from series 4 (BLEND). All lines show an increase with increasing excess air ratios and the angle of inclination is more or less the same for all trials, except for the lowest excess air ratios of series 6 (indicated with the dashed line). This anomalous behaviour was caused by an undesired change of coal type during the experiment with series 6. The tests with this series were carried out (six runs) in one single day. The upper three burner levels should have received the high-volatile coal and the lower two burner levels the low-volatile coal. This was done by separately feeding the two coals to the respective coal bunkers. During the first series it appeared already that the milling behaviour of both coals was quite different. The moisture content in the high-volatile coal was high compared to the low-volatile coal, which resulted in higher primary air temperatures entering the pulverisers. Furthermore, the low-volatile coal was more difficult to grind whereby the speed of the rotating classifiers had to be reduced.

Table 10.9 lists the temperatures of the primary air entering the pulverisers for the various tests performed with series 6. The first measurement was performed with run A followed by the runs E, F and G. The last runs were the runs B and C. The 'normal' primary air temperatures were for the low- and high-volatile coals approximately 235 and 310 °C, respectively. **Table 10.9** shows that the temperatures in the first run (A, oxygen concentration of 4%) are as expected. The same accounts for run E, which was the second run that day. But with run F it is observed that the temperature of the primary air entering pulveriser 30 was reduced. Low-volatile coal instead of high-volatile coal was delivered to this pulveriser. At the same time unstable pulveriser behaviour was observed (the speed of the rotating classifiers had to be reduced, because of rumbling). During run G it was observed that the other pulverisers also showed a similar behaviour.

Table 10.9 Temperature (°C) of the primary air entering the pulveriser for series 6

Pulveriser	Coal	Run	A	E	F	G	B	C
	Sequence of execution		1	2	3	4	5	6
10	HV		311	311	313	249	250	317
20	HV		310	300	311	270	240	317
30	HV		311	311	244	302	247	293
50	LV		236	239	233	235	232	226
60	LV		244	249	245	243	238	236

The next run (B, oxygen concentration of 3.2%) also indicated that all pulverisers were fed with low-volatile coal instead of high-volatile coal. Finally, with run C the primary air temperatures of the upper burner levels increased again. It is apparent that during the run with the lowest excess air ratio the NO_x emissions in series 6 almost reached the values of the low-volatile coal. Assuming that runs A and C of series 6 were performed correctly, it is observed that the NO_x emissions from this series approach the NO_x emissions of the high-volatile coal. The NO_x emissions from series 5 are somewhat higher and finally with series 7 it can be seen that NO_x emissions increase and equal almost the NO_x emissions of the 'regular' blend (series 4).

Comparable results were obtained with the overfire air experiments (**figure 10.13**). Again a more pronounced increase in NO_x emissions is observed with series 6 which is caused by the unwanted change in coal quality (indicated by the dashed lines). All series 5, 6 (the correct runs) and 7 show NO_x emissions lower than the NO_x emissions of the blend (series 4), even in the case with 60% low-volatile coal. Again it is observed that for series 6 the NO_x emissions almost reach the NO_x emissions of the low-volatile coal with only two open OFA ports.

The effect of blending on burnout for the excess air experiments is shown in **figure 10.14**. The burnout was in all blend tests slightly better than the average values based on the burnout of the single coals. The sequence from low to high burnout is as expected. An increasing amount of low-volatile coals in the blend results in a lower burnout, although the differences are small. It is apparent that the burnout of series 6 for the lowest excess air ratio is also high, despite the change in coal quality during this series. **Figure 10.15** shows the burnout values of the tests with the overfire air. The low burnout of series 6 with two overfire air ports opened is caused by the increase of low-volatile coal.

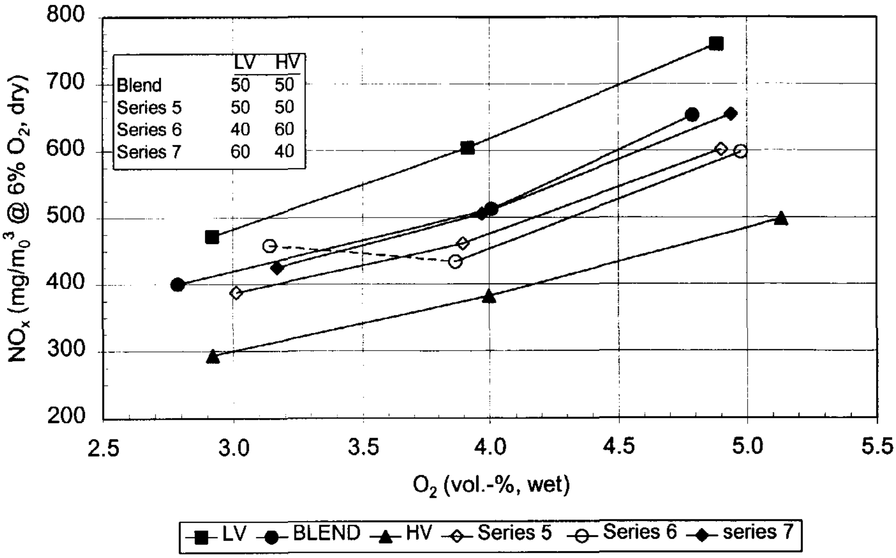


Figure 10.12 Impact of coal blending method on the NO_x emissions (run A, B and C) (note that the scale on the y-axis is different from the previous figures)

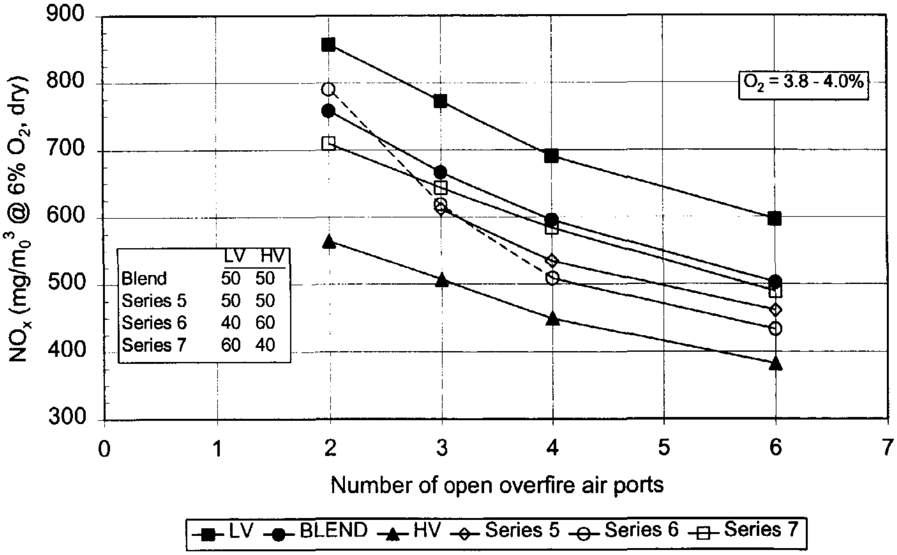


Figure 10.13 NO_x emissions as function of the overfire air (run A, D, E, F and G) (note that the scale on the y-axis is different from the previous figures)

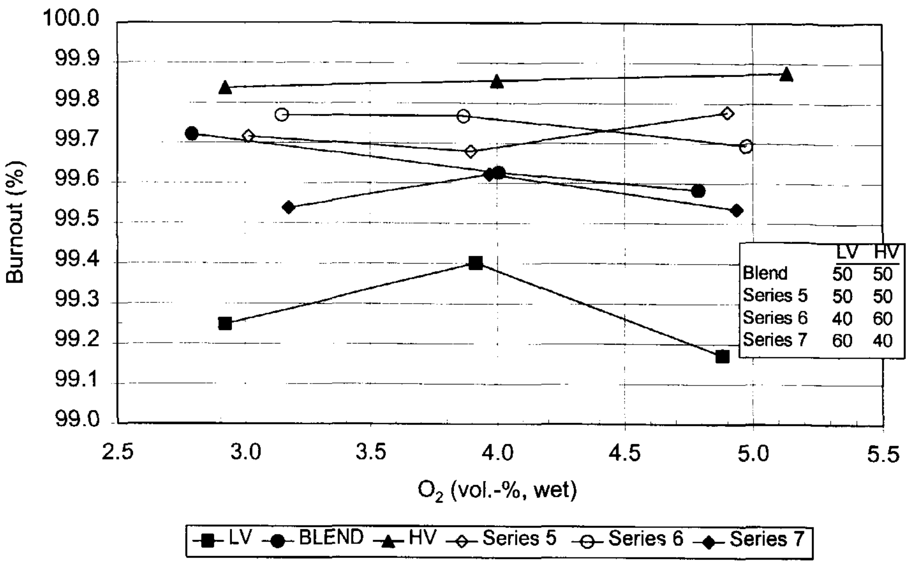


Figure 10.14 Impact of coal blending method on burnout (run A, B and C)

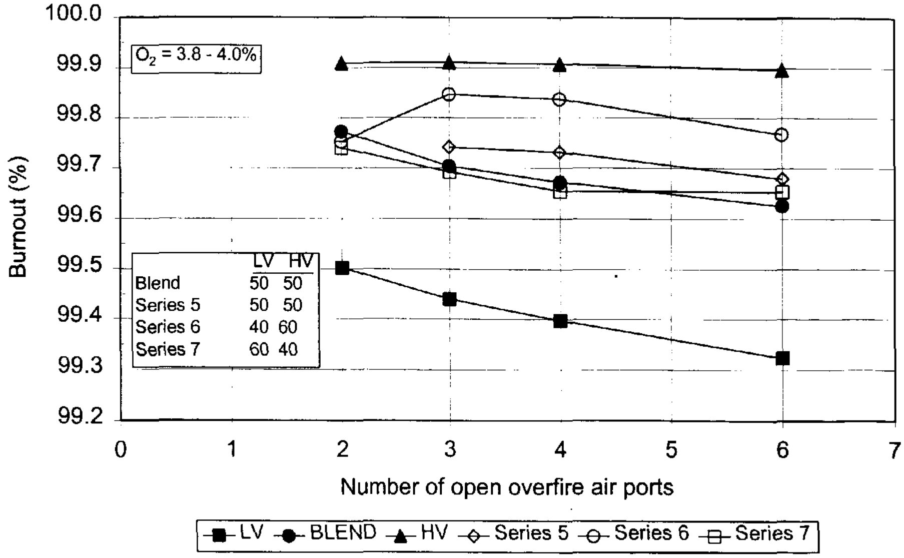


Figure 10.15 Impact of blending on burnout for the overfire air experiments (run A, D, E, F, G)

10.4.3 Discussion

10.4.3.1 Boiler settings

The experiments with replacement of the recirculated flue gases with air showed that NO_x emissions and burnout were not affected, but unit efficiency increased with approximately 0.3% (absolute).

The amount of overfire air has a major impact on the NO_x emissions. A decrease of overfire air results in an increase of the stoichiometry in the burner zone. The burnout is only marginally affected by the amount of overfire air. The low-volatile coal showed an increase of the burnout with a decrease of overfire air ratios. The marginal effect of the overfire air on burnout is a result of the large furnace volume (and hence a large residence time) and the fine particle size (e.g. compare to, for instance, the particle size of Maasvlakte).

10.4.3.2 Coal blending

To explain the impact of coal blending on NO_x emissions and burnout a number of aspects should be considered.

With respect to the accuracy of blending the following can be said. The high-volatile coal was delivered from the blending terminal at EMO (Maasvlakte). This coal was in fact a blend of two Colombian coals. In the course of the tests it could have been possible that the composition of this blend varied to some extent as a result of inaccuracies of the blending equipment (see also section 10.3.3). A complicating factor was that in the period between the tests of the high-volatile coal (series 3) and the blend trials heavy rain fall occurred whereby the moisture content in the high-volatile coal increased (see coal analysis in **table D.2** in appendix D). The low-volatile coal consisted of three low-volatile South African coals. These were blended using the blending facility on the site of Amer power plant. The characteristics of the low-volatile coal varied over time, as can be seen from **table D.2** in appendix D. Variations may be partly due to inaccuracies of the analysis, but also to differences of the blend ratio over time. The blending of the low- and high-volatile coals was performed provisionally. The low-volatile coal was reclaimed from the stockyard whereas the high-volatile coal was simultaneously recovered from the ships and supplied to the high-volatile coal onto the conveyor belt. Although this operation was carefully performed, a large inaccuracy may have occurred, since no accurate weighing devices could be used.

With respect to the experiments with the separated feeding of the low- and high-volatile coals on the different burner levels it can be stated that the coal flow was constant for all stock feeders. Due to the increasing moisture content the lower heating value of the high-volatile blend decreased. As a result the effective blend ratio based on the coal input on a dry basis and a dry ash-free basis changed with time. Virtually this means that more low-volatile coal was used in the blending experiments compared to the high-volatile coal. **Table 10.10** illustrates the differences in blend ratio of the raw coal and the blend ratios based on a dry and a dry ash-free basis.

Table 10.10 Comparison of the blend ratio of raw coal and the blend ratio on a dry and a dry ash-free basis

Blend ratio (LV/HV)	Series 4	Series 5	Series 6	Series 7
raw coal	50/50	50/50	40/60	60/40
dry basis	51.9/48.1	51.9/48.1	42.3/57.7	62.1/37.9
dry ash-free basis	49.7/50.3	50.4/49.6	41.0/59.0	61.4/38.6

To compare the burnout behaviour of the blend with the single coals the dry ash-free blend ratio should be used. For the comparison of the NO_x emissions of the single coals and the blends the differences in the feed rates of both coals and the differences in specific flue gas volumes should also be taken into account. One way of doing this is to calculate the amount of dry flue gases per kg. raw coal for both components in the blend. Based on the coal analysis given in **table D.2** in appendix D the specific flue gas volumes were calculated. Based on the blend ratios, the specific flue gas volumes and the NO_x emissions of the single coals, the expected NO_x emissions from the blend tests were calculated and compared to the measured values. The results of the calculations for all runs are given in **table D.5** in appendix D.

The measured NO_x emissions from series 4 (blend on all burner levels) are for most runs higher than the calculated NO_x emissions. The differences are small (ranging from -1.4% to +7.9% with the calculated NO_x emissions as reference values). Due to the uncertainty of the precise blend ratio, which may be rather large for this experiment because of the simultaneous feeding of coals from the stockyard and from the ship, it can not be concluded that blending low- and high-volatile coals leads to higher NO_x emissions. In addition, as is pointed out in appendix C the error introduced by the measurement of the flue gas species is in the order of 8%. Also from that point of view it is concluded that there is no proof that NO_x emissions of a blend are different from the weighted average.

With respect to the in-furnace blending experiments (series 5, 6 and 7) it is observed from **table D.5** in appendix D that the measured NO_x emissions are generally lower than the calculated NO_x emissions. The problem with the precise blend ratio may only be applicable for series 5 for the pulverisers 20, 30 and 50, since the other pulverisers were fed with the single coals. One would expect lower NO_x emissions than calculated since the contribution of the upper burner level to the overall NO_x emissions is large compared to the other burner levels (see also chapter 7). A high-volatile coal might have lost more of its fuel nitrogen in the small section between the upper burner and the OFA ports compared to low-volatile coals. The increased residence times of the low-volatile coal under reducing conditions with the in-furnace blending experiments compared to the normal blending method might also have a NO_x reducing effect. However, the difference between the measured and calculated NO_x emissions is too small with respect to the measurement inaccuracy to be conclusive.

With respect to the burnout the following compensating effects might occur. A (supposed) rapid oxygen consumption of the high-volatile coal might reduce the availability of oxygen for the low-volatile coal. A positive effect on burnout might occur since the low-volatile coal heats up faster as a result of the early combustion of the high-volatile coal. In these experiments the particle size of the blended coal was in general smaller than was expected from the particle size distribution of the single coals. It is possible that during grinding a positive interaction (the load of the difficult-to-grind coal reduced with a factor two during the experiments) has occurred which resulted in a finer particle size of the blend. With respect to the in-furnace blending experiments it can be concluded that the burnout was positively affected by the larger overall residence time of the low-volatile coal. This is best shown with series 7 where 60% of low-volatile coal and 40% of high-volatile coal was used (in practice somewhat different see **table 10.11**). The low-volatile coal was also burned at pulveriser 30 resulting in a coarse particle size (see **table D.3** in appendix D) as was the case with the combustion of the low-volatile coal (series 2). Nevertheless the burnout of the blend is slightly better than the average burnout. The increased burnout is in the order of 0.1%.

10.5 HEMWEG BLEND TRIALS

10.5.1 Experimental program

The blending experiments performed at Hemweg power station included three coals; a low-volatile South African coal and two Colombian coals. Two blends were burned both on a 50/50 basis (wt/wt). The South African coal was blended with the Colombian coal Col2 and with the Colombian coal Col3. **Table 10.11** lists the proximate and ultimate analyses of the single coals and the blends.

The tests performed at unit 8 at Hemweg power plant were performed with three excess air ratios. The excess air in this boiler is adjusted by controlling the amount of overfire air (also referred to as after air). The stoichiometry on the burners was maintained at 0.80. The unit load and all other boiler settings were constant for all measurements. The blends were composed with the blending facility on the site of Hemweg power plant.

