Delft University of Technology
Department of Aerospace Engineering

Prins Maurits Laboratory TNO
Rijswijk

Report LR - 389
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APPLICATION OF SOLID FUEL COMBUSTION CHAMBERS FOR POWER PLANTS AND COAL GASIFICATION

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Summary

Solid Fuel Combustion Chambers (SFCC) may find various applications: electric power generation, combustion of waste materials, possibly combined with electric power generation, aerospace propulsion units and coal gasification.

This report concerns itself with the application of SFCC's for electric power generation and coal gasification.
The efficiency of an electric powerplant, based on a combination of a compressor, an SFCC, an impulse turbine and a classical steamcycle is estimated. It is concluded that, if a low efficiency for the steamcycle is assumed, the overall efficiency for such a powerplant may lie between 40% and 45%. If a more efficient steamcycle is assumed the efficiency is estimated between 45% to 51%.
In addition it has been found that with brown coal, there is a tendency for higher combustion temperatures, which might make brown coal an attractive choice for SFCC and MHD applications.
Two different coal gasification processes have been considered. One process uses pure oxygen (dry process) the other one employs a mixture of oxygen and water (wet process). The composition of the gasified coal is very different for the two processes. The dry process has an overall efficiency of about 80% with specific heats of combustion varying between roughly 13 and 19 MJ/kg, while the wet process has an overall efficiency of about 94% with specific heats of combustion roughly between 12 and 16 MJ/kg. By removal of carbondioxide from the wet process gases, the specific heat of combustion may be raised to values between 45 and 53 MJ/kg.

1. Contents.

2. Nomenclature.

c_p	specific heat capacity at constant pressure
c_v	specific heat capacity at constant volume
m	mass flow
P	power
p	pressure
Q	heat, heat of combustion
T	temperature
v	velocity
γ	ratio of specific heats
η	efficiency
ρ	density

Subscripts

1	at compressor inlet
2	at compressor outlet
3	at the end of the SFCC
4	at turbine inlet
5	at turbine outlet
6	condition of the gas when leaving the boiler
a	air
boiler	boiler
c	combustion
coal	coal
compr	compressor
f	flame
f	fuel
g	gas
gen	generator
steam	steam
t	total
tk	kinetic
turb	turbine

3. Introduction.

At present a research project is caried out to investigate the possibility of the combustion of solid fuels in the presence of a high velocity airflow. As the combustion takes place within a cylindrical bore of the fuel, the burning fuel insulates the walls of the combustion chamber from the very hot combustion products. This allows much higher combustion temperatures than in conventional combustors and furnaces. The main emphasis of the research project is on understanding and describing the flow and combustion processes within such a channel.

The research is carried out by the Department of Aerospace Engineering of Delft University of Technology and the Prins Maurits Laboratory TNO. It is funded by the Netherlands Foundation for Technical Research (STW) (project DLR 11.0120), the Project Office for Energy Research (PBE), Delft University of Technology (THD) and the Organization for Applied Scientific Research (TNO).

The main applications of Solid Fuel Combustion Chambers, as these are seen now, are:- "Clean" combustion of waste in combination with power generation
- Power generation by the combustion of coal
- Aerospace propulsion (solid fuel ramjets)
- Coal gasification.

In a previous report (1) various possiblities for an efficient power generation from the combustion of waste material have been investigated. It was concluded that a very reasonable efficiency (39 %) can be achieved by a combination of a compressor, an SFCC, an impulse turbine and a steamcycle.
The choice of the impulse turbine is dictated by the high combustion temperatures. The inlet temperatures of turbines is limited (we took 1100 K) and hence the temperature of the combustion gases would be much too high for a reaction turbine. If the gases first expand in a stator where they are accellerated to very high velocities the gases cool down to acceptable levels. The momentum of the gases then is transferred to the rotors of the impulse turbine. Ideally this is an isobaric and isothermal process. Therefore by taking an impulse turbine instead of a reaction turbine many of the technical difficulties that are associated with high temperature gases in turbines may be overcome. In this respect it should be noted that impulse turbines are common practice in liquid propellant rocket motors. On the other hand, the method supposes that solids can be removed from the hot gases, without much affecting the overall efficiency.
In this report, the feasibility of an SFCC for electric power generation, with coal as a fuel is estimated. The main parameter that has been investigated is the overall efficiency of such a power plant.
Of course, a high efficiency is not the only parameter that determines the feasibility of such power plants. Technical problems and costs of realization (investments) and operational costs will be of paramount importance.