Table 10.11 Coal characteristics (Hemweg blend trials)

	SA2	Col2	BLEND1	Col3	BLEND2
Proximate analysis (ar)					
Moisture (wt.-%)	7.0	13.8	10.6	12.2	10.7
Ash (wt.-%)	14.0	6.1	10.4	3.7	9.7
Volatile matter (wt.-%)	22.6	32.7	27.5	35.5	28.3
Lower heating value (MJ/kg)	25.69	25.30	25.29	25.96	25.05
Fuel ratio	2.49	1.45	1.87	1.37	1.81
Ultimate analysis (daf)					
C (wt.-%)	85.72	82.15	82.93	78.91	80.92
H (wt.-%)	4.56	5.17	4.76	4.96	4.92
N (wt.-%)	2.19	1.72	1.89	1.52	1.70
S (wt.-%)	0.63	0.84	0.72	0.42	0.65
O (wt.-%)	6.90	10.12	9.72	14.19	11.81

Table 10.12 Results of the blend trials at Hemweg power plant

		SA2			Col2			BLEND1			Col3			BLEND2		
O_2 1)		2.8	3.5	3.9	2.5	3.2	4.1	2.7	3.1	4.1	2.5	3.1	4.2	2.8	3.4	4.1
NO_x 2)		354	386	429	259	262	282	311	320	354	197	205	218	292	302	308
UBC	%	6.4	4.8	3.4	10.1	10.2	7.2	7.3	7.6	4.6	2.4	2.0	2.1	6.0	5.2	4.6
Bu	%	98.8	99.1	99.4	99.2	99.2	99.4	99.0	98.9	99.4	99.9	99.9	99.9	99.2	99.3	99.4

1) Oxygen concentration in the flue gases measured upstream the air heater in vol.-% (wet)

2) mg/m_0^3 @ 6% O_2, dry, measured downstream the FGD

Table 10.13 Particle size distribution of the coals and blends burned at Hemweg power plant

		SA2	Col2	BLEND1	Col3	BLEND2
D10	µm	7	7	6	8	7
D50	µm	31	33	28	37	32
D90	µm	120	129	128	135	133
< 150 µm	wt.-%	92.2	91.8	91.8	91.1	90.8

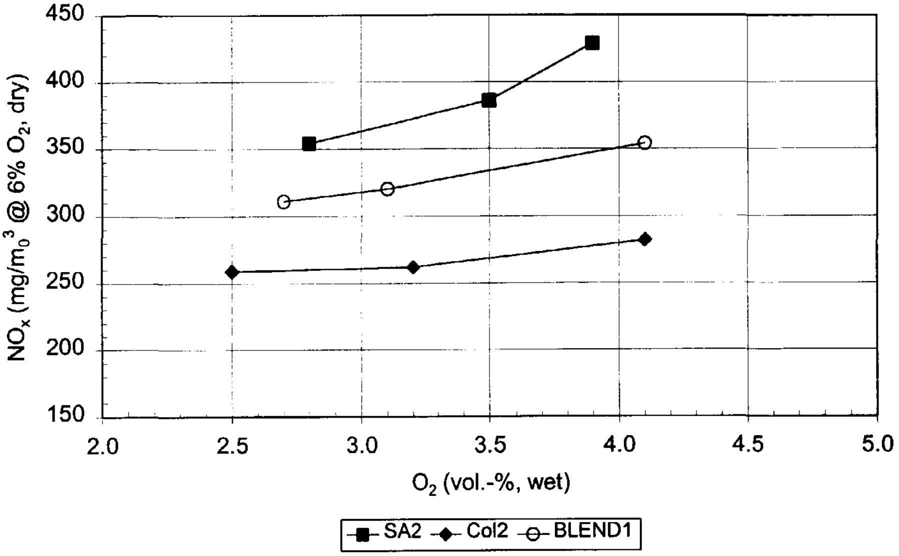


Figure 10.16 NO_x emissions of BLEND1 and the single coals (Hemweg power plant)

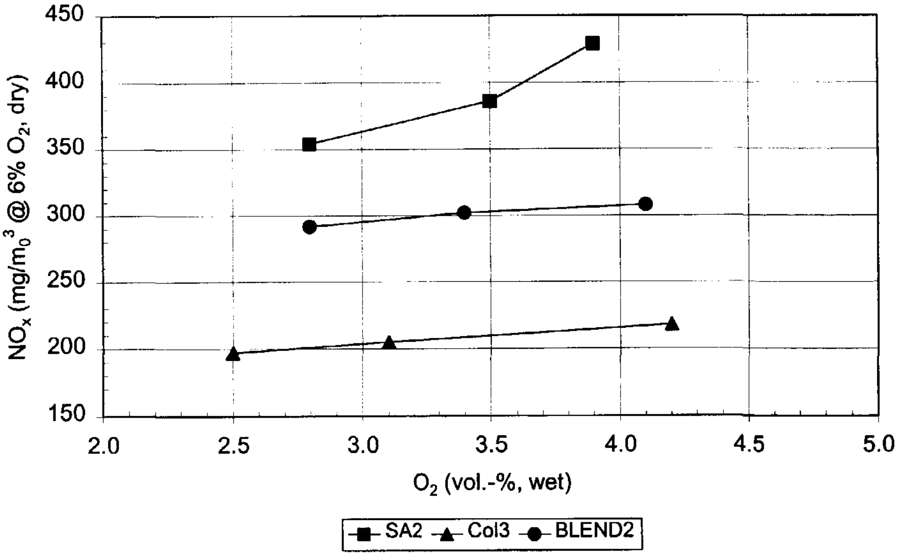


Figure 10.17 NO_x emissions of BLEND2 and the single coals (Hemweg power plant)

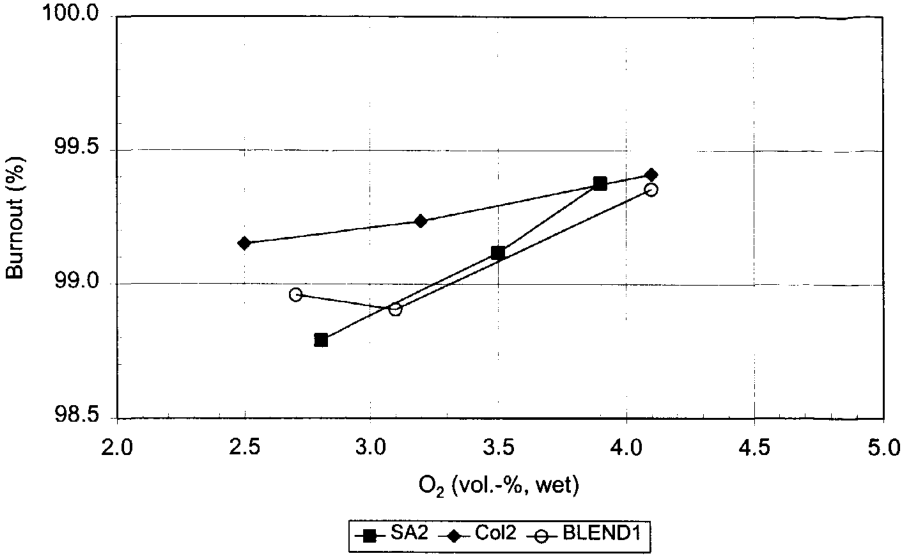


Figure 10.18 Burnout of BLEND1 and the single coals (Hemweg power plant)

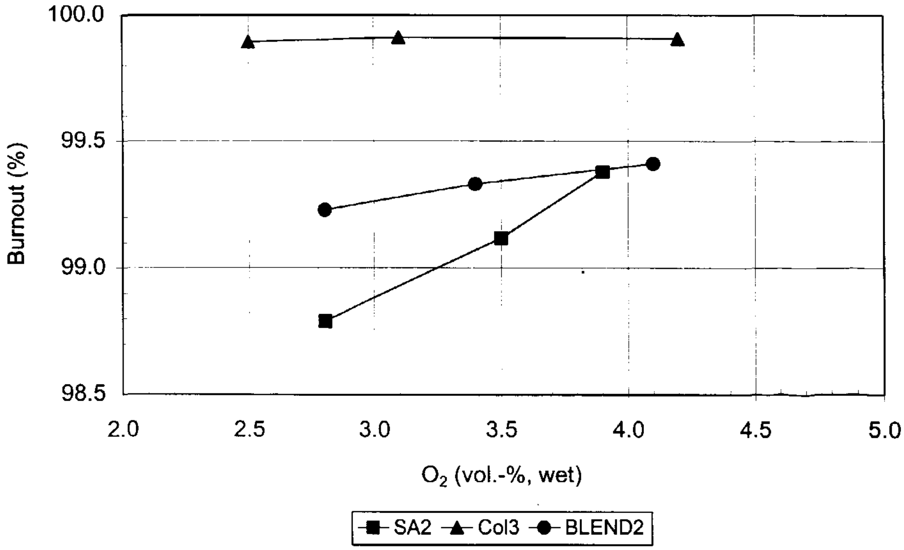


Figure 10.19 Burnout of Blend2 and the single coals (Hemweg power plant)

10.5.2 Results and discussion of the Hemweg blend experiments

The results of all trials are listed in **table 10.12**. Each run lasted about two to three hours. The values given in the table are values averaged over the last 30 – 45 minutes. The fly ash samples for the determination of the burnout were collected on eight positions in the flue gas ducts upstream the ESP. The particle size distribution of the pulverised coal is given in **table 10.13**. The values are averages of three pulverised coal samples collected from three different pulverised coal transport lines.

Figures 10.16 and **10.17** show the NO_x emissions of the single coals and the blends for three oxygen concentrations in the flue gases. The NO_x emissions from the blends are in both cases almost similar to the weighted averaged NO_x emissions of the single coals. Taking the inaccuracy into account of the concentration measurements, as is done in appendix C than the conclusion is that there is no statistical proof to suggest that the NO_x emissions from the blend are different from the weighted average.

The burnout of the blends is compared with the burnout of the single coals in the **figures 10.18** and **10.19**. The figures suggest that the burnout of the blends is somewhat lower than the average burnout of the single coals. The particle size distributions of the single coals and the blends (given in **table 10.13**) show no large differences. The coarsest coal (Col3) is also the coal with the best burnout of 99.9%.

10.6 DISCUSSION

The impact of coal blending on NO_x emissions and burnout has been investigated in three utility boilers with coals from South Africa and Colombia. A major advantage of full-scale experiments is that there is no need to extrapolate the experimental data to practical situations. A disadvantage is that controlling the combustion conditions as well as controlling the desired blend ratios is much more difficult in full-scale experiments than in a laboratory environment. Furthermore, it is almost impossible to perform in-flame measurements for a better understanding of the reactions and interactions prevailing in the combustion processes. For the interpretation of the results, the in- and output parameters have to be considered.

All boilers used in this study are equipped with overfire air and the primary combustion zone is normally operated with a stoichiometric ratio of about 0.8. The stoichiometric ratio has been calculated to evaluate the influence of excess air ratios of the impact of coal blending. The overall excess air ratio (λ_{tot}) has been calculated on basis of the oxygen concentration in the flue gases using equation 10.1.

$$\lambda_{tot} = \frac{21-(1-a)\cdot[O_2]}{21-[O_2]} \qquad (10.1)$$

with: a varying from 0.97 to 0.99 for bituminous coals

$[O_2]$ oxygen concentration in dry flue gas (vol.-%)

Table 10.14 Stoichiometric ratios in the primary combustion zone and the burnout zone

	Case 1 O_2 = 3% (wet)		Case 2 O_2 = 4% (wet)		Case 3: O_2 = 4% (wet) OFA = 10% (Amer)	
	λ_{prim}	λ_{tot}	λ_{prim}	λ_{tot}	λ_{prim}	λ_{tot}
Maasvlakte	0.77	1.18	0.84	1.25		
Amer	0.83	1.18	0.90	1.25	1.06	1.25
Hemweg	0.80	1.18	0.80	1.25		

The overfire air ratio of Maasvlakte and Amer is under normal conditions 35 and 30%, respectively (Meerkerk, 1998). Normal conditions mean a nominal windbox-to-furnace pressure differential, all OFA ports opened and oxygen concentrations in the flue gases of 3%. The stoichiometric ratio of the primary combustion zone of Hemweg power plant was, also with the variation of the excess air, maintained at 0.80.

The stoichiometric ratios for three cases have been considered:

- oxygen concentration is 3% (wet)
- oxygen concentration is 4% (wet)
- oxygen concentration is 4% (wet) and two of the six OFA ports are opened.

The last one is only applicable for Amer unit 9. The results are presented in **table 10.14**. It should be noted here that these stoichiometric ratios are calculated as overall values. Locally in the near burner zone the stoichiometric ratios differ, with high excess air ratios at the boundary of the flame and low excess air ratios in the inner part of the flame.

Taking the inaccuracies, imposed by the scale of the experimental equipment, into account it was already concluded that within the experimental envelope (coal characteristics and boilers considered), NO_x emissions from blends are virtually the weighted average of the NO_x emissions of the single coals. From **table 10.14** it can be deduced that additivity of NO_x emissions is valid for reducing conditions in the primary combustion zone as well as for oxidising conditions in the combustion zone. Under low NO_x conditions the main contributor to the overall NO_x emissions is the nitrogen in the char. Major deviations of the additivity rule for NO_x emissions are therefore only possible when coal blending influences the char nitrogen content. The amount of char nitrogen is besides the coal characteristics influenced by the heating rate and the final temperature. During these experiments the heating rate and the temperature during combustion are probably comparable to the single coal tests. The differences in coal quality are too small to create a major change in process conditions.

From the experiments at Amer unit 9 it can be concluded that also under oxidising conditions NO_x emissions from blends are the weighted average of the NO_x emissions of the single coals (at least for tangential-fired boilers). The NO_x emissions increased with opening the OFA ports, which means that besides the char nitrogen contribution also the contribution of volatile nitrogen to overall NO_x

emissions becomes important. Since the additivity rule is also valid for these experiments it can be concluded that interaction during NO_x formation and reduction in the primary combustion zone is either not occurring or is of minor importance. A major implication of above conclusions is that relating the characteristics of coal blends with NO_x emissions (as is described in chapter 7) is allowed.

With respect to the effect of the combustion of different coals on different burner levels (Amer power plant) it was shown that this may result in reduced NO_x emissions if high-volatile coals are introduced at the highest burner levels and the low-volatile coals on the lowest burner levels. The reduction, however, is small and is, because of the inaccuracies in blend ratio and the concentration measurements, from a statistical point of view not significant.

The results suggested that the burnout of coal blends is not aggravated because of a preferential burning of the high-volatile coal. Maybe in case more widely divergent coals are used burnout is aggravated. Special attention is required for the impact of grinding on blend combustion. It is possible that the particle size of a blend is larger than the particle sizes of the single coals. However, for the coals used in this study this effect was not observed.

10.7 CONCLUSIONS

Coal blending experiments have been performed at three full-scale pulverised coal-fired utility boilers. In all experiments low-volatile coals from South Africa and high-volatile coals from Colombia were involved, which are typical coals for the Dutch coal-fired power plants.

The NO_x emissions of coal blends burned in full-scale utility boilers are comparable to the weighted average of the NO_x emissions of the single coals. This applies for tangential-fired as well as opposed wall-fired units and within the range of coal characteristics used in this study. This finding supports the approach used in correlating coal characteristics of blends with NO_x emissions presented in the previous chapters.

The burnout of the blend may be better than the weighted average burnout of the single coals (found in the experiments performed at the tangential-fired units) as well as somewhat less than the weighted average. In no single case the burnout was strongly aggravated by a preferential burning of the high-volatile coal. The general validity of this result is to some extent questionable, since interactions during grinding may affect the particle size distribution of the pulverised coal to such an extent that segregation of the coals over the various size fractions may occur.

The experiments with burning different coals on different burner levels have shown that a trend exists of lower NO_x emissions and higher burnout values if high-volatile coals are inserted into the furnace at higher elevations and the low-volatile coals at lower elevations. The differences, however, are small and because of the inaccuracies involved in full-scale trials, it is concluded that more experiments are needed to be conclusive.

Chapter 11 DISCUSSION AND EXTRAPOLATION OF RESULTS

11.1 COAL CHARACTERISTICS AND NO_x EMISSIONS

11.1.1 Impact of volatile matter

A major advantage of NO_x prediction formulas based on coal characteristics measured with the proximate and ultimate analyses is that these are often included in basic coal contracts. As a result a decision can be made before procurement whether that particular coal can be burned in the power plant of interest. The study presented in this thesis showed that the NO_x emissions from the tangential-fired Amer unit 9 and Maasvlakte unit 2 are predicted within acceptable tolerances with the proximate volatile matter. It was observed that a linear relationship exists between the NO_x emissions and the proximate volatile matter. A higher volatile coal results in lower NO_x emissions, which is a well-known tendency for units equipped with primary low NO_x measures (Simon et al., 1995; Schlessing et al., 1997; Hesselman et al., 1997). The overview presented in chapter 3 also showed that low NO_x emissions in boilers equipped with low NO_x measures are obtained with coals with a high volatile matter content or a low fuel ratio.

The NO_x emissions from the opposed-wall-fired unit Hemweg unit 8 did not observe a straightforward relationship with the proximate volatile matter, unlike with the Maasvlakte and Amer units. Although lower NO_x emissions were achieved with high-volatile coals compared to low-volatile coals, two coals observed an anomalous behaviour. The explanation for this result is given below.

11.1.2 Nitrogen content

The total nitrogen content in coal proved to be of minor importance and from a statistical point of view had no impact on the NO_x emissions. However, as was suggested in the first part of this thesis, the nitrogen partitioning into char and volatile nitrogen affects the NO_x emissions. The majority of the NO_x emissions from low NO_x boilers originates from the nitrogen in the char, since the substoichiometric conditions in the main primary combustion zone lead to a conversion of the nitrogen released with the volatiles to N_2. This also explains the impact of volatile matter on NO_x emissions. In general, the more volatiles are released in the primary combustion zone, the more nitrogen is released together with the volatiles. The result that volatile matter is a better predictor than the nitrogen content of coal indicates that the extent of partitioning of nitrogen into volatile and char nitrogen is more dependent on the volatile release than on total nitrogen content.

11.1.3 High temperature volatile matter and char nitrogen

The statement mentioned above already indicates that the proximate volatile matter is an indirect coal characteristic to predict NO_x emissions. Besides the fact that the nitrogen in coal in the form of char nitrogen plays a major role, also the conditions used for the determination of the proximate volatile matter are quite different from the conditions prevailing in actual coal flames.

In order to determine whether the NO_x emissions are better described by the high temperature volatile matter or the char nitrogen content, this study focussed on the determination of these parameters. Research by others had already shown that more volatiles are released at higher temperatures and higher heating rates compared to the conditions with the proximate analysis. In addition, it was observed that the extent of enhanced volatile release at those conditions was coal dependent (Jamaluddin et al., 1986; Knill et al., 1990; Thompson et al., 1993; Gibbins et al., 1994). With respect to char nitrogen it was shown that heating rate and temperature were major parameters affecting the release of volatile nitrogen. Thomas (1997) concluded therefore that it is important to select suitable test conditions for the determination of the nitrogen content in char in order to predict NO_x emissions obtained in low NO_x combustion. The underlying reason is that prediction of the nitrogen content in char on basis of the proximate and ultimate analyses is not possible (Morgan et al., 1989; Man et al., 1997).

In this study the high temperature volatile matter was measured of different coals using a variety of experimental techniques and conditions. The nitrogen content in the resulting char was analysed to determine the partitioning of nitrogen into volatile and char nitrogen. The experiments showed that both the volatile and nitrogen release depended on the experimental conditions. **Table 11.1** compares the yield factors (ratio of high temperature volatile matter to the proximate volatile matter) determined with a drop tube furnace (DTF) and two heated wire grid reactors (HWG). It should be noted that different coal(blend)s were used in the various experiments. However, since the coal ranks are comparable it is assumed that the differences in the average values indicate the effect of the experimental conditions and techniques.

The largest yield factors were obtained with the HWG reactor of Imperial College (IC), which was operated at a temperature of 1600 °C and a heating rate of 10^4 °C/s. The milder conditions in the other equipment resulted in a volatile release that was somewhat smaller. The impact of the experimental conditions appears to be even greater on the nitrogen retention in the char ($\%N_{retained}$). The chars produced in the HWG reactor of IC contained relatively less nitrogen than the chars produced in the other equipment.

The NO_x emissions from two full-scale installations Amer unit 9 and Hemweg unit 8 were correlated with the high temperature volatile matter and char nitrogen. The NO_x emissions from Amer unit 9 correlated to some extent with char nitrogen determined with the heated wire grid reactor of DMT, but the proximate volatile matter, although an indirect parameter, obtained the best result. However, correlation of char nitrogen with the NO_x emissions from Hemweg unit 8 showed that char nitrogen was a much better predictor than the volatile matter content.

Table 11.1 Comparison of the yield factors and the percentage of nitrogen retained in the char

	temp.	heat rate	unit	yield factor		$\%N_{retained}$	
	°C	°C/s		range	avg.	range	avg.
DTF	1200	10^4	$1MW_{th}$	1.18 – 1.50	1.36	45.8 – 69.3	53.7
DTF	1200	10^4	Amer 9	1.20 – 1.44	1.32	63.9 – 75.6	70.1
HWG (DMT)	1500	10^3	Amer 9	1.28 – 1.43	1.35	38.5 – 56.3	45.5
HWG (IC)	1600	10^4	Hemweg 8	1.42 – 1.58	1.54	27.8 – 41.4	33.7

The result that NO_x emissions from Amer unit 9 are better predicted with the proximate volatile matter, on contrary to Hemweg unit 8, is partly due to the fact that the conditions in the devolatilisation experiments with the Amer coals were not severe enough to obtain the char nitrogen content relevant for the practical situation. The other aspect that needs to be considered is the residence time in the primary combustion zone, since a (nearly) complete conversion of volatile nitrogen into N_2 is only possible under reducing conditions. As is shown in more detail in the following sections, the residence time in the primary combustion zone of Amer unit deviates from that of Hemweg unit 8.

Table 11.2 summarises the results of the correlation of coal characteristics with NO_x emissions, including the major boiler settings. Some remarks should be made on the computation of the primary and overall stoichiometric ratios. The combustion air of the Maasvlakte and Amer units is supplied through a windbox. This means that the partitioning of the combustion air into secondary (auxiliary) and overfire air is controlled by the air valves. On basis of the valve characteristics and the actual valve settings the air distribution can be calculated. Under nominal conditions (OFA fully opened, nominal windbox-to-furnace pressure differential and an overall stoichiometric ratio of 1.18) it was calculated that in the Maasvlakte unit 35% of the total combustion air (including the primary air) is introduced into the furnace as overfire air. For the Amer unit this is 30% (Meerkerk, 1998). These ratios were used in the computation of the stoichiometric ratio in the main (or primary) combustion zone and the residence time in the various combustion zones.

The stoichiometric ratio in the primary combustion of the Maasvlakte unit is lower than the stoichiometric ratio in both other units. Nevertheless, the NO_x emissions from the Maasvlakte unit are higher than the NO_x emissions from both other units. This is due to the operating conditions and the residence time in the various combustion zones, since the characteristics of the coals used in the various studies are essentially the same.

Table 11.2 Comparison of the full-scale test trials, including the coal parameter that observed the best correlation with NO_x emissions

	$\lambda_{prim}/\lambda_{tot}$	Burner mode	Fuel ratio	NO_x range (mg/m$_0^3$ @ 6% O_2)	Coal parameter
Maasvlakte	0.77/1.18	Centre burner level out of operation	1.53 - 2.30	335 - 534	VM
Amer 9	0.83/1.18	Upper burner out of operation	1.29 - 2.00	222 - 371	VM
Amer 9	0.83/1.18	Burner 40 out of operation	1.30 - 2.22	352 - 472	VM
Hemweg	0.80/1.18	All burners in operation	1.37 - 2.49	201 - 351	N_{char}

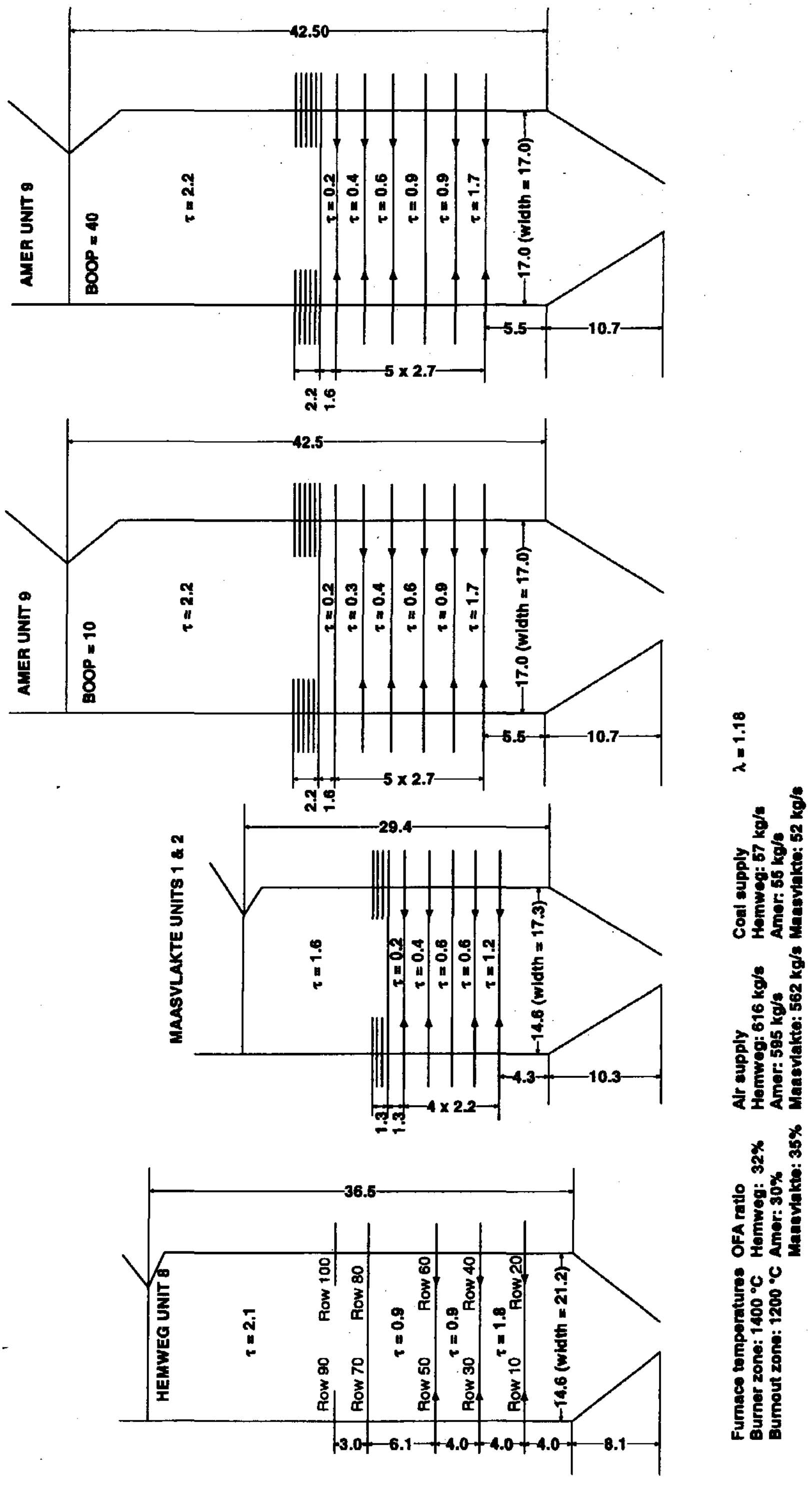


Figure 11.1 Residence times in the full-scale boilers

11.2 RESIDENCE TIME AND BURNER CONFIGURATION

In studies performed by Maier (1998) and Greul (1998) it was concluded that both the stoichiometry and the residence time in the primary combustion zone are dominant factors in the reduction of NO_x emissions with air staging. Greul (1998) observed that the lowest NO_x emissions of about 250 mg/m_0^3 were obtained with temperatures in the laboratory reactor of about 1300 °C, a stoichiometry in the primary combustion zone of 0.75 and a residence time of 4 seconds in the primary combustion zone.

To explain the differences in NO_x emissions from the power plants and the coal parameters that obtained the best correlation it is useful to compare the boiler geometry and the residence times in the different zones (plug flow resident times). **Figure 11.1** illustrates the residence times in various zones in the furnace. The residence times have been calculated on basis of the average amounts of coal used in the individual experimental programmes. The data used for the calculations are given in the figure. It is assumed that the average temperatures in the primary combustion and the burnout zone are 1400 and 1200 °C, respectively. These are based on temperatures measured in a tangential-fired unit equipped with low NO_x burners and OFA ports (Tree et al., 1997). The volume of the various zones in the burner area is based on the distance between the centrelines of the burners (for Amer 9 the distance between the fuel-rich burners has been chosen). The volume of the area between the upper burner level and the OFA ports is based on the distance between the centreline of the upper burner level and the centreline of the lowest OFA port.

Figure 11.1 clearly indicates that the residence time in the substoichiometric burner zone of coal particles entering the furnace at the lowest burner level is large compared to the coal particles injected into the furnace through the upper burner level. For instance, for Maasvlakte power plant the residence time in the primary combustion zone of the coal particles entering at the lowest burner level is approximately 3.0 seconds, whereas the coal particles injected into the furnace through the upper burner level only have a residence time of 0.2 seconds in the primary combustion zone.

For Amer power plant two cases have been computed. The first case is with the upper burner level out of operation, whereas the second case is with burner level 40 out of operation, corresponding to the full-scale tests described in chapter 7. In the first case the coal particles inserted at the highest burner level in operation (i.e. one below the most upper burner level) still have a residence time of 0.5 seconds in the substoichiometric primary combustion zone. This is only 0.2 seconds for the coal particles introduced into the furnace through the most upper burner level.

The coal particles entering the furnace of Hemweg unit 8 at the lowest level have a residence time of approximately 3.5 seconds, whereas the coal particles injected into the furnace through the upper burner level have a residence time of about 0.9 seconds. Especially, the residence time of those particles is substantially longer than the coal particles introduced into the furnace of the Maasvlakte and Amer units through the upper burner level.

Since the combustion of volatile matter is fast, the impact of volatile nitrogen will become more pronounced when the overfire air ports are situated close above the upper burners (the so-called close coupled overfire air) as is the case for Maasvlakte and Amer power plant. Especially, with the upper burner level in operation the residence time of the coal particles entering through these burners is short. Although the average residence time for the Maasvlakte and Amer power plant is about 1.4 and 1.7 seconds, respectively, the residence time in the substoichiometric primary combustion zone of the coal particles entering into the furnace through the upper burner level is only 0.2 seconds. The effect of the reduced residence time was clearly observed with the experiments performed at Amer unit 9. These experiments showed that operation with burner level 10 (upper burner level) in operation instead of burner level 40 increased the NO_x emissions with approximately 75-110 mg/m_0^3, whereas the average residence time in the primary combustion zone remains nearly constant. The contribution to overall NO_x emissions of the upper burner level is therefore much larger than the contribution of the lower burner levels. A simplified computation of the contribution of the upper burner level to NO_x emissions can be made if is assumed that the contribution of the burner levels, apart from the upper burner level, are identical. **Figure 11.2** illustrates the effect on NO_x emissions of operation with the upper burner in operation for a coal with a volatile matter content of 30% (wt.-%, db). With the lower burners in operation (BOOP = 10) NO_x emissions are approximately 300 mg/m_0^3. Assuming that all burner levels contribute equally to the overall NO_x emissions, all burner levels produce a NO_x emission of 300 mg/m_0^3. If the same coal is burned with burner level 40 out of operation (BOOP = 40) the NO_x emissions are about 400 mg/m_0^3. Assuming that the lower burner levels still contribute 300 mg/m_0^3 then the contribution of the upper burner level is approximately 800 mg/m_0^3. This is not unlikely regarding the short residence time and it suggests that much higher char nitrogen conversion ratios should be used for the coal particles entering the furnace through the upper burner level or that volatile nitrogen contributes to the overall NO_x emissions.

The residence time in the primary combustion zone of the coal particles in the Hemweg unit is at least 0.9 seconds which is sufficient for the majority of the volatiles to be burned. The nitrogen released with the volatiles is due to the high residence time under reducing conditions probably almost completely converted to N_2. Consequently, the nitrogen in the char is responsible for the majority of the NO_x produced.

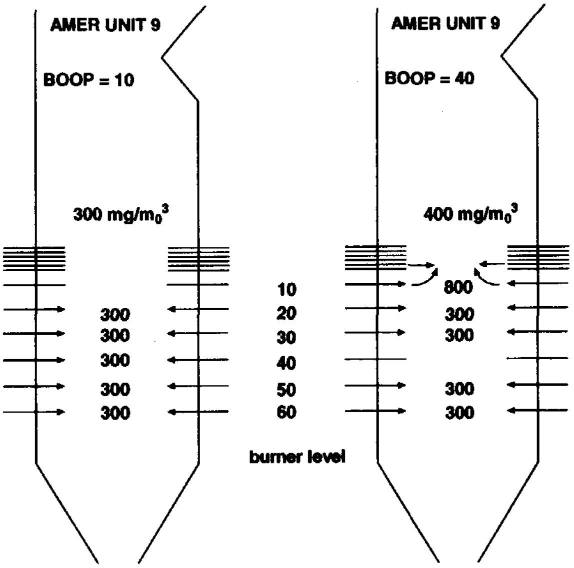


Figure 11.2 Impact of burner out of operation on NO_x emissions from Amer unit 9

11.3 IMPACT OF EXCESS AIR

The impact of excess air on NO_x emissions is boiler dependent. The NO_x emissions of Hemweg unit 8 only marginally increased with an increase of the excess air. During normal operation the stoichiometry of the primary combustion zone remains constant with a variation of the excess air ratios. An increase of excess air results therefore in an increase of the amount of overfire air. The impact of this increase is, however, much smaller than an increase of the stoichiometry of the primary combustion zone. Earlier experiments at this plant with variation of the stoichiometry of the primary combustion zone showed a strong and non-linear increase of NO_x emissions with an increase of the primary zone stoichiometry (see **figure 5.12**). This non-linear effect of primary zone stoichiometry on NO_x emissions is consistent with observations at Amer unit 9 (**figure 7.11**) and confirmed by others with experiments in a laboratory-scale furnace (Greul, 1998).

An increase of the excess air in the Maasvlakte and Amer units during normal operation results in an increase of the primary zone stoichiometry. If the windbox-to-furnace pressure differential and the number of opened OFA ports are kept constant the amount of overfire air remains constant. The percentage of overfire air is for the Maasvlakte units 35% under nominal conditions and is 30% for Amer unit 9 under nominal conditions. Consequently, the stoichiometry in the primary combustion zone is higher for Amer unit 9 (see **table 11.2**). Because of the non-linear impact of the primary zone stoichiometry an increase of the excess air will have a more pronounced effect on the NO_x emissions of Amer unit 9 compared to the Maasvlakte unit when the overall stoichiometry is identical for both units.

11.4 COMPARISON OF THE MAASVLAKTE AND AMER BASELINE NO_x MODELS

The NO_x emissions from Maasvlakte and Amer power plant showed the best correlation with the proximate volatile matter (db). **Figure 11.3** shows the NO_x predictions as function of the volatile matter content. The 95% confidence intervals are also included in this figure. The model of Amer power plant with the upper burner level out of operation (BOOP = 10) gives significantly lower NO_x emissions than the other two models. It seems that the Maasvlakte power plant is slightly more sensitive for the volatile matter content, but as is shown in **figure 11.3** the Maasvlakte model falls within the confidence interval of the Amer model (BOOP = 40). From a statistical perspective these models are therefore not different. The operational conditions during the tests at both units were to some extent comparable. In both cases the most upper burner level was in service, and as explained previously, this burner level is a major contributor to overall NO_x emissions. The overall stoichiometry was similar, unlike the primary combustion zone stoichiometry, which was 0.77 for Maasvlakte power plant and 0.83 for Amer power plant. The lower primary zone stoichiometry of Maasvlakte power plant is compensated by the longer residence time in the primary combustion zone of Amer power plant, as is illustrated in **figure 11.1**. In addition, the particle size of the pulverised coal of Amer power plant is smaller than the pulverised coal of Maasvlakte power plant. On average, 90% of the pulverised coal is smaller than 110 μm for Amer unit 9, whereas this is 154 μm for Maasvlakte power plant. Apparently, the smaller particle size and the longer residence time in the Amer boiler weigh up to the lower stoichiometric ratio in the primary combustion zone in the Maasvlakte boiler.

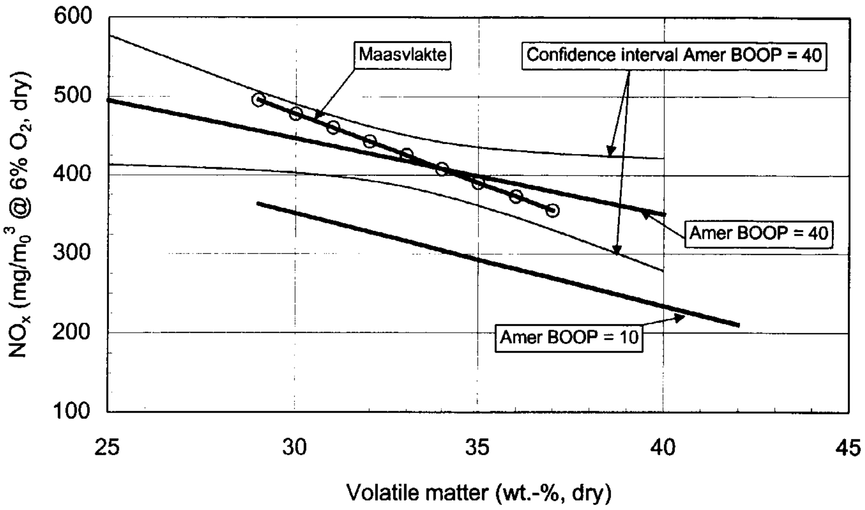


Figure 11.3 Comparison of the Maasvlakte and Amer baseline NO_x models

As noted previously, the volatile matter content or any other simple coal characteristic did not observe a straightforward relationship with the NO_x emissions from Hemweg unit 8. Because of the relatively long residence time in the substoichiometric combustion zone the NO_x emissions could be correlated within acceptable tolerances with the char nitrogen content. The char nitrogen was also measured for the coals burned at Amer unit 9 (see **table 12.1**). It is obvious from **table 12.1** that the maximum nitrogen release was not reached with the conditions applied for these coals. Nevertheless, the char nitrogen (chars produced in the HWG reactor of DMT) correlated fairly well with the NO_x emissions obtained with the upper burner level out of operation (**table 8.6**). The NO_x emissions measured with burner level 40 out of operation, however, showed a very poor correlation with the char nitrogen content. This poor correlation is enhanced by the fact that volatile nitrogen is becoming more dominant with the upper burner level in operation. Generally, the results with the char nitrogen correlation for Amer power plant underline the necessity for char nitrogen measurements of char prepared under realistic conditions.

11.5 CHAR NITROGEN CONVERSION

The results with Hemweg unit 8 showed that the conversion ratio of char nitrogen to NO_x varies from approximately 17 to 19 per cent. **Figure 11.4** illustrates the partitioning of coal nitrogen into volatile and char nitrogen including the nitrogen conversion ratios. As is observed the partitioning of coal nitrogen into char and volatile nitrogen varies and is apparently coal dependent. It is also observed that the conversion ratio of char nitrogen to NO_x is about constant, and is therefore independent of coal quality. However, a number of remarks needs to be made.

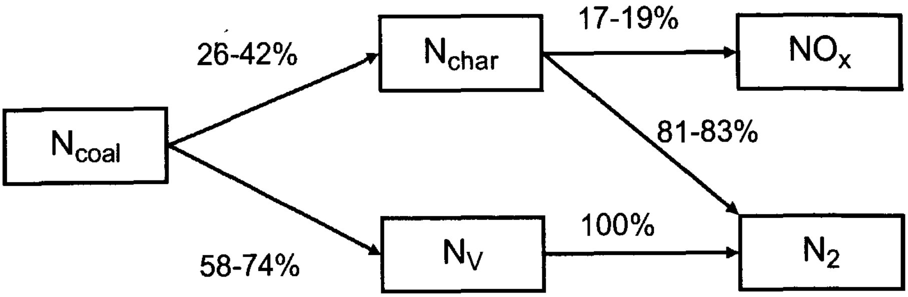


Figure 11.4 Partitioning of coal nitrogen into volatile and char nitrogen and the conversion ratios (results Hemweg unit 8)

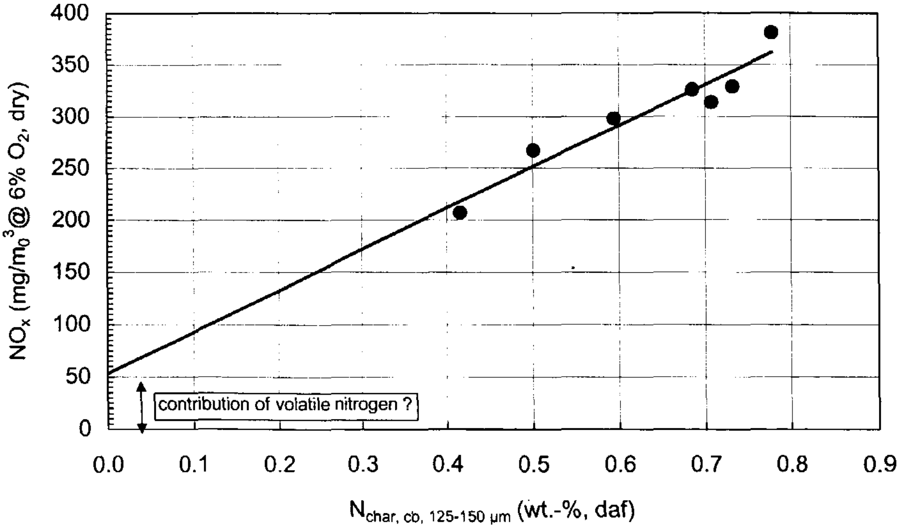


Figure 11.5 NO_x model Hemweg unit 8, extrapolated to char with a zero nitrogen content

As was already shown in chapter 9, the NO_x emissions from Hemweg unit 8 are affected by the stoichiometric ratio in the burnout zone, although the effect was limited. Earlier experiments at Hemweg unit 8 showed that the NO_x emissions also vary as function of the distribution of overfire air over the two rows of after air ports (Witkamp et al., 1996). Minimum NO_x emissions were achieved when 30-60% of the overfire air was introduced into the furnace through the lower after air ports. At all other settings the NO_x emissions increased with about 30 to 50 mg/m_0^3. This effect as well as the effect of the stoichiometric ratio in the burnout zone on NO_x emissions is a result of the penetration into the furnace and the mixing of the overfire air with the flue gases and combustion products from the primary combustion zone. An increase of the amount of overfire air results in a higher momentum of the overfire air as a result of which the overfire air penetrates deeper in the core of flue gases. The flue gases flowing in the centre of the furnace are earlier exposed to an oxygen-rich environment. The same holds for the distribution of the overfire air over the rows of after air ports.

In the computation of the char nitrogen conversion ratio it is assumed that volatile nitrogen does not contribute to the NO_x emissions. Regarding the NO_x model of Hemweg unit 8 (shown in **figure 11.5**) and extrapolating the model to a char nitrogen content of zero, it is suggested that still some NO_x other than originating from char nitrogen contribute to overall NO_x emissions. The same sort of plot was illustrated in **figure 9.10** with NO_x emissions (in ppm) versus the 100% char nitrogen to NO_x conversion. The approach used in **figure 9.10** is more accurate since this avoids systematic scatter due to the slightly different flue gas volumes from the coals. **Figure 11.5** can be used as an approximation when the complete coal analysis is not known.

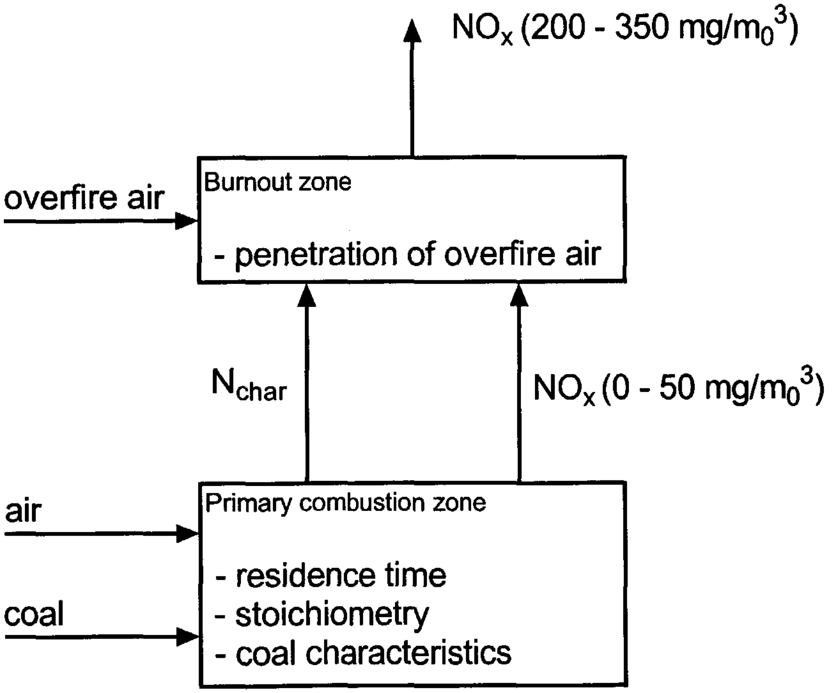


Figure 11.6 Schematic representation of the impact of the main parameters on NO_x emissions from Hemweg unit 8

It is unclear if the assumption of the linear relationship between char nitrogen and NO_x emissions also holds for coals with a low char nitrogen content. In addition, more experiments are needed to establish the relationship between char nitrogen and NO_x emissions with a higher accuracy.

Figure 11.6 illustrates the main parameters affecting the NO_x emissions. To summarise, the primary combustion zone is the most dominant in the formation and reduction of NO_x emissions. The main parameter in the burnout zone affecting the NO_x emissions is the penetration depth of the overfire air, although this effect is less important than the primary zone stoichiometry and the residence time in the primary zone. The conversion ratio of char nitrogen that is transported into the burnout zone to NO_x is more or less constant, apart from the effect of overfire air penetration depth. The amount of char nitrogen that is transported into the burnout zone is strongly dependent on coal characteristics.

11.6 BURNOUT

The burnout of a coal is affected by many coal-related factors. In this study it was found that the volatile matter content might be used for predicting the burnout in the low NO_x units considered. Burnout is mainly governed by the reaction of fixed carbon with oxygen in the later stages of combustion. Factors, which are not considered in this study or did not happen to have a statistical relevant impact are, for instance, particle size, free swelling index, petrographic or maceral composition, char morphology and mineral matter distribution.

Comparison of the residence times in the burnout zone shows that the Maasvlakte units have the shortest residence time. In addition, the pulverised coal for Maasvlakte is coarser (average D90 values for Maasvlakte, Hemweg and Amer are 154, 126 and 110, respectively) and the stoichiometry in the primary combustion zone is the lowest of the three units (see **table 11.2**). It is therefore not surprising that the burnout is worst for this boiler.

11.7 COAL BLENDING

In laboratory furnaces NO_x reductions are reported with coal blending (Rozendaal et al., 1992b; Maier et al., 1995; Monroe et al., 1997c). Probably the decisive role for NO_x reduction to occur with coal blends in laboratory burners (most of them are of the swirl-burner type) is the size of the particles in combination with the near burner aerodynamics. The internal recirculation zone of a swirl burner is oxygen lean, whereas in the outer region of the flames the conditions are oxidising. The particle trajectories in a swirling flame of the aerodynamically air staged burner were identified by the IFRF (Knill et al., 1989). The position of the coal gun as well as particle size play a decisive role to what extent particles follow the NO_x promoting route or the NO_x inhibiting route. Large particles having a large momentum will enter the reducing flame zone more easily than small particles. Depending on the gun position and the gun injector design, particle size affects NO_x emissions. The velocity of the primary air also influences the momentum of the particles. Burner design and operation are therefore important factors in the aerodynamics in the near burner region and may have a large effect on NO_x emissions.

Interactions during grinding resulting in a different particle size distribution compared to the single coals may therefore be of major importance on the impact of coal blending on NO_x emissions. This was shown for instance by Monroe et al (1997c, see also chapter 4). Due to particle segregation during grinding a NO_x reduction effect may occur. Monroe suggested that the larger particle size of the high-volatile coal resulted in a further penetration of the high-volatile coal into the furnace. During the combustion of the low-volatile and also smaller coal particles the large high-volatile coal particles are releasing volatile species, which may reduce the NO_x formed by the low-volatile coal.

The impact of blending of two different coals on NO_x emissions and burnout was studied with full-scale experiments at Maasvlakte unit 1, Amer unit 9 and Hemweg unit 8. It was shown that within the range of coals investigated, the NO_x emissions of the blends are the weighted average of the NO_x emissions of the single coals under both unstaged and staged combustion conditions. On basis of these results it is suggested that the rate of pyrolysis and combustion of the different coals in the blend are comparable.

After injection into the furnace, the coal particles are completely surrounded by air (primary and secondary air) and combustion products and burn independently of the other coal particles. The degree of mixing of air, combustion products and coal particles is strongly dependent on burner design and the way of air injection. The main flow patterns in the vicinity of full-scale burners are, however, within certain limits, independent of the coal characteristics. When the limits are reached has not been investigated but if, for instance, anthracite and a very young reactive coal are blended interactions may occur since the combustion behaviour and rate of pyrolysis of both coal types are quite different (Wong, 1987). The coals used in this investigation are, however quite similar and it is therefore suggested that the coal particles burn independently and are practically not influenced by the behaviour of other particles.

Except for the coal reactivity, the grinding characteristics may determine the degree of interaction in blend combustion. A very hard coal blended with a very soft coal may eventually result in a segregation of the coals over the particle size fractions. The soft coal may end up after grinding in the smaller size fractions, whereas the harder coal dominates the larger particle size fractions. This may have negative effects on NO_x emissions and burnout. The pyrolysis of coal particles is completed in about 50-100 milliseconds, which is very fast in comparison to the char burnout. Larger particles probably take some more time to devolatilise and will probably also devolatilise to a lesser extent. The time frame of 50-100 milliseconds corresponds approximately to a distance of 1-2.5 m from the burner exit, assuming an initial velocity of 20-25 m/s. Depending on the flow patterns near the burner and the air supply and hence the stoichiometry in the different flame zones it is possible that larger particles release part of the volatiles in flame zones with other conditions compared to the smaller particles. The release of volatiles in other flame zones will result in a different nitrogen chemistry. Volatile nitrogen released in an oxidising environment will be converted to NO_x much easier than in a reducing environment. Additionally, it can be assumed that larger particles will release less volatiles and hence release less nitrogen with the volatiles. The char is partly burned in an oxidising environment after the injection of overfire air. If more char nitrogen is present, also more NO_x in the burnout zone will be generated.

A strong difference in grinding behaviour may also affect burnout behaviour. Generally, coal characteristics and particle size affect burnout. The larger particles are the main contributors to the unburned carbon in the ash. In case lower reactive coals end up after grinding in the coarser size fractions the burnout will be negatively affected.

11.8 EXTRAPOLATION OF NO_X MODELS TO OTHER BOILERS

The NO_x predictions developed in this study are specific for the boilers involved. The use of these models for other boilers is only possible if these boilers have similar features. The residence times in the primary combustion and burnout zone as well as the stoichiometric ratios should be comparable to boilers considered in this study. In the previous sections these parameters have been extensively discussed. If similar programs are performed at other boilers it should be noted that process conditions for all coals are the same, since otherwise the impact of boiler settings will obscure the impact of coal quality.

11.9 POSSIBILITIES FOR A FURTHER NO_X REDUCTION

A possibility to reduce the NO_x emissions from the tangential-fired units is to improve the fineness of especially the upper pulverisers. A study performed by Maier (1998) showed that lower NO_x emissions are possible with smaller particles under the condition that the residence time of the particles in the substoichiometric combustion zone is higher than 0.25 and below 2.5 seconds. Experiments with furnace air staging in a 0.35 MW_{th} furnace showed that the NO_x emissions reduced with about 20% with a finer grind (2% > 90 mm versus 20% > 90 mm) due to a faster volatile and nitrogen release (Maier, 1998). Extrapolation of this reduction to full scale applications means that the contribution of the upper burner to the overall NO_x emission is reduced by 20%.

Extrapolation to the Amer power plant (see **figure 11.2**) would mean that the upper burner level would contribute only 640 mg/m_0^3 instead of 800 mg/m_0^3. The NO_x emissions would then reduce from 400 to 368 mg/m_0^3. The virtual NO_x emissions (800 mg/m_0^3) of the upper burner level are comparable to the NO_x emissions presented by Maier (1998). The primary air stoichiometry (0.62) and the residence time (1-1.5 seconds) in the experiments by Maier are, however, different from the values for Amer unit 9 (0.83 and 0.20, respectively). The short residence time of the particles is close to the lower limit for a NO_x reduction effect. Consequently, it may be possible that the residence time in the substoichiometric zone is too short resulting in increasing NO_x emissions instead, simply because there is not enough time available to destroy the NO_x that is formed in the initial phase of combustion. The particles entering the second burner level (seen from above) have a residence time long enough (about 0.5 seconds) to reduce the earlier formed NO_x, however, the contribution of this burner level is assumed to be substantially lower than the upper burner level.

This shows, however, that the residence time in the upper burner region is very important and that with a proper design of the pulveriser (and classifier) of especially those pulverisers feeding the upper burner levels a further NO_x reduction is possible. In case of existing boilers it should be considered to minimise the load of the upper burners by increasing the load on the resulting burner levels to allow the pulveriser feeding the upper burner levels to produce the finest possible product.

A more rigorous measure to lower NO_x emissions from both tangential-fired units is to reposition the overfire air ports and locate them some meters above the main burners. This will increase the residence time in the primary combustion zone. However, this may result in a poor burnout, especially for the Maasvlakte unit. An improved grinding of especially the upper burners may compensate this effect. Another possibility for NO_x reduction for Amer unit 9 is a reduction of the primary zone stoichiometry, since the stoichiometry is, compared to both other units, rather high.

Chapter 12 CONCLUSIONS AND RECOMMENDATIONS

12.1 GENERAL CONCLUSIONS

NO_x emissions from low NO_x pulverised coal-fired boilers are influenced by many factors. The most dominant are coal characteristics, burner configuration and boiler settings.

In general, coal is characterised by the proximate and ultimate analysis. However, to understand the formation and destruction of NO_x during the combustion process and to predict the resulting NO_x emissions, additional information is needed. In present-day low NO_x boilers the major source that contributes to the overall NO_x emissions is the nitrogen that remains in the char after the volatile matter has been released. Both the proximate and the ultimate analysis do not provide the essential information on the partitioning of nitrogen into volatile and char nitrogen. The proximate analysis fails since the temperature as well as the heating rate during the analysis is substantially lower than in actual pulverised coal flames, where peak temperatures are obtained of approximately 1600 °C and a heating rate is achieved of approximately 10^4 °C/s. The ultimate analysis fails because the total nitrogen content is hardly of influence on the amount of nitrogen retained in the char.

The prediction of NO_x emissions is complex due to the multiple-burner and air staging concept of the pulverised coal-fired boilers. In general, a large number of burners is installed and the coal particles introduced into the furnace through these burners experience each a distinct environment with respect to oxygen availability over time. The coal particles introduced into the furnace through the burners that are located close to the overfire air ports remain only for a short period of time in an oxygen-lean environment. The residence time of the coal particles injected into the furnace at lower burner levels is longer and often sufficient to convert the nitrogen released with the volatile matter to atmospheric nitrogen.

Fine-tuning of the boiler settings, such as adjustments of the auxiliary air injection, excess air ratio and burner tilts can control and reduce NO_x emissions to a certain extent, but other plant performance parameters such as steam temperature and unburned carbon content also need to be considered. Optimisation of all performance aspects simultaneously may conflict in some cases. The effect of coal quality on NO_x emissions is often obscured by the variation of boiler settings when various coals are burned.

12.2 NO_X PREDICTIONS BASED ON COAL CHARACTERISTICS

The NO_x emissions from the tangential-fired units Maasvlakte and Amer 9, both equipped with close coupled overfire air ports, observed a relationship with the proximate volatile matter content. The total nitrogen content in the coal was of minor importance. It was also observed that the char nitrogen content correlated with the NO_x emissions from Amer unit 9, although to a lesser extent compared to the proximate volatile matter. This was attributed to the relatively mild conditions in the heated wire grid reactor, as a result of which the char nitrogen content was too high. This was confirmed by later experiments in a heated wire grid reactor operated under more severe conditions.

In addition, the residence time in a substoichiometric environment of the coal particles introduced into the furnace through the upper burner level is short. As a result, volatile nitrogen from these coal particles may contribute to the NO_x emissions.

The NO_x emissions from the opposed-wall-fired unit Hemweg 8, equipped with separated overfire air ports, observed the best correlation with the nitrogen content in the char. The chars were produced in a heated wire grid reactor that was operated at a peak temperature of 1600 °C and a heating rate of 1600 °C/s. The reasons for the result that, unlike the NO_x emissions from Amer unit 9, the NO_x emissions of Hemweg unit 8 can be predicted by the char nitrogen content are:

- the chars were produced under more realistic conditions
- the longer residence time in the substoichiometric combustion zone in the furnace of Hemweg unit 8 inhibits a substantial contribution of NO_x produced in this zone to total NO_x emissions.

The char nitrogen content can not be predicted from the proximate and ultimate analysis, although a tendency is observed of a reduced nitrogen content in chars of higher volatile coals. It is concluded that suitable experimental conditions in the production of chars for the determination of char nitrogen are essential to produce chars that are representative for the actual conditions. Peak temperature and heating rate should be in the order of 1600 °C and 10^4 °C/s, respectively.

With respect to the NO_x emissions from Hemweg unit 8, it was observed that the char nitrogen conversion ratio to NO_x varied from 17 to 19%, whereas the percentage of nitrogen retained in the char varied from 26 to 42%. It is therefore suggested that the partitioning of nitrogen is dependent on coal characteristics, whereas the char nitrogen conversion is mainly governed by the operating conditions.

12.3 BURNER CONFIGURATION AND OPERATION

The extent of NO_x reduction is limited in boilers equipped with close coupled overfire air ports, since the residence time in the primary combustion zone of coal particles introduced into the furnace at the upper burner levels is relatively short. Boilers that are equipped with separated overfire air ports have the ability to operate with lower NO_x emissions, since the coal particles introduced into the furnace at the upper burner levels still have (enough) time to reduce the contribution of NO_x formed in the primary combustion zone.

To obtain low NO_x emissions it is essential to operate at a low stoichiometry in the primary combustion zone (approximately 0.75 – 0.80). With increasing stoichiometric ratios, NO_x emissions will increase progressively. The conditions in the burnout zone are less important, but may affect NO_x emissions to some extent if the penetration of overfire air is varied either by a variation of the amount of overfire air or by a redistribution of the overfire air over the various overfire air ports.

12.4 COAL BLENDING

The impact of the simultaneous combustion of various coals on NO_x emissions is of minor importance. Full-scale tests performed at Maasvlakte, Amer and Hemweg power plants showed that the NO_x emissions of the coal blends investigated are the weighted average of the NO_x emissions of the parent coals. The burnout of the coal blend was also comparable to the weighted average burnout of the parent coals. It is suggested that deviations from this rule in present-day low NO_x boilers are only possible when:

- widely diverging coals with respect to rank are blended
- interaction during the grinding process occurs that results in a segregation of the coals over the particle size fractions.

12.5 RECOMMENDATIONS

The NO_x emissions from the tangential-fired units Maasvlakte and Amer 9 were successfully correlated with the proximate volatile matter and useful prediction formulas were developed. The main advantage of the result that the proximate volatile matter can be used as a predictor is that this information is usually present in standard coal contracts. However, the proximate volatile matter is an indirect coal parameter that is determined under conditions far from the actual conditions and is therefore a substitute of the actual coal parameter that affects NO_x emissions. The results of the correlation of the NO_x emissions from the opposed-wall-fired unit Hemweg showed that the NO_x emissions from this unit are closely related to the char nitrogen content. Recommendations for future work are the following:

- more coals should be tested at Hemweg power plant to confirm the results presented in this thesis. The chars should be produced at peak temperature of 1600 °C and at a heating rate of 10^4 °C/s
- a NO_x prediction formula should be developed for Hemweg power plant on basis of the proximate and ultimate analysis to obtain a first assessment of the NO_x emissions. This is needed since it is not expected that in the near future a standardised char nitrogen determination is developed
- the NO_x emissions from the tangential-fired units should be related to the char nitrogen content measured under realistic conditions to improve the accuracy of the NO_x prediction.

After the results presented in this thesis are confirmed it is recommended that the coal parameters *char nitrogen and high temperature volatile matter* should be analysed on a regular basis and under standardised conditions. Subsequently, they should be included in basic coal contracts, since these parameters are essential for present-day low NO_x pulverised coal combustion.

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LIST OF SYMBOLS

a	factor		(-)
A	factor	= 50 for FR ≥ 1.6	(-)
		= 80 for FR < 1.6	(-)
ash	ash content in coal		(wt.-%)
Ash_{char}	ash content in char		(wt.-%, db)
Ash_{coal}	ash content in coal		(wt.-%, db)
Bu	burnout		(wt.-%)
C	carbon content		(wt.-%)
CF	Combustibility factor		(-)
CR_{CN}	conversion ratio of char nitrogen to NO		(-)
CR_{fuelN}	conversion ratio of fuel N to NO		(-)
CR_{VN}	conversion ratio of volatile N to NO		(-)
D10	10 wt.-% of the sample has a particle size below this diameter		(µm)
D50	50 wt.-% of the sample has a particle size below this diameter		(µm)
D90	90 wt.-% of the sample has a particle size below this diameter		(µm)
e	residual		(-)
FC	fixed carbon		(wt.-%)
FR	fuel ratio (ratio of fixed carbon to volatile matter)		(-)
M_N	nitrogen atomic weight = 14		(kg/kmol)
MS_E	error mean square		(-)
n	number, pairs of data		(-)
N	nitrogen content in coal		(wt.-%)
$N_{char,\ ar}$	percentage of nitrogen per kg coal retained in the char		(wt.-%, ar)
$N_{V,\ ar}$	percentage of nitrogen per kg coal released with the volatiles		(wt.-%, ar)
NO	NO emission/concentration		(ppm)
NO_{char}	NO production from char combustion		(ppm)
$NO_{char,\ max}$	maximum NO concentration from char combustion		(ppm)
NO_{fuel}	sum of NO from NO_{char} and NO_{VM}		(ppm)
$NO_{fuel,\ max}$	maximum NO concentration from the nitrogen in coal		(ppm)
NO_V	NO production from the combustion of volatiles		(ppm)
$NO_{V,\ max}$	maximum NO concentration from the combustion of volatiles		(ppm)
NO_x	NO_x emission		(ppm)
P	property		(-)
PdN	pyridinic nitrogen		(wt.-%, daf)
PrN	pyrolic nitrogen		(wt.-%, daf)
QN	quaternary nitrogen		(wt.-%, daf)
R factor	see yield factor		(-)
R^2	coefficient of determination		(-)
S0	swirl number		(-)
S_{xx}	corrected sum of squares of x		(-)
S_{xy}	corrected sum of cross-products x and y		(-)

SS_E	error sum of squares	(-)
t	t-statistic	(-)
UBC	unburned carbon content in fly ash	(wt.-%)
V_0	ideal gas volume at 0 °C and 1 bar = 22.41	(m_0^3/kmol)
$V_{FG,\,dry}$	dry flue gas volume per kg raw coal	(m_0^3/kg)
V	volatile yield at elevated temperatures (higher than 900 °C)	(wt.-%)
VM	volatile matter determined with the proximate analysis	(wt.-%)
x	fraction	(wt.-%)
x	independent variable	(-)
y	response variable	(-)
yield factor	ratio of HTVM to the proximate volatile matter	(-)
β_0	intercept of regression model	(-)
β_1	slope of the regression model	(-)
$\hat{\beta}_0$	least square estimator of the intercept of the regression model	(-)
$\hat{\beta}_1$	least square estimator of the slope of the regression model	(-)
ε	error	(-)
λ_{prim}	stoichiometric ratio in the primary combustion zone	(-)
λ_{tot}	stoichiometric ratio in the burnout zone	(-)
τ	residence time	(s)
σ^2	variance	(-)
$\hat{\sigma}^2$	estimated average variance	(-)

ACRONYMS AND ABBREVIATIONS

AAP	after air port
AASB	aerodynamically air staged burner
ad	air-dried
AFT	ash fusion temperatures
AH	air heater
ant.	anthracite
ar	as received
ASTM	American Society for Testing and Materials
aux	auxiliary
avg.	average
bitum.	bituminous
BOOP	burner out of operation
BOOS	burner out of service
Bu	burnout
calc.	calculated
cap.	capacity
CCSEM	computer-controlled scanning electron microscopy
CE	Combustion Engineering (USA)
CFD	computational fluid dynamics
conc	concentrated
daf	dry ash-free
db	dry basis
dmmf	dry mineral matter-free
DMT	Deutsche Montan Technologie (Essen, Germany)
DTF	drop tube furnace
EASB	externally air staged burner
EC	El Cerrejon
EFR	entrained flow reactor
EMO	Europees Massagoed Overslagbedrijf (Blending facility)
EPRI	Electric Power Research Institute (USA)
EPZ	N.V. Elektriciteits-Produktiemaatschappij Zuid-Nederland
ESP	electrostatic precipitator
EZH	N.V. Electriciteitsbedrijf Zuid-Holland
FC	fixed carbon
FGD	flue gas desulphurisation
FGF	flue gas fan
FGR	flue gas recirculation
FGRF	flue gas recirculation fan
FR	fuel ratio (ratio of FC to VM)
FSI	free swelling index
FT	fluid temperature

GH	gas heater
GKE	N.V. Gemeenschappelijk Kolenbureau Elektriciteitsproduktiebedrijven
GP	gun position
HGI	Hardgrove grindability index
HHV	higher heating value
HO	Hobet
HT	hemispherical temperature
HTNR	high temperature NO_x reduction
HTVM	high temperature volatile matter
HTWM	high temperature wire mesh (HWG)
HV	high-volatile
HVB	high-volatile bituminous coal
HWG	heated wire grid
i.c.	in control
IC	Mechanical Engineering Department, Imperial College (London, UK)
ID	induced draft
IFRF	International Flame Research Foundation (IJmuiden, the Netherlands)
IGI	Idemitsu grindability index
ISO	International Standards Organisation
Il	Illawarra
IRZ	internal recirculation zone
KF	Koornfontein
kW_{th}	kilowatts thermal
lig.	lignite
LOI	loss on ignition
LV	low-volatile
LVB	low-volatile bituminous coal
m	meter
MHI	Mitsubishi Heavy Industries (Japan)
mmf	mineral matter-free
MW_e	megawatts electrical
MW_{th}	megawatts thermal
n.d.	not determined
No.	number
NO_x	nitrogen oxides
OFA	over fire air
Opp.	opposed
ox	oxidising
pc	pulverised coal
p.f.	pulverised fuel
PM	Pollution Minimum
ppm	parts per million
PRB	Powder River Basin
prim.	primary
pulv.	pulveriser
RC	rotating classifier

red	reducing
s	seconds
SCR	selective catalytic reduction
SGR	separate gas recirculation
ST	softening temperature
subb.	subbituminous coal
T-fired	tangential-fired
temp.	temperature
TGA	thermal gravimetric analyser
turb.	turbulent
UBC	unburned carbon
UNA	N.V. Energieproduktiebedrijf UNA
u.r.	unreliable result
USA	United States of America
VM_{max}	volatile matter measured at elevated temperatures (> 900 °C) and a rapid heating rate
VM	volatile matter (proximate analysis, ISO 1998)
vol.	volume
wt.	weight
XPS	X-ray photoelectron spectroscopy
YGI	Yamada grindability index

Appendix A REGRESSION ANALYSIS

A.1 INTRODUCTION

Regression analysis is a statistical technique for investigating and modelling the relationship between variables (Montgomery et al., 1982). A simple linear regression model is described as

$$y = \beta_0 + \beta_1 x + \varepsilon \tag{A.1}$$

where y represents the dependent or response variable, x the independent variable or regressor (predictor) and β_0 and β_1 the regression coefficients. β_0 is the intercept and β_1 is the slope of the model. The relationship between the response y and the predictor x is a straight line. The difference between the observed value of y and the straight line is the error ε. In a simple linear regression model the errors are assumed to have mean zero and unknown variance σ^2. Additionally, it is usually assumed that the errors are not correlated.

A.2 METHOD OF LEAST SQUARES

The regression coefficients are unknown and must be estimated from the sample data. In many cases the method of least squares is used for estimating β_0 and β_1. This means that the sum of squares of the differences between the observation y_i and the straight line is a minimum. Suppose that there are n pairs of data $(y_1, x_1), (y_2, x_2), ..., (y_n, x_n)$. Equation A.1 may then be written as

$$y_i = \beta_0 + \beta_1 x_i + e_i, \qquad i = 1,2,....,n \tag{A.2}$$

The least squares criterion is

$$S(\beta_0, \beta_1) = \sum_{i=1}^{n} e_i^2 = \sum_{i=1}^{n} (y_i - \beta_0 - \beta_1 x_i)^2 \tag{A.3}$$

The least squares estimators of β_0 and β_1 ($\hat{\beta}_0$, $\hat{\beta}_1$) must satisfy

$$\frac{\partial S}{\partial \beta_0}\bigg|_{\hat{\beta}_0, \hat{\beta}_1} = -2\sum_{i=1}^{n}\left(y_i - \hat{\beta}_0 - \hat{\beta}_1 x_i\right) = 0 \tag{A.4}$$

$$\frac{\partial S}{\partial \beta_1}\bigg|_{\hat{\beta}_0, \hat{\beta}_1} = -2\sum_{i=1}^{n}\left(y_i - \hat{\beta}_0 - \hat{\beta}_1 x_i\right)x_i = 0 \tag{A.5}$$

The solution of these equations may be written as follows:

$$\hat{\beta}_0 = \bar{y} - \hat{\beta}_1 \bar{x} \tag{A.6}$$

$$\hat{\beta}_1 = \frac{S_{xy}}{S_{xx}} \tag{A.7}$$

with:

$$S_{xx} = \sum_{i=1}^{n} (x_i - \bar{x})^2 \tag{A.8}$$

$$S_{xy} = \sum_{i=1}^{n} y_i (x_i - \bar{x}) \tag{A.9}$$

The fitted simple linear regression model is then

$$\hat{y} = \hat{\beta}_0 + \hat{\beta}_1 x \tag{A.10}$$

The residuals e_i equal the difference between the observed value y_i and the corresponding fitted value $\hat{y}_i$

$$e_i = y_i - \hat{y}_i \qquad i = 1, 2, \ldots, n \tag{A.11}$$

A.3 CONFIDENCE AND PREDICTION INTERVAL

By assuming that the errors are normally and independently distributed with mean 0 and variance σ^2 it is possible to construct an interval estimation of the mean response. The confidence interval on the mean response is given by (Montgomery et al., 182)

$$\hat{y}_0 - t_{\alpha/2,n-2}\sqrt{MS_E\left(\frac{1}{n}+\frac{(x_0-\bar{x})^2}{S_{xx}}\right)} \le E(y|x_0) \le \hat{y}_0 + t_{\alpha/2,n-2}\sqrt{MS_E\left(\frac{1}{n}+\frac{(x_0-\bar{x})^2}{S_{xx}}\right)} \tag{A.12}$$

The prediction interval for new observations is given by

$$\hat{y}_0 - t_{\alpha/2,n-2}\sqrt{MS_E\left(1+\frac{1}{n}+\frac{(x_0-\bar{x})^2}{S_{xx}}\right)} \le E(y|x_0) \le \hat{y}_0 + t_{\alpha/2,n-2}\sqrt{MS_E\left(1+\frac{1}{n}+\frac{(x_0-\bar{x})^2}{S_{xx}}\right)} \tag{A.13}$$

Usually a 95% confidence interval on the mean response and a 95% prediction interval on future observations are considered, which corresponds to α is 0.05 (for a two-sided test $\alpha/2$ is used).

A.4 RESIDUAL ANALYSIS

In order to test the model adequacy it is needed to consider the assumptions made on the errors. It is assumed that the error term has a mean zero and a constant variance σ^2. It is also assumed that the errors are uncorrelated and normally distributed. The residuals are defined in equation A.11. The residuals have zero mean and the estimated average variance $\hat{\sigma}^2$ or MS_E (error mean square) is

$$\hat{\sigma}^2 = \frac{\sum_{i=1}^{n}(e_i - \bar{e})^2}{n-2} = \frac{SS_E}{n-2} = MS_E \tag{A.14}$$

Residual plots are usually used for detecting model inadequacies. Commonly used plots are the normal probability plot, a plot of residuals against $\hat{y}_i$ and a plot of residuals against x_i (Montgomery et al., 1982).

Appendix B RESULTS NO_x PREDICTION MAASVLAKTE AND AMER

Appendix B contains details of the Maasvlakte and Amer tests discussed in chapter 7.

B.1 COAL CHARACTERISTICS

Table B.1 Coal characteristics of Maasvlakte blends (as received)

Blend	Moisture (wt.-%)	Ash (wt.-%)	VM (wt.-%)	FC (wt.-%)	HHV MJ/kg	LHV MJ/kg	FR -	S (wt.-%)	N (wt.-%)	HGI
MV1	11.0	9.0	29.9	50.1	29.1	25.0	1.68	0.32	1.52	45
MV2	11.8	8.6	28.7	50.9	25.8	24.8	1.77	0.39	1.46	49
MV3	8.9	9.0	30.5	51.6	27.2	26.1	1.69	0.47	1.13	49
MV4	13.6	7.3	31.3	47.8	25.7	24.5	1.53	0.41	0.92	48
MV5	8.1	11.0	24.5	56.4	27.9	26.9	2.30	0.41	1.24	64
MV6	13.5	8.4	30.8	47.3	25.4	24.2	1.54	0.41	1.17	47
MV7	13.9	7.8	29.9	48.4	25.9	24.7	1.62	0.48	1.17	47
MV8	11.8	9.5	28.6	50.1	26.2	25.1	1.75	0.47	1.19	52
MV9	8.5	11.0	29.7	50.8	26.8	25.8	1.71	0.61	1.20	52
MV10	7.5	9.9	29.2	53.4	28.0	26.9	1.83	0.66	1.54	53
MV11	9.0	14.1	25.8	51.1	25.6	24.6	1.98	0.57	1.55	50
MV12	9.0	12.3	26.4	52.3	26.6	25.6	1.98	0.55	1.64	54

Table B.2 Malvern particle size distribution of the pulverised coal (Maasvlakte blends)

Blend	D10 (μm)	D50 (μm)	D90 (μm)	% < 75 μm	% < 150 μm
MV1	7.4	54.9	153.8	60.7	89.3
MV2	7.5	53.1	156.1	61.4	89.0
MV3	7.2	50.1	149.8	63.0	90.0
MV5	5.8	39.9	150.8	68.5	89.7
MV6	8.6	53.6	161.6	61.3	87.3
MV7	6.7	48.2	155.1	64.5	89.0
MV8	6.4	48.2	155.5	63.6	88.9
MV10	6.2	47.6	145.6	65.6	90.8
MV11	6.4	52.5	167.7	60.6	86.4
MV12	6.1	46.1	148.2	65.2	90.1

Table B.3 Coal characteristics of Amer blends (as received)

Blend	Moisture (wt.-%)	Ash (wt.-%)	VM (wt.-%)	FC (wt.-%)	HHV (MJ/kg)	LHV (MJ/kg)	FR -	S (wt.-%)	N (wt.-%)	HGI
A1	12.8	9.5	31.1	46.6	29.1	24.2	1.50	0.53	1.40	44
A2	13.3	5.0	35.6	46.1	30.4	25.2	1.29	0.40	1.10	39
A3	9.9	12.0	28.2	49.9	28.4	24.5	1.77	0.66	1.50	52
A4	7.5	12.2	26.8	53.5	29.2	26.0	2.00	0.53	1.60	47
A5	6.9	10.3	29.4	53.4	30.2	27.5	1.82	1.15	1.52	52
A6	7.0	11.2	28.1	53.7	30.2	27.1	1.91	1.05	1.50	51
A7	7.3	10.6	29.3	52.8	30.5	27.2	1.80	1.20	1.40	51
A8	8.0	11.1	32.8	48.1	30.3	26.8	1.47	1.14	1.30	46
A9	9.7	10.6	28.7	51.0	29.1	25.9	1.78	0.97	1.30	52
A10	13.9	7.0	31.0	48.1	30.0	25.0	1.55	0.40	1.20	44
A11	12.1	8.2	34.6	45.1	30.3	25.5	1.30	0.59	1.20	47
A12	8.0	15.4	23.8	52.8	27.7	24.6	2.22	0.68	1.53	51
A13	10.0	11.8	29.2	49.0	29.0	25.1	1.68	0.63	1.37	49

Table B.4 Malvern particle size distribution of the pulverised coal (Amer blends)

Blend	D50 (μm)	D90 (μm)
A1	37.0	108.4
A2	43.1	113.4
A3	30.0	91.2
A4	34.0	98.9
A5	31.3	98.9
A6	34.6	104.3
A7	32.5	104.9
A8	35.3	105.6
A9	52.6	161.5
A10	38.1	105.6
A11	41.5	112.4
A12	42.3	137.7
A13	36.5	110.7

B.2 BASELINE RESULTS

Table B.5 NO_x and O_2 data for the Maasvlakte baseline tests
(*NO_x in mg/m$_0^3$ @ 6% O_2, dry; O_2 measured upstream air heater in vol.-%, wet*)

Blend			Results		Relation of NO_x and O_2	NO_x @3% O_2
MV1	O_2	2.3	3.4	4.9	$NO_x = 315 + 31*O_2$	**407**
	NO_x	389	414	468		
MV2	O_2	3.3	4.5	5.4	$NO_x = 321 + 28*O_2$	**407**
	NO_x	418	442	479		
MV3	O_2	2.6	3.5	4.9	$NO_x = 314 + 35*O_2$	**418**
	NO_x	405	435	485		
MV4	O_2	2.5	3.9	-	$NO_x = 261 + 25*O_2$	**335**
	NO_x	323	357	-		
MV5	O_2	2.2	2.8	4.3	$NO_x = 415 + 29*O_2$	**501**
	NO_x	478	495	539		
MV6	O_2	3.1	4.1	5.5	$NO_x = 280 + 42*O_2$	**404**
	NO_x	413	442	511		
MV7	O_2	2.5	3.8	4.9	$NO_x = 287 + 40*O_2$	**407**
	NO_x	387	439	483		
MV8	O_2	2.7	3.8	5.0	$NO_x = 289 + 37*O_2$	**402**
	NO_x	392	428	478		
MV9	O_2	1.9	2.9	-	$NO_x = 343 + 42*O_2$	**468**
	NO_x	422	464	-		
MV10	O_2	1.9	2.6	3.3	$NO_x = 390 + 29*O_2$	**477**
	NO_x	442	472	483		
MV11	O_2	1.7	2.9	-	$NO_x = 414 + 40*O_2$	**534**
	NO_x	482	530	-		
MV12	O_2	1.7	2.9	4.2	$NO_x = 392 + 39*O_2$	**508**
	NO_x	453	513	551		

Table B.6 NO_x and O_2 data for the Amer baseline tests
(NO_x in mg/m$_0^3$ @ 6% O_2, dry; O_2 measured upstream air heater in vol.-%, wet)

Blend	BOOP	Results				Slope NO_x-O_2 relation		NO_x @ 3% O_2	NO_x @ 4.9% O_2
						3-4%	4-5%		
A1	10	O_2	3.3	4.0	4.9	57.5	191.1	**261**	**485**
		NO_x	277	321	480				
A2		O_2	2.9	3.9	5.0	97.1	165.0	**222**	**476**
		NO_x	210	307	495				
A3		O_2	2.8	4.0	5.0	73.5	179.9	**299**	**538**
		NO_x	287	370	549				
A4		O_2	2.8	3.9	4.9	80.3	215.4	**367**	**654**
		NO_x	353	439	662				
A5		O_2	2.7	3.8	4.9	75.9	102.1	**345**	**519**
		NO_x	379	390	617				
A6		O_2	3.3	3.7	4.9	27.1	189.4	**371**	**617**
		NO_x	379	390	617				
A7		O_2	2.8	3.9	5.0	69.1	179.8	**325**	**568**
		NO_x	312	387	577				
A8		O_2	3.0	4.0	4.9	58.0	58.7	**313**	**424**
		NO_x	312	369	425				
A9	40	O_2	3.0	3.9	5.0	73.1	142.5	**455**	**667**
		NO_x	458	517	675				
A10		O_2	2.8	3.8	4.9	102.4	125.2	**352**	**572**
		NO_x	333	430	577				
A11		O_2	2.9	4.0	5.1	90.7	120.1	**364**	**563**
		NO_x	357	454	591				
A12		O_2	2.9	3.9	4.9	125.4	170.7	**472**	**755**
		NO_x	455	588	747				
A13		O_2	2.8	4.0	4.8	93.0	167.1	**440**	**683**
		NO_x	419	534	665				

Table B.7 Burnout values used in the regression analysis (baseline tests Maasvlakte and Amer)

Maasvlakte		Amer		
Blend	Burnout (%)	Combustion mode	Blend	Burnout (%)
MV1	99.18	BOOP = 10	A1	99.68
MV2	99.46		A2	99.95
MV3	99.19		A3	99.63
MV4	99.53		A4	99.51
MV5	98.56		A5	99.58
MV6	99.44		A6	99.50
MV7	99.24		A7	99.57
MV8	99.53		A8	99.60
MV9	99.21	BOOP = 40	A9	99.42
MV10	99.58		A10	99.71
MV11	98.93		A11	99.86
MV12	98.81		A12	99.23
			A13	99.64

B.3 LINEAR REGRESSION ANALYSIS BASELINE TESTS

Table B.8 Results from the linear regression analysis (coefficient of determination R^2) of NO_x emissions (baseline tests Maasvlakte and Amer power plant)

Parameter		Maasvlakte	Amer 9 (BOOP = 10)	Amer 9 (BOOP = 40)
Moisture	wt.-%, ar	0.63	0.87	0.93
Ash	wt.-%, ar	0.85	0.63	0.82
Ash	wt.-%, db	0.82	0.55	0.81
Volatile matter	wt.-%, ar	0.66	0.67	0.70
Volatile matter	wt.-%, db	0.79	0.82	0.79
Volatile matter	wt.-%, daf	0.68	0.81	0.72
Fixed carbon	wt.-%, ar	0.49	0.85	0.74
Fixed carbon	wt.-%, db	0.22	0.63	0.36
Fixed carbon	wt.-%, daf	0.68	0.81	0.72
Fuel ratio	-	0.64	0.81	0.69
N	wt.-%, ar	0.42	0.67	0.75
N	wt.-%, db	0.31	0.44	0.66
N	wt.-%, daf	0.42	0.50	0.68
HHV	MJ/kg, ar	0.05	0.00	0.81
LHV	MJ/kg, ar	0.25	0.46	0.00
HGI		0.35	0.56	0.86
D50	µm	0.21	0.46	0.17
D90	µm	0.01	0.29	0.51
FR•Ndaf	wt.-%	0.71	0.72	0.68
VMar/Nar	-	0.63	0.68	0.79
VMdb/Ndb	-	0.63	0.67	0.79
VMdaf/Ndaf	-	0.64	0.68	0.78

Table B.9 Results from the linear regression analysis (coefficient of determination R^2) of burnout (baseline tests Maasvlakte and Amer power plant)

Parameter		Maasvlakte	Amer 9 (BOOP = 10)	Amer 9 (BOOP = 40)
Moisture	wt.-%, ar	0.24	0.73	0.67
Ash	wt.-%, ar	0.42	0.86	0.70
Ash	wt.-%, db	0.41	0.80	0.69
Volatile matter	wt.-%, ar	0.63	0.74	0.91
Volatile matter	wt.-%, db	0.61	0.85	0.96
Volatile matter	wt.-%, daf	0.59	0.76	0.97
Fixed carbon	wt.-%, ar	0.38	0.65	0.96
Fixed carbon	wt.-%, db	0.34	0.44	0.74
Fixed carbon	wt.-%, daf	0.60	0.77	0.94
Fuel ratio	-	0.63	0.73	0.97
N	wt.-%, ar	0.07	0.76	0.71
N	wt.-%, db	0.04	0.58	0.67
N	wt.-%, daf	0.08	0.66	0.68
HHV	MJ/kg	0.07	0.02	0.86
LHV	MJ/kg	0.12	0.27	0.07
HGI	°H	0.37	0.64	0.57
D50	μm	0.29	0.63	0.21
D90	μm	0.00	0.35	0.55

B.4 RESIDUAL ANALYSIS OF THE FITTED MODELS, CONFIDENCE AND PREDICTION INTERVAL

B.4.1 Maasvlakte and Amer baseline NO_x model (O_2 = 3%)

It is required to determine if the models developed for estimating the NO_x emissions are an adequate fit to the data. This is done by means of residual analysis. The residuals or the differences between the fitted and the observed values for the Maasvlakte and Amer baseline models (O_2 = 3%) are given in **table B.10** and **B.11**, respectively.

Table B.10 The value of the regressor (VM_{db} in wt.-%, dry), the measured and fitted NO_x emissions, and the residuals (all in mg/m_0^3) for the Maasvlakte measurements

Blend	Regressor variable (VM_{db})	Measured NO_x emission	Fitted NO_x emission	Residual
MV1	33.6	407	415	-7.8
MV2	32.5	407	433	-26.4
MV3	33.5	418	417	1.1
MV4	36.2	335	369	-33.5
MV5	26.7	501	537	-35.8
MV6	35.6	404	379	24.6
MV7	34.7	407	395	12.1
MV8	32.4	402	435	-33.3
MV9	32.5	468	435	33.2
MV10	31.6	477	451	26.5
MV11	28.4	534	507	26.9
MV12	29.0	508	496	12.5

Table B.11 The value of the regressor (VM_{db} in wt.-%, dry), the measured and fitted NO_x emissions, and residuals (all in mg/m_0^3) for the Amer measurements

	BLEND	Regressor variable (VM_d)	Measured NO_x	Fitted NO_x	Residual
BOOP=10	A1	35.7	261	284	-23.1
	A2	41.1	222	221	1.0
	A3	31.3	299	336	-37.0
	A4	29.0	367	363	3.4
	A5	31.6	345	333	12.2
	A6	30.2	371	349	22.6
	A7	31.6	325	332	-7.2
	A8	35.7	313	285	28.1
BOOP=40	A9	31.8	455	429	25.9
	A10	36.0	352	389	-36.7
	A11	39.4	364	356	7.9
	A12	25.9	472	486	-14.1
	A13	32.5	440	423	17.2

The residual analysis showed that the standardised residuals for the Maasvlakte NO_x model are normally distributed. Furthermore, no clear pattern was detected in the scatter plots of the measured NO_x emissions against the predicted NO_x and the nitrogen content (on a dry ash-free basis) of the coal blends. Because the errors are normally and independently distributed with mean 0 and variance σ^2 the confidence and prediction intervals can be computed. The parameters for the interval equations (equations A.11 and A.12 of appendix A) are derived from the statistical analysis and are given in **table B.12**. The models in combination with the confidence and prediction intervals are illustrated in **figure 7.4** (Maasvlakte), **figure 7.5** (Amer BOOP = 10) and **figure 7.6** (Amer BOOP = 40).

Table B.12 Parameters for the interval equations (Maasvlakte and Amer baseline NO_x models (O_2 = 3%))

	Maasvlakte	Amer models	
		BOOP = 10	BOOP = 40
$\bar{x}$	32.22	33.26	33.10
n	12	8	5
$t_{0.025,n-2}$	2.228	2.447	3.182
MS_E	771.82	569.91	858.37
S_{xx}	94.10	109.43	101.71

B.4.2 Amer baseline NO_x models (O_2 = 4.9%)

The residual analysis of the Amer model (BOOP = 10) showed that one data point has a major impact on the model. This possible outlier belongs to a coal blend with a volatile matter content of 41.1% on a dry basis (blend A2). The different behaviour of this blend may be caused by the low ash content (5.0% ar), as a result of which the volatile matter content on a dry basis is somewhat higher compared to blends with higher ash contents. A better fit may therefore be possible if the volatile matter content on a dry and ash-free basis is used. This is not performed in this thesis. The parameters for the interval equations are derived from the statistical analysis and are given in **table B.13**. The models and intervals are shown in **figures 7.7 and 7.8**.

Table B.13 Parameters for the interval equations (Amer baseline NO_x models (O_2 = 4.9%))

	Amer NO_x models (O_2 = 4.9%)	
	BOOP = 10	BOOP = 40
$\bar{x}$	33.26	33.10
n	8	5
$t_{0.025,n-2}$	2.447	3.182
MS_E	2666.70	570.56
S_{xx}	109.43	101.71

B.4.3 Indirect coal quality effect on Maasvlakte NO_x model (optimal case, O_2 = 3%)

The standardised residuals for this case are normally distributed. The scatter plots of the residuals against the predicted NO_x emission and the nitrogen content in the coal (on a dry ash-free basis) showed no obvious model defects. For the parameters in the confidence and prediction intervals the values given in **table B.12** can be used, except for MS_E which is 463.79 in this case. The model and intervals are shown in **figure 7. 13**.

B.4.4 Maasvlakte and Amer baseline burnout model

The residuals of the burnout base case models are considered to determine any model deficiencies. **Table B.14** and **table B.15** show the observed values of burnout, the fitted values and the residuals for Maasvlakte and Amer Power Plant, respectively.

Table B.14 Measured and fitted burnout values, value of the regressor and residuals for the Maasvlakte measurements

BLEND	Regressor variable (VM_d)	Measured burnout	Fitted burnout	Residual
MV1	33.6	99.18	99.34	-0.155
MV2	32.5	99.46	99.25	0.206
MV3	33.5	99.19	99.33	-0.135
MV4	36.2	99.53	99.56	-0.033
MV5	26.7	98.56	98.75	-0.194
MV6	35.6	99.44	99.51	-0.065
MV7	34.7	99.24	99.44	-0.196
MV8	32.4	99.53	99.24	0.292
MV9	32.5	99.21	99.24	-0.030
MV10	31.6	99.58	99.17	0.411
MV11	28.4	98.93	98.89	0.037
MV12	29.0	98.81	98.95	-0.138

Table B.15 Measured and fitted burnout values, value of the regressor and residuals for the Amer measurements

Blend	Regressor variable (VM_d)	Measured burnout	Fitted burnout	Residual
BOOP=10				
A1	35.7	99.68	99.71	-0.026
A2	41.1	99.95	99.89	0.062
A3	31.3	99.63	99.56	0.065
A4	29.0	99.51	99.48	0.029
A5	31.6	99.58	99.57	0.004
A6	30.2	99.50	99.53	-0.029
A7	31.6	99.57	99.57	-0.000
A8	35.7	99.60	99.71	-0.104
BOOP=40				
A9	31.8	99.42	99.51	-0.094
A10	36.0	99.71	99.71	-0.001
A11	39.4	99.86	99.87	-0.008
A12	25.9	99.23	99.23	0.001
A13	32.5	99.64	99.54	0.102

The standardised residuals of the Maasvlakte model are normally distributed. The residual plot of Maasvlakte showed that one data point near the centre of the data does have a positive residual which is somewhat larger than average. This possible outlier belongs to the blend MV10. From the particle size analysis listed in **table B.2** it can be seen that this pulverised coal from this blend is somewhat finer than the pulverised coal of the other blends, which could have resulted in an improved burnout for this blend.

The standardised residuals of the Amer models are normally distributed. The residual plot for the Amer case (BOOP = 10) showed that the model is affected to a large extent by one data point (blend A5). This blend happened to be a single coal originating from Colombia. Also at other power plants in the Netherlands this particular coal behaved extremely well with respect to burnout. The parameters for constructing the confidence and prediction intervals are given in **table B.16**. The models including the intervals are shown in **figure 7.21** (Maasvlakte), **figure 7.22** (Amer BOOP = 10) and **figure 7.23** (Amer BOOP = 40), respectively.

Table B.16 Parameters for the interval equations (burnout models)

	Maasvlakte	Amer models	
		BOOP = 10	BOOP = 40
$\bar{x}$	32.22	33.26	33.10
n	12	8	5
$t_{0.025,n-2}$	2.228	2.447	3.182
MS_E	0.04422	0.00351	0.00641
S_{xx}	94.10	109.43	101.71

B.5 RESULTS POWDER RIVER BASIN COAL (AMER 9)

Table B.17 NO_x data of the tests with Powder River Basin coals at Amer unit 9 (NO_x in mg/m_0^3 @ 6% O_2, dry; O_2 measured upstream air heater in vol.-%, wet)

Blend	BOOP	Results				Slope NO_x O_2 correlation	
						$2.3 < O_2 < 3.5$	$3.5 < O_2 < 4.3$
PRB0	10	O_2	2.3	3.1	-	35	-
		NO_x	284	313	-		
PRB25		O_2	2.5	3.5	4.2	30	66
		NO_x	278	308	360		
PRB40		O_2	2.4	3.5	4.3	22	81
		NO_x	249	273	330		

Table B.18 Burnout data of the tests with Powder River Basin coals at Amer unit 9 (O_2 measured upstream air heater in vol.-%, wet)

BLEND	BOOP	Measurements			
PRB0	10	O_2	2.3	3.1	-
		Burnout	99.45	99.48	-
PRB25		O_2	2.5	3.5	4.2
		Burnout	99.53	99.66	99.60
PRB40		O_2	2.4	3.5	4.3
		Burnout	99.51	99.66	99.70

B.5 RESULTS AND BOILER SETTINGS OPTIMISED CASE (MAASVLAKTE)

Table B.19 NO_x emissions and boiler settings for Maasvlakte (optimised case)

	NO_x	O_2 upstream air heater	Burner tilt 1)	OFA tilt 1)	NR41S004 2)	NR51S005 2)	windbox-to-furnace pressure differential
	mg/m_0^3 @ 6% O_2, dry	vol.-%, wet	degree	degree	%	%	mbar
MV1	418	3.8	0	+13	25	100	14
MV2	447	3.4	+2	+13	28	37	15
MV3	424	3.6	-5	+14	29	29	16
MV4	347	3.9	0	+9	28	28	16
MV5	495	3.8	-1	+10	35	35	14
MV6	407	3.1	+2	+16	36	36	13
MV7	441	3.7	-1	+13	30	31	15
MV8	418	4.2	+3	+14	38	44	13
MV9	449	4.2	+12	+18	10	100	14
MV10	417	2.2	+6	+19	100	35	12
MV11	492	2.3	+9	+18	28	100	12
MV12	476	1.9	-4	+9	22	100	12

1) with respect to the horizontal. The average burner and OFA tilt is given here. In a number of cases tilts were not the same for all corners.

2) more details on the position of the secondary air ports in the burner box is given in chapter 5.

Appendix C ERROR ANALYSIS

C.1 GENERAL

Errors in the determination and subsequent calculation of flue gas concentrations are introduced in many ways. Some of these errors are systematic and others random. Systematic errors in the measurements of flue gas components are introduced by malfunction of emission monitoring equipment, stratification of flue gases in flue gas ducts, etc. Since observations are always subject to random fluctuations, random errors are unavoidable. This section presents a general error analysis in the measurement of flue gases components in the exhaust gases of power plants.

Two principles exist for the determination of gaseous species in flue gases, i.e. in-situ and extractive measurements. Several stages, all of which may introduce errors, can be distinguished in extractive measurements (Witkamp, 1991):

- sampling. The sample taken from the flue gases has to be representative for the average composition of the flue gases.
- transport of the sample to the monitor. Only quantifiable changes in composition are allowed to occur.
- analysis of the sample. There should be an unambiguous correlation between the concentration of the measured species and the signal of the monitor.
- measurement of additional data. In many occasions the concentration given in ppm has to be converted into another standardised form (e.g. normalised to 6% O_2, corrected for moisture).
- calibration. A regular calibration of the analyser is required to ensure the quality of the measurement.

With in-situ measurements there is no transport of the sample.

In order to obtain a representative sample, the sampling location has to be chosen carefully, since stratification of the flue gases may occur. Especially, single point measurements may therefore lead to erroneous results. A multiple-point measurement is often more appropriate. For example, in the air heater air leaks from the air side to the flue gas side which will result in an oxygen profile in the flue gases. Because of the differences in viscosity of air and flue gases the flows are not mixed homogeneously and stratification appears. Downstream the air heater a multiple-point measurement is more suited than a single-point measurement.

For the analysis of the data from the full-scale experiments a number of flue gas components was used which were measured on different locations in the flue gas flow (see the simplified flow diagrams in chapter 6). The oxygen concentration in the flue gases measured upstream the air heater was used for the control of the excess air ratio and was used to interpolate the NO_x emissions to a 'fixed' oxygen concentration. The O_2 concentrations measured downstream the flue gas desulphurisation units were used to normalise the NO_x emissions measured downstream the FGD. The NO_x measurement downstream FGD was used, since the FGD acts as a mixer by which the flue gases are homogenised. Furthermore, monitors for NO_x measurements in SO_2 rich flue gases (upstream FGD) are sometimes biased by high SO_2 concentrations.

The effect of potential errors in the measurement of flue gas components is discussed on basis of an example that is generally valid for the full-scale measurements. The total error (empirical variation coefficient) is calculated as the sum of the individual contributions according to

$$s_{tot} = 2 \cdot \sigma = \sqrt{s_1^2 + s_2^2 + s_3^2 + \ldots} \tag{C.1}$$

Table C.1 lists the potential errors in the oxygen measurement upstream air heater, the oxygen measurement downstream FGD and the NO_x measurement downstream FGD.

Oxygen measurement upstream air heater (in-situ; single point measurement)

The oxygen measurement upstream air heater may suffer from stratification resulting in a high potential error of 25% in case of a single point measurement. Stratification is a result of the injection of overfire air and of fluctuations in coal and air distribution. Measurement errors due to stratification in the flue gases caused by the overfire air injection are systematic errors, since the experiments at each plant were performed at the same load and with the same boiler settings (OFA ratio). Stratification by an unbalanced coal and air distribution is considered as random errors, since this may vary with each experiment. This random error is estimated at 10%. The error introduced by the monitor depends on the accuracy of the monitoring equipment and is estimated at 3%. Before each experiment the monitoring equipment was calibrated carefully by the people of the power plant. The error introduced by calibration is estimated at 1.5%. The error introduced by other components originates from the conversion from wet to dry conditions in case the oxygen concentration is measured as wet. The total error is calculated using equation C.1.

Oxygen measurement downstream FGD (in-situ; single point measurement)

The oxygen measurement downstream the FGD is less hindered by stratification because the flue gases are intensively mixed in the FGD. The error is estimated at 7%. The errors introduced by the other components are similar to the errors of the oxygen measurement upstream air heater. The oxygen measurement downstream the FGD is used for the conversion of the actual NO_x emission (ppm) to the normalised conditions (6% O_2, dry). The error introduced by normalising the NO_x concentration by the error in the oxygen concentration is therefore smaller (3.3%, assuming an average O_2 concentration of 6% downstream FGD).

NO_x measurement downstream FGD (in situ; single point measurement)

As is the case for the oxygen measurement, downstream the FGD there is much less stratification which may affect the accuracy of the NO_x measurement. The errors introduced by the other components are similar to the errors of the oxygen measurement.

Table C.1 Potential errors in flue gas concentration measurements

	O_2 upstream air heater in-situ	O_2 downstream FGD in-situ	NO_x downstream FGD in-situ
Sampling	10%	7%	7%
Transport and conditioning	-	-	
Analysis	3%	3%	3%
Calibration	1.5%	1.5%	1.5%
Disturbing components	-	-	-
Calculation	2%	2%	3.9% (3.3% + 2%)
Sum	10.7%	8.0% (3.3% on NO_x)	8.7%

All observations (NO_x and O_2) used throughout this thesis are average values based on at least 100 individual (dependent) observations covering a sampling period of approximately one and a half-hour. Therefore, the errors caused by time-dependent variations of the process variables are small and considered negligible compared to the errors in the measurement of the flue gas components.

Figure C.1 shows the NO_x emissions of blend MV7 as function of the oxygen concentration in the flue gases (measured upstream air heater), including the error bars. The horizontal error bar in the oxygen concentration is calculated as 10.7% (see **table C.1**) of the nominal oxygen concentration of 4% (is 0.428% absolute). The vertical error bar in the NO_x concentration is calculated as 8.7% (see **table C.1**) of the actual value.

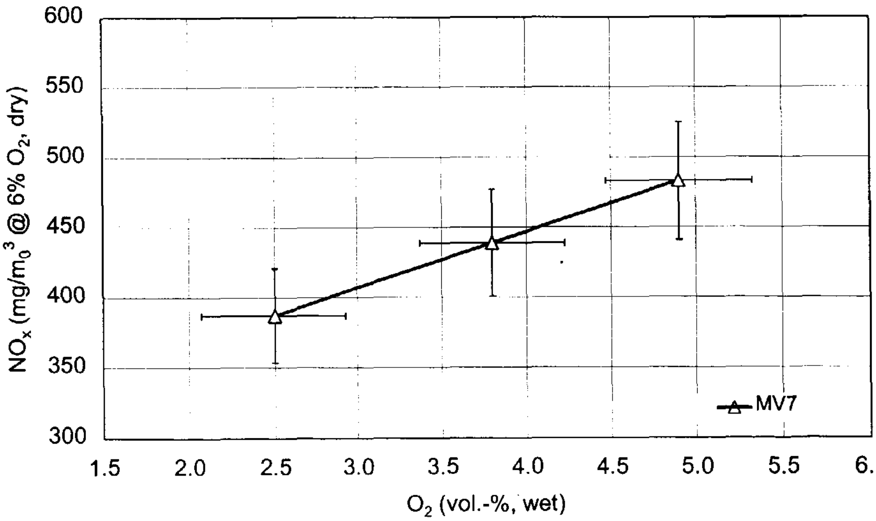

Figure C.1 NO_x emissions of blend MV7 as function of the oxygen concentration (measured upstream air heater)

C.2 REGRESSION MODELS FOR MAASVLAKTE AND AMER POWER PLANT

By means of linear regression analysis the best fit of the NO_x-O_2 relation was used to interpolate the NO_x emission at a 'fixed' excess air ratio (3% O_2). The calculated NO_x emission at 3% O_2 is for blend MV7 407 mg/m_0^3 (normalised to 6% O_2, dry). The error in the oxygen concentration (upstream air heater) contributes to the error in the (interpolated) NO_x concentration. The error depends on the slope of the regression curve. Every 1% increase in O_2 concentration (upstream air heater) results in an increase of the NO_x emission of 40 mg/m_0^3. The error in oxygen concentration was calculated as 0.428% (absolute). This results in an average NO_x emission variation of 17.1 mg/m_0^3. The estimated error in the NO_x emissions because of the error in the oxygen concentration is then 4.2%. Consequently, the total error in the NO_x concentration is calculated as:

$$s_{NO_{x,\text{inerpolation}}} = \sqrt{s_{O_2}^{\ 2} + s_{NO_x}^{\ 2}} = \sqrt{4.2^2 + 8.7^2} = 9.7\% \tag{C.2}$$

The calculated value overestimates the error to some extent, since the NO_x concentration is measured (independent observations) at three oxygen concentrations (upstream air heater), which reduces the error in the NO_x concentration. However, since not all coals were measured at three oxygen concentrations this worst case is adopted for all other values.

It is thus assumed that this error also holds for all other NO_x values used in the regression analysis. **Figure C.2** shows the regression model for the Maasvlakte experiments where the NO_x emissions were correlated with the volatile matter content in the coal. The error bars on all NO_x values are shown. The errors in the determination of the volatile matter are considered negligible.

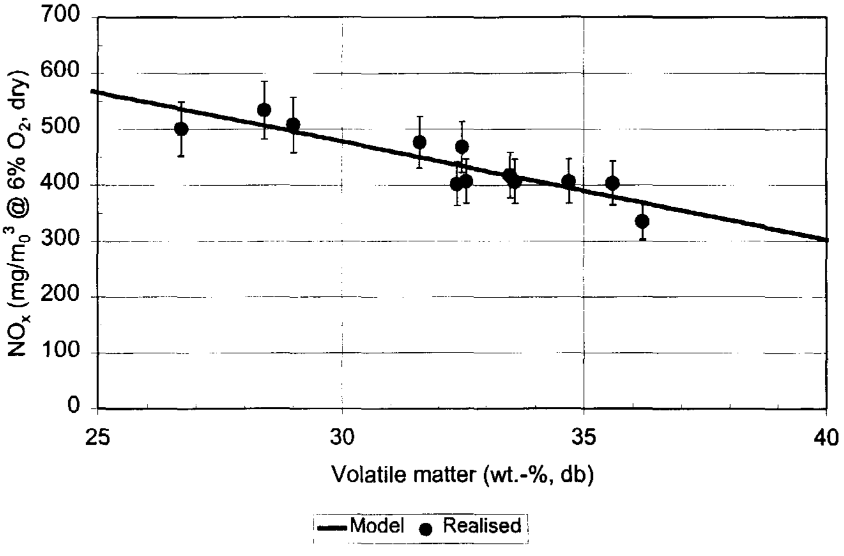

Figure C.2 Error bars on the normalised NO_x concentrations of Maasvlakte power plant displayed against the volatile matter (example taken from chapter 7)

The errors in the use of regression analysis account for measurement errors and the effects of other variables (Montgomery et al., 1982). The error mean square (MS_E) is the estimated average variance (equation A.14 in appendix A). The error mean squares for the regression models developed in chapter 7 are listed in **table C.2** and compared to the variance calculated with equations C.1 and C.2 on basis of an average NO_x emission for each model.

Table C.2 Comparison of the measurement errors and the errors in the use of regression analysis

Model	Equation	average NO_x (mg/m_0^3)	MS_E	σ^2
Maasvlakte (O_2 = 3%)	$NO_x = 1006 - 17.6\ VM_{db}$	439	772	453
Amer (O_2 = 3%)				
BOOP = 10	$NO_x = 704 - 11.8VM_{db}$	313	570	230
BOOP = 40	$NO_x = 737 - 9.7VM_{db}$	417	858	409
Amer (O_2 = 4.9%)				
BOOP = 10	$NO_x = 1033 - 15.0VM_{db}$	535	2667	637
BOOP = 40	$NO_x = 1159 - 15.4VM_{db}$	648	571	988

The error mean square (MS_E) is for all models (except for one) larger than the variance due to errors in the flue gas concentration measurements (σ^2). This suggests that the errors in the regression analysis models account for the measurement errors. Consequently, the confidence and prediction intervals include the measurement errors, except for the Amer model (O_2 = 4.9%, BOOP = 40). The confidence and prediction intervals for this model should be somewhat wider.

C.3 COAL BLENDING EXPERIMENTS

With respect to the blend trials at Maasvlakte power plant described in chapter 10 the measurement errors are smaller since the flue gas concentrations were measured with a multiple-point sampling grid. As a result the sampling is more accurate, estimated at 3% instead of 7% (see **table C.1**). Secondly, the analysis accuracy improves from 3 to 2%. The potential measurement error in the oxygen concentration downstream the FGD is reduced to 4.4% instead of 8.0%. Since the oxygen concentration is used to normalise the NO_x measurement to 6% O_2, the error introduced is reduced to 1.8% instead of 3.3%. The multiple-point sampling grid also reduces the error in the NOx concentration measurement. The sampling and analysis error is reduced to 3% and 2%, respectively. The total error in the NO_x concentration is than reduced to 4.7%. For example, the error bars on the NO_x measurement are displayed in **figure C.3**.

The flue gas concentrations with the blending experiments performed at Amer and Hemweg power plant were measured with the equipment of the plant itself. These measurement errors are listed in **table C.1**. **Figure C.4** shows an example for the Amer blend trials and **figure C.5** for the Hemweg blend trials.

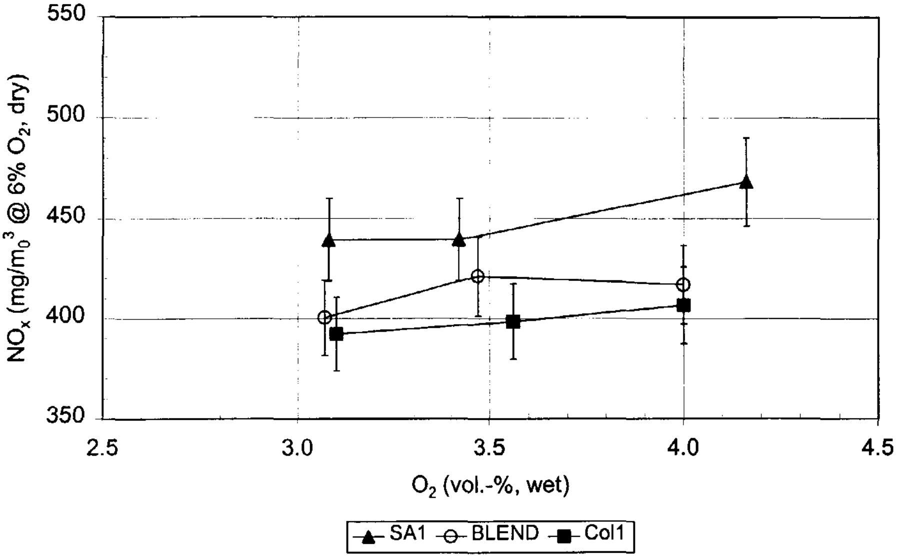

Figure C.3 Error bars on the NO$_x$ emissions from the Maasvlakte blend trials (chapter 10)

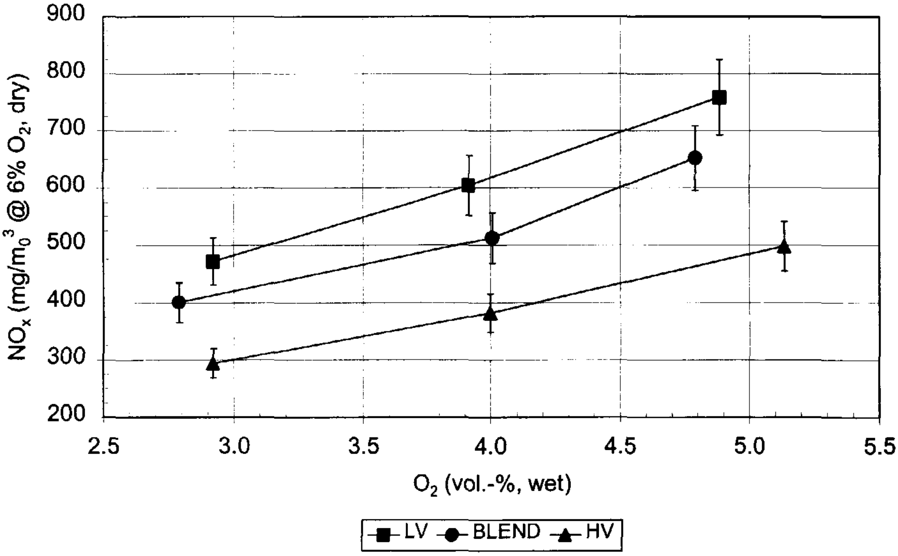

Figure C.4 Error bars on the NO$_x$ emissions from the Amer blend trials (chapter 10)

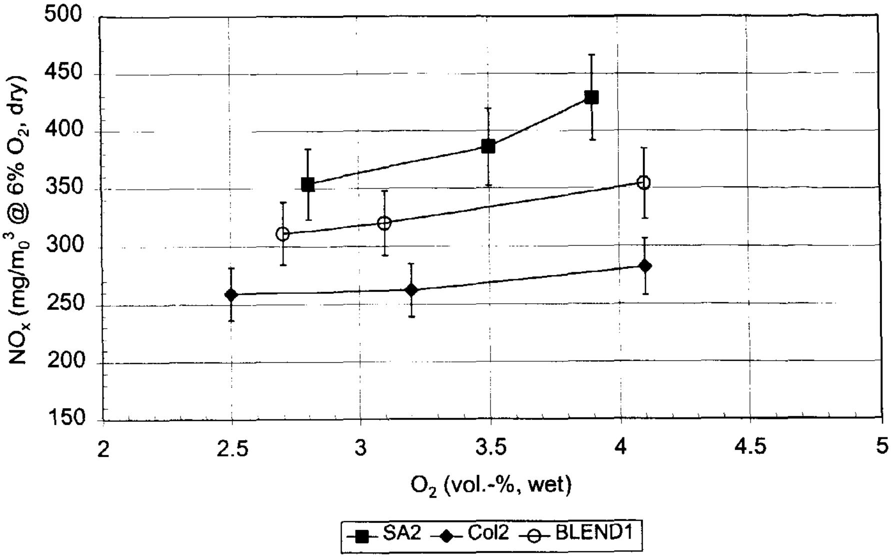

Figure C.5 Error bars on the NO_x emissions from the Hemweg blend trials (chapter 10)

Appendix D RESULTS BLEND EXPERIMENTS

Table D.1 Flue gas monitors used for the blend trials at Maasvlakte power plant

	Monitor	Range	Lower detection limit	Accuracy
O_2 (dry)	Maihak OXOR 6N	0-10%	0.05%	< 2%
CO_2 (dry)	Maihak UNOR 6N	0-20%	0.4%	< 2.5%
CO	Maihak UNOR 6N	0-200 ppm	2 ppm	< 2%
NO/NO_x	TECAN CLD700 EL ht	0-1000 ppm	1 ppm	< 2%

Before and after each measurement (i.e. each day) the monitors were calibrated using calibration gases. If necessary the measurements were corrected.

Table D.2 Coal analysis of the Amer blend trials

Series		1	2	Calculated values based on analyses of series 1 and 2		
		LV	HV	40/60	50/50	60/40
LHV	MJ/kg (ar)	24.92	25.31	25.15	25.12	25.08
Moisture	wt.-% (ar)	7.93	11.33	10.97	10.63	10.29
Ash	wt.-% (ar)	14.85	8.43	11.00	11.64	12.28
VM	wt.-% (ar)	24.05	34.90	30.56	210.48	28.39
FC	wt.-% (ar)	53.17	45.33	48.47	410.25	50.03
C	wt.-% (daf)	83.70	81.68	82.47	82.67	82.87
H	wt.-% (daf)	4.55	5.48	5.12	5.02	4.93
N	wt.-% (daf)	2.09	1.55	1.76	1.81	1.87
S	wt.-% (daf)	0.76	0.57	0.64	0.66	0.68
O	wt.-% (daf)	8.92	10.72	10.01	10.83	10.65

Series		Series 4			Series 5			Series 6			Series 7		
		LV	HV	50/50	LV	HV	50/50	LV	HV	40/60	LV	HV	60/40
LHV	MJ/kg (ar)	24.50	24.52	24.51	24.57	23.77	24.17	25.28	23.69	24.33	25.75	23.68	24.92
Moisture	wt.-% (ar)	7.80	14.63	11.21	8.85	15.40	12.13	7.10	15.50	12.14	7.20	14.85	10.26
Ash	wt.-% (ar)	15.88	8.13	12.00	14.85	10.65	12.25	14.50	10.20	11.32	13.00	10.85	11.74
VM	wt.-% (ar)	24.00	32.40	28.20	24.10	31.25	27.68	23.40	31.90	28.50	24.20	31.70	27.20
FC	wt.-% (ar)	52.32	44.85	48.59	52.20	43.70	47.95	55.00	43.40	48.04	55.60	43.60	50.80
C	wt.-% (daf)	84.36	82.20	83.27	84.63	81.58	83.12	85.49	81.37	83.06	84.84	82.29	83.86
H	wt.-% (daf)	4.53	5.45	4.99	4.57	5.49	5.03	4.58	5.49	5.12	4.52	5.49	4.89
N	wt.-% (daf)	2.13	1.68	1.90	2.22	1.64	1.93	1.96	1.58	1.74	1.96	1.62	1.83
S	wt.-% (daf)	0.90	0.76	0.83	0.89	0.87	0.88	0.86	0.70	0.77	0.55	0.69	0.60
O	wt.-% (daf)	8.08	10.91	10.00	7.69	10.42	10.04	7.11	10.86	10.32	8.13	10.91	8.82

Table D.3 Measured O_2 (upstream air heater in vol.-% wet), NO_x (mg/m_0^3 6% O_2, dry; measured downstream the FGD) and burnout values for the Amer experiments

Series	1			2 (LV)			3 (HV)			4 (BLEND)		
	O_2	NO_x	Bu	O_2	NO_x	Bu	O_2	NO_x	Bu	O_2	NO_x	Bu
run												
A	3.9	394	99.86	3.9	604	99.40	4.0	382	99.86	4.0	513	99.63
B	2.9	347	99.83	2.9	472	99.25	2.9	294	99.84	2.8	400	99.72
C	4.9	485	99.82	4.9	759	99.17	5.1	498	99.88	4.8	653	99.58
D	3.9	394	99.86	3.8	597	99.32	4.0	383	99.90	3.9	502	99.63
E	3.7	449	99.87	3.8	691	99.40	4.0	449	99.91	3.9	596	99.67
F	3.8	497	99.87	3.9	773	99.44				3.9	667	99.70
G	3.8	557	99.90	3.9	857	99.50	4.0	564	99.91	3.9	758	99.77
H	3.7	373	99.86	3.9	612	99.45	4.0	393	99.84	3.9	521	99.61
I	3.8	381	99.83	4.0	625	99.47	3.9	393	99.88	4.0	507	99.70
J	2.9	321	99.74	3.0	510	99.35	3.3	342	99.85	2.9	419	99.71

Series	5			6			7		
·	O_2	NO_x	Bu	O_2	NO_x	Bu	O_2	NO_x	Bu
run									
A	3.9	461	99.68	3.9	433	99.77	4.0	505	99.62
B	3.0	387	99.72	3.1	458	99.77	3.2	425	99.54
C	4.9	602	99.78	5.0	598	99.69	4.9	654	99.53
D	3.9	461	99.68	3.9	433	99.77	3.9	489	99.65
E	3.9	535	99.73	3.8	509	99.84	3.8	584	99.65
F	4.0	612	99.74	3.8	619	99.85	3.9	643	99.69
G				3.9	790	99.75	3.9	709	99.74

Table D.4 Particle size distribution of the Amer blend experiments

Series		pulv. 10	pulv. 20	pulv. 30	pulv. 50	pulv. 60	Average		
Series 2		LV	LV	LV	LV	LV	LV		
		pulv. 10	pulv. 20	pulv. 30	pulv. 50	pulv. 60	Average		
	D10	7	6	6	6	6	6		
	D50	41	31	48	37	36	39		
	D90	133	101	211	128	119	138		
	< 150	93.0	96.5	80.9	93.4	94.2	91.6		
Series 3		HV	HV	HV	HV	HV	HV		
		pulv. 10	pulv. 20	pulv. 30	pulv. 50	pulv. 60	Average		
	D10	7	7	7	7	7	7		
	D50	42	40	41	41	40	41		
	D90	112	112	109	115	114	112		
	< 150	96.1	96.1	96.6	95.9	96.2	96.2		
Series 4		BLEND	BLEND	BLEND	BLEND	BLEND	BLEND		
		pulv. 10	pulv. 20	pulv. 30	pulv. 50	pulv. 60	Average		
	D10	7	7	6	7	7	7		
	D50	39	37	35	35	36	36		
	D90	112	109	113	111	109	111		
	< 150	95.4	95.6	94.8	95.1	95.4	95.2		
Series 5		HV	BLEND	BLEND	BLEND	LV	HV	BLEND	LV
		pulv. 10	pulv. 20	pulv. 30	pulv. 50	pulv. 60	Average	Average	Average
	D10	8	7	7	7	7	8	7	7
	D50	43	40	37	39	37	43	38	37
	D90	123	117	106	116	112	123	113	112
	< 150	94.2	94.9	96.2	94.8	95.5	94.2	95.3	95.5
Series 6		HV	HV	HV	LV	LV	HV	LV	
		pulv. 10	pulv. 20	pulv. 30	pulv. 50	pulv. 60	Average	Average	
	D10	9	8	8	7	7	8	7	
	D50	47	42	49	38	40	46	39	
	D90	121	121	146	103	108	129	106	
	< 150	94.8	94.4	90.6	96.7	96.2	93.3	96.5	
Series 7		HV	HV	LV	LV	LV	HV	LV	
		pulv. 10	pulv. 20	pulv. 30	pulv. 50	pulv. 60	Average	Average	
	D10	8	7	7	7	7	8	7	
	D50	42	42	59	46	41	42	49	
	D90	116	125	210	138	122	120	157	
	< 150	95.2	93.6	710.3	91.6	94.1	94.4	88.4	

Table D.5 Comparison of the calculated and measured NO_x emissions of blends (Amer trials)

	Blend ratio (wt./wt.)		V_{FG} (m_0^3, dry) per kg raw coal		O_2 (vol.-%, wet)	NO_x (mg/m_0^3 @ 6% O_2)				% difference
	LV	HV	LV	HV		LV	HV	Calc.	Meas.	
Series 4										
A	50	50	6.405	6.425	3.9	604	373	488	500	2.4
B	50	50	6.405	6.425	2.9	472	294	383	413	7.9
C	50	50	6.405	6.425	4.9	759	479	619	666	7.6
D	50	50	6.405	6.425	3.9	611	374	492	502	2.0
E	50	50	6.405	6.425	3.9	705	440	572	596	4.1
F	50	50	6.405	6.425			n.d.			
G	50	50	6.405	6.425	3.9	857	555	706	758	7.4
H	50	50	6.405	6.425	3.9	612	384	498	521	4.7
I	50	50	6.405	6.425	3.9	611	393	502	495	-1.4
J	50	50	6.405	6.425	3.1	524	324	424	444	4.8
Series 5										
A	50	50	6.439	6.191	3.9	604	373	491	461	-6.1
B	50	50	6.439	6.191	2.9	472	294	385	376	-2.3
C	50	50	6.439	6.191	4.9	759	479	622	602	-3.2
D	50	50	6.439	6.191					see A	run
E	50	50	6.439	6.191	3.9	705	440	575	535	-7.0
F	50	50	6.439	6.191			n.d.			
G	50	50	6.439	6.191					n.d.	
Series 6										
A	40	60	6.680	6.191	3.9	604	373	470	433	-7.8
B	40	60	6.680	6.191					u.r.	
C	40	60	6.680	6.191					u.r.	
D	40	60	6.680	6.191					u.r.	
E	40	60	6.680	6.191	3.9	705	440	551	520	-5.6
F	40	60	6.680	6.191			n.d.		u.r.	
G	40	60	6.680	6.191					u.r.	
Series 7										
A	60	40	6.713	6.272	3.9	604	373	515	491	-4.7
B	60	40	6.713	6.272	2.9	472	294	404	385	-4.6
C	60	40	6.713	6.272	4.9	759	479	652	654	0.4
D	60	40	6.713	6.272	3.9	611	374	520	489	-6.0
E	60	40	6.713	6.272	3.9	705	440	603	598	-0.9
F	60	40	6.713	6.272			n.d.			
G	60	40	6.713	6.272	3.9	857	555	741	709	-4.3

n.d.	not determined
u.r.	unreliable result (other coal in the bunkers than planned)

SUMMARY

Impact of coal quality on NO_x emissions from power plants

A major part of the Dutch electricity supply is accomplished by means of pulverised coal-fired power plants. Approximately 9 million tonnes of coal are burned in seven coal-fired units annually, which contributes towards 40% of the Dutch electricity supply. Since no commercially recoverable quantities of coal are found in the Netherlands, coal is imported from countries all over the world. A characteristic feature of coal is its heterogeneous nature due to the geological background and characteristics of the parent material that is expressed in the large variety of coal types and qualities.

Characterisation of coal is amongst others based on the proximate and ultimate analysis. The proximate analysis yields the physical properties of coal, such as the volatile matter, ash and moisture content. The ultimate analysis results in an elementary breakdown of coal in the components carbon, hydrogen, nitrogen, sulphur and oxygen. On the basis of these and other data, such as the ash composition, the heating value and the grindability, it is assessed if a coal type can be burned satisfactorily. The generation cost and the availability of coal-fired plants are major concerns in this respect. The generation cost is influenced by the fuel cost on one hand and on the other hand by the operating and maintenance cost. The coal purchase policy aims at minimising the generation cost and in order to increase the flexibility coals are often burned in blends. Out-of-specification coals can then be burned, which lowers the fuel cost.

In the overall assessment of a particular coal it is also assessed if the power plant can be operated without exceeding the emissions limits imposed by the authorities. A concern in this respect is the emission of nitrogen oxides (NO_x emissions). The NO_x emissions are affected by many factors, such as coal quality, the operation and the design of the power plant. NO_x emissions can be reduced by primary measures (combustion modifications) and by secondary measures by which the nitrogen oxides are removed from the flue gases. At present, the main methodology applied in the Netherlands aims at the reduction of the formation of nitrogen oxides during the combustion process, mainly by a controlled and staged supply of combustion air. Apart from the combustion equipment and its features, NO_x emissions are controlled by the quality of coal and the operating conditions. Fine-tuning of the boiler may result in lower NO_x emissions, however, effects on, for instance, the heat rate and the unburned carbon content in the fly ash have to be considered simultaneously.

The study described in this thesis focussed therefore on the impact of coal quality on NO_x emissions from pulverised coal-fired power plants, including the effect of blending various types of coal. It was investigated which coal and operating parameters play a major role in the formation of NO_x emissions.

The investigation was performed at three full-scale coal-fired power plants; Maasvlakte units 1 and 2, Amer unit 9 and Hemweg unit 8. Performance data of the units obtained under controlled conditions were gathered and related to the quality of coal, the boiler design and the operating parameters. The impact of blending was also investigated by full-scale trials at these plants.

NO_x emissions from the tangential-fired units Maasvlakte and Amer equipped with close coupled overfire air ports observed a correlation with the proximate volatile matter, despite the fact that the volatile matter is determined under conditions not comparable to the conditions prevailing in actual flames. On the basis of the results obtained, prediction formulas were developed that can be used to assess the NO_x emissions from both units with a certain accuracy and for specific boiler settings.

The NO_x emissions from the opposed wall-fired unit Hemweg 8 equipped with separated overfire air ports observed a much weaker tendency with the proximate volatile matter or other standard coal analyses. It was shown, however, that the NO_x emissions were influenced by the nitrogen content in the char. It was observed that the conditions during treatment of the coals were important on the quantity of char nitrogen. In addition, it was observed that the char nitrogen content could not be predicted from the standard coal analyses.

On the basis of the results obtained from the various investigations it was concluded that the residence time in the substoichiometric combustion zone as well as the stoichiometry in this zone affect NO_x emissions to a large extent. When the overfire air ports are directly located above the burners, the residence time in the primary combustion zone of part of the pulverised coal is short, especially with the upper burner levels in operation, resulting in a substantial increase of the NO_x emissions.

From the coal blending experiments it was concluded that the NO_x emissions of the blend equal the weighted average of the NO_x emissions of the parent coals. It was suggested that deviations from this rule are possible when widely diverging coals with respect to rank are blended or when interaction during grinding occurs that results in a segregation of the coals over the different size fractions.

This research contributed to a better understanding of the impact of coal quality on NO_x emissions from pulverised coal-fired units and resulted in a number of prediction formulas that are helpful to assess the NO_x emissions before the coals are actually burned. It was recommended that the standard coal analyses are supported by a representative determination of the char nitrogen content, since this parameter controls the NO_x emissions from modern low NO_x units, whereas the proximate volatile matter content is only an indirect parameter.

C.M. Rozendaal

SAMENVATTING

De invloed van kolenkwaliteit op de NO_x-emissie van kolengestookte centrales

Een belangrijk deel van de Nederlandse elektriciteitsopwekking wordt bewerkstelligd met behulp van poederkoolgestookte centrales. Jaarlijks wordt in Nederland ongeveer 9 miljoen ton kolen verstookt in 7 poederkoolgestookte eenheden en daarmee wordt ongeveer 40% van de elektriciteitsbehoefte gedekt. Aangezien Nederland geen eigen economisch winbare voorraden bezit, wordt steenkool geïmporteerd uit andere landen verspreid over de wereld. Kenmerkend voor steenkool is de heterogene samenstelling, onder meer bepaald door de ouderdom en de samenstelling van het uitgangsmateriaal, hetgeen tot uiting komt in de grote variatie in de kwaliteit van steenkool.

Steenkool wordt onder meer gekarakteriseerd door de proximate en ultimate analyse. De eerste zegt iets over de fysische eigenschappen van kolen, zoals het gehalte aan vluchtige bestanddelen, vocht en as. De ultimate analyse levert de chemische samenstelling van de kolen en geeft de massaverhoudingen aan van de elementen koolstof, waterstof, stikstof, zwavel en zuurstof. Op basis van deze en andere gegevens, zoals de assamenstelling, de stookwaarde en de maalbaarheid, wordt bepaald of een kolensoort geschikt is om ingezet te worden in een kolengestookte centrale. De opwekkingskosten en de beschikbaarheid van de eenheid zijn hierbij uiteraard van groot belang. De opwekkingskosten worden enerzijds bepaald door de brandstofkosten en anderzijds door de bedrijfsvoerings- en onderhoudskosten. Het koleninkoopbeleid is erop gericht om de opwekkingskosten te minimaliseren. Om de flexibiliteit ten aanzien van de koleninkoop te vergroten worden in Nederland de kolen vaak gemengd verstookt om ook met afwijkende kolenkwaliteiten binnen de gewenste kolenbandbreedte van de eenheid te kunnen opereren.

In de afweging of een bepaalde kolensoort, al dan niet gemengd, kan worden ingezet, wordt beoordeeld of de uitstoot van stikstofoxides (NO_x-emissie) aan de eisen zal voldoen. De NO_x-emissie wordt bepaald door een groot aantal factoren, zoals de kwaliteit van de brandstof, de bedrijfsvoering en het ontwerp van de eenheid. De NO_x-emissie kan worden gereduceerd door verbrandingstechnische maatregelen en door secundaire maatregelen, waarmee de stikstofoxides (deels) worden verwijderd uit de rookgassenstroom. De meest toegepaste benadering is momenteel om door middel van verbrandingstechnische maatregelen de vorming van stikstofoxides tijdens het verbrandingsproces op een zodanige manier te beïnvloeden dat de uitstoot wordt geminimaliseerd. Veel van de verbrandingstechnische maatregelen zijn erop gericht om de brandstof en de verbrandingslucht gefaseerd en gecontroleerd toe te voeren. Naast deze installatie-afhankelijke factoren wordt de uitstoot van stikstofoxides bepaald door de bedrijfsvoering en de kwaliteit van de kolen. Door middel van het optimaliseren van de ketelinstellingen kan de NO_x-emissie worden beperkt, echter hierbij moeten ook andere aspecten, als het rendement en het percentage onverbrand in de vliegas in ogenschouw worden genomen.

Deze studie is uitgevoerd om de invloed van de kolenkwaliteit op de NO_x-emissie, inclusief het effect van het mengen van verschillende kolensoorten, te kwantificeren. Hierbij is onderzocht welke kolenparameters en welke bedrijfsvoeringsparameters wezenlijk van invloed zijn.

Dit onderzoek is uitgevoerd door bij grootschalige kolengestookte installaties, te weten Maasvlakte eenheid 1 en 2, Amer eenheid 9 en Hemweg eenheid 8, gegevens te verzamelen onder geconditioneerde omstandigheden en deze te relateren aan de kwaliteit van de kolen, het ketelontwerp en de ketelinstellingen. Het effect van het mengen van verschillende kolen is eveneens door middel van grootschalige stookproeven onderzocht.

De NO_x-emissie van de tangentiaal gestookte eenheden Maasvlakte en Amer, uitgerust met bovenluchtpoorten voor het gefaseerd toevoeren van de verbrandingslucht, bleek goed te correleren met de vluchtige bestanddelen van de kolen, ondanks het feit dat de vluchtige bestanddelen bepaald worden onder condities die aanmerkelijk milder zijn dan de condities in de vuurhaard. Op basis van de verkregen resultaten zijn voorspelformules ontwikkeld, waarmee met een zekere nauwkeurigheid en voor bepaalde ketelinstellingen de NO_x-emissie kan worden geschat.

De NO_x-emissie van de boxerketel (branders in de voor- en achterwand van de ketel) van Hemweg 8, uitgerust met gescheiden bovenluchtpoorten, bleek niet goed te correleren met de standaard kolenanalyses, maar bleek te worden bepaald door het stikstofgehalte in de char (product dat overblijft nadat de vluchtige bestanddelen zijn ontweken uit de kolendeeltjes). De bepaling van het stikstofgehalte in de char is echter geen standaardanalyse, en het is gebleken dat de condities waarbij deze wordt bepaald van groot belang zijn om realistische waarden te verkrijgen. Bovendien is uit het onderzoek gebleken dat het stikstofgehalte in de char niet of nauwelijks uit de standaardanalyses van de kolen kan worden voorspeld.

De vergelijking van de resultaten van de diverse onderzoeken heeft opgeleverd dat de verblijftijd van de kolendeeltjes in een onderstoichiometrische zone en de mate van onderstoichiometrie van wezenlijk belang zijn voor de te bereiken NO_x-emissie. In het geval van bovenluchtpoorten die direct boven de branders zijn geplaatst is, met name als de bovenste branders in bedrijf zijn, de verblijftijd in deze zone gering en neemt de NO_x-emissie toe.

Het onderzoek naar de invloed van het mengen van kolen op de NO_x-emissie heeft uitgewezen dat de NO_x-emissie van het mengsel overeenkomt met het gewogen gemiddelde van de NO_x-emissies van de afzonderlijke kolen. Een afwijking van deze regel is wellicht mogelijk als kolen worden gemengd die sterk verschillen in verbrandingsgedrag (bijvoorbeeld mengsels van zeer hoog- en zeer laagvluchtige kolen) of als er segregatie van de kolensoorten optreedt tijdens het maalproces op een zodanige wijze dat de grove of de fijne fractie van de poederkool wordt overheerst door een bepaalde kolensoort.

Dit onderzoek heeft een bijdrage geleverd aan een beter begrip van het effect van de kolenkwaliteit op de NO_x-emissie en heeft een aantal voorspelformules opgeleverd waarmee vooraf de NO_x-emissie op basis van de standaard kolenanalyses kan worden geschat. Het verdient echter aanbeveling om de standaard kolenanalyses uit te breiden met een representatieve bepaling van het stikstofgehalte in de char, aangezien deze een meer direct verband heeft met de NO_x-emissie dan de vluchtige bestanddelen bepaald met de proximate analyse.

C.M. Rozendaal

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In de eerste fase van het onderzoek heb ik een belangrijk deel van de tijd doorgebracht bij Centrale Maasvlakte waar met name Jaap Arends mij de eerste beginselen van het kolenstoken heeft bijgebracht. Tot op de dag van vandaag heb ik van deze privé kolencursus nog enorm veel plezier. Jaap, tegenwoordig genietend van zijn pensioen, verstond het vak van kolenstoken als geen ander en wist (bijna) altijd haarfijn te voorspellen hoe het verbrandingsproces zou reageren op bepaalde ingrepen. Zat het proces er dan toch een keer naast, dan werd daar altijd een goede verklaring voor gevonden. De uitgebreide meetsessies, die toen en ook later onder begeleiding van Joop Pegels zijn uitgevoerd, waren slechts mogelijk door de inzet van nagenoeg iedereen op de centrale, van de kolenlogistiek en de wacht tot het laboratorium en de meet- en regeltechnici. De discussies met de operators over het werk maar ook over hele andere zaken werkten vaak zeer verhelderend. Bert van Vliet zorgde in de tussentijd voor de nodige inspiraties en aanmoedigingen. Ik wil niemand tekort doen, vandaar: Maasvlakte bedankt!

In een latere fase is het onderzoek uitgebreid met experimenten bij de Amercentrale en centrale Hemweg. Ook hier geldt dat de operators en alle andere betrokken personen een belangrijke rol hebben gespeeld bij de totstandkoming van de metingen. Speciale dank gaat uit naar Ad Korthout, Peter Voet en Maurice Vissers van EPZ voor hun inzet om de experimenten op de Amercentrale te doen slagen. Odilia Rens, André van Beelen en Bert de Boer van UNA worden bedankt voor hun bijdrage aan het slagen van de metingen bij de Hemwegcentrale. De discussies met Odilia, die op haar geheel eigen wijze de inhoud van een rapport te lijf ging, zijn roemrucht en hebben zeker bijgedragen aan het uiteindelijke niveau. De medewerkers van GKE, in het bijzonder Jos Moret, wil ik hartelijk bedanken voor de levering van de gewenste kolen, ook al paste dat niet altijd in de planning. In het algemeen wil ik de leden van de begeleidingsgroep van speerpunt 5 en 17, onder leiding van Ad Korthout, bedanken voor de waardevolle discussies en steun bij de totstandkoming van de projecten.

Veel van mijn KEMA-collegae zijn betrokken geweest bij dit proefschrift. De bij KEMA uitgevoerde experimenten met de poederkoolproefketel waren niet mogelijk zonder de inzet van Toon Krebbers, Jan Slotboom, Frans Witjes en Frans Teering. Rolf Benneker heeft een belangrijke bijdrage geleverd aan de valbuisoven- en de poederkoolproefketelexperimenten. Bovendien loste Rolf alle voorkomende problemen met computers, op vaak niet mis te verstane wijze, op, zelfs als hij ze zelf had veroorzaakt. Martin de Jong (spreadsheet engineer), Jaap Bunschoten en John Visser (declaratie-adviseur) ben ik zeer erkentelijk voor hun inzet bij de metingen bij Maasvlakte, Amer en Hemweg. Ton Konings heeft het mogelijk gemaakt dat de noodzakelijke tijd beschikbaar kwam om tot afronding van het proefschrift te komen. Aan de statistische analyse van de meetresultaten heeft Hans Visser een bijdrage geleverd. Ronald Meijer heeft, naast zijn hoedanigheid als klankbord voor alle zinnige en onzinnige vragen van een kamergenoot, een waardevolle bijdrage geleverd aan de evaluatie van de Hemweg metingen. Mieke Sciaroni wil ik bedanken voor de verwerking van niet-leesbare krabbeltjes tot een proefschrift. In het bijzonder wil ik Kees Gast, Joop Witkamp en Alwin Hoogendoorn nog noemen. (Majoor) Kees was gedurende het hele project een belangrijke schakel in het geheel. Gaandeweg raakte Joop meer en meer betrokken bij dit project en zijn hulp bij de interpretatie van de meetresultaten bleek al gauw zeer waardevol. Alwin Hoogendoorn, begonnen als stagiaire (meetslaaf) en ondertussen opgeklommen tot een zeer gewaardeerd collega, heeft mij af en toe over de dode momenten heen geholpen. Samen hebben we belangrijke delen van dit proefschrift onder het genot van een Italiaans wijntje nader onder de loep genomen. KEMA-vrienden, allemaal bedankt!

Vele stagiaires en afstudeerders zijn op een of andere manier betrokken geweest bij dit werk. Alwin Hoogendoorn (zie boven), Edwin Stevenson (valbuisoven en experimenten Hemweg), Rutger Borgmeijer (experimenten Maasvlakte), Roy Sörensen (modellering Maasvlakte), Ivo Krausz (valbuisoven en maalexperimenten), Stephan Wehning (metingen poederkoolproefketel), Ruben Kort (verwerking van Maasvlakte bedrijfsgegevens), Bart Rijpers (valbuisoven en verwerking van Amer metingen) en Bart Doeve (verwerking Maasvlakte gegevens) hebben een belangrijke bijdrage geleverd aan dit gehele project. Helaas (of misschien wel gelukkig) heb ik niet al jullie werk op kunnen nemen.

Professor Klaus Hein en Dick Boersma van de Technische Universiteit Delft worden hartelijk bedankt voor hun begeleiding van het onderzoek vanuit de universiteit en de voortdurende motivatie om het proefschrift te schrijven.

Op een gegeven moment werd het schipperen met de tijd tussen het proefschrift, het werk en het gezin (enigszins vergelijkbaar met de 'helse driehoek' van Maasvlakte). Met name het laatste jaar heeft veel geëist van de flexibiliteit van het gezinsleven. Ik was er wel, maar eigenlijk toch niet (wie is die man die elke zondag achter de computer zit). De steun van Trudy in deze is dan ook zeer belangrijk geweest daar zij het grootste deel van de verzorging en opvoeding van onze kinderen Sanne (2 jaar) en Daan (1 jaar) voor haar rekening heeft genomen en met succes. Ik beloof beterschap en verwacht na een korte cursus huishouden ook daarin weer een rol te kunnen spelen. Sanne en Daan worden op hun beurt bedankt voor de afleiding. Zonder dat ze het wisten zijn ze bovendien een belangrijke stimulans geweest om het proefschrift af te ronden en slaagden ze er regelmatig in mij de betrekkelijkheid van het schrijven van een proefschrift in te laten zien. Mijn ouders wil ik bedanken voor de onvoorwaardelijke steun en stimulans die ik heb ontvangen tijdens de studie en het promotie-onderzoek. Mijn beide zussen Alma en Marja die elk op hun eigen manier mij hebben gestimuleerd om te bereiken wat nu bereikt is. Joop Rozendaal wordt bedankt voor de prachtige omslag, die, voor de niet-deskundigen, een impressie vormt van het vuur in een tangentiaal gestookte ketel.

Ik ben klaar.

CURRICULUM VITAE

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