One other aspect should be mentioned.
The time to get the SFCC started is believed to be very short. Disregarding the steamcycle, the SFCC and impulse turbine can be assumed to have reached full power within seconds after ignition.

A second possible application of SFCC's for power generation concerns its use as gas generators from coal. Roughly 10-15% of coal consists of solids that have to be removed from the combustion products before the gases are fed into an (impulse) turbine. For the calculation of the efficiency of SFCC's for electric power generation it has tacitly been assumed that is is possible to do this without much energy loss, before the gases enter the turbine. It is also possible, however, to burn the coal with oxygen or with a mixture of oxygen and water to produce combustible gases. The hot gases that are generated by the combustion then are cooled, and the solids may be removed from the cool gases. These gases, mainly constituing CH_4, CO, CO_2 and H_2 then may be transported to customers where they can be used for either electric power generation or other applications such as heating, or various forms of mechanical power generation. The heat that is released during coal gasification again may be used for electric power generation.

In the second part of this report the heat content of the gasified coal is calculated in relation to the oxidizer/fuel ratio, and also the amount of electric power, that may be generated, is calculated assuming the use of a conventional steam cycle with the same efficiency as the steam cycle in Secion 4.

Finally, an advantage of the SFCC concept from an economic and environmental point of view should be mentioned.

If the coal is shipped from abroad to one or a few ports in the country, central processing units may be built there to fill the cartridges for the SFCC's with coal fuel grains. These cartridges then may be transported by ship or by rail to power/coal gasification plants in the country. Empty cartridges are returned to the central processing plant(s) to be refilled. Central processing plants will limit dust pollution to only that specific area where the cartridges are filled, while also one or a few large central plants may be more economical than many small facilities together with coal storage at the various power/coal gasification plants.

4. Calculation of the Efficiency of an SFCC Electric Power Plant.

A diagram of a possible installation is given in Fig. 1. The system consists of

- a Compressor
- an SFCC
- a Row of Expansion Nozzles
- an Impulse Turbine
- a Boiler
- a Steam Turbine

The total efficiency of the system may be estimated from the following relation:

$$\eta_t = \frac{P_{turb} + P_{steam} - P_{compr}}{Q_{coal}} \qquad (1)$$

Here P_{turb} is the power output of the impulse turbine, P_{steam} is the power output of the steam turbine system, P_{compr} is the power necessary to drive the compressor while Q_{coal} is the total heat of combustion of the coal.

The power required for the compressor follows from

$$P_{compr}/m_a = c_{p_a} . T_1 \left[\left(\frac{p_2}{p_1} \right)^{\frac{\gamma_a - 1}{\gamma a}} - 1 \right] / \eta_{compr} \qquad (2)$$

$$T_2 = T_1 . \left(\frac{p_2}{p_1} \right)^{\frac{\gamma_a - 1}{\gamma a}} \qquad (3)$$

T_2 is the inlet temperature of the air for the SFCC. The combustion temperature, T_f, depends on the kind of fuel, the mixture ratio and the inlet temperature of the air. For a given fuel and mixture ratio, Oxidizer/Fuel, the flame temperature, T_f, follows, once T_2 is known$^{(2)}$. The combustion in the SFCC is assumed to be isobaric.

In the row of expansion nozzles the combustion gases expand which is accompanied by a decrease of the gas temperature. The gas velocity at the end of the row of expansion nozzles follows from

$$\tfrac{1}{2} v_4^2 = c_p T_3 - c_p T_4 = c_p T_3 \left(1 - \frac{T_4}{T_3} \right) = c_p T_3 \left[1 - \left(\frac{p_4}{p_3} \right)^{\frac{\gamma_g - 1}{\gamma g}} \right] \qquad (4)$$

The temperature of the gases at entrance of the impulse turbine follows from

$$T_4 = T_3 \left(\frac{p_4}{p_3} \right)^{\frac{\gamma_g - 1}{\gamma g}} \qquad (5)$$

In the impulse turbine the velocity of the gases is converted into kinetic energy of the turbine rotors. The power from the turbine follows from

$$P_{turb}/m_a = \left(1 + \frac{m_f}{m_a} \right) . \frac{1}{2} v_4^2 . \eta_{turb} \qquad (6)$$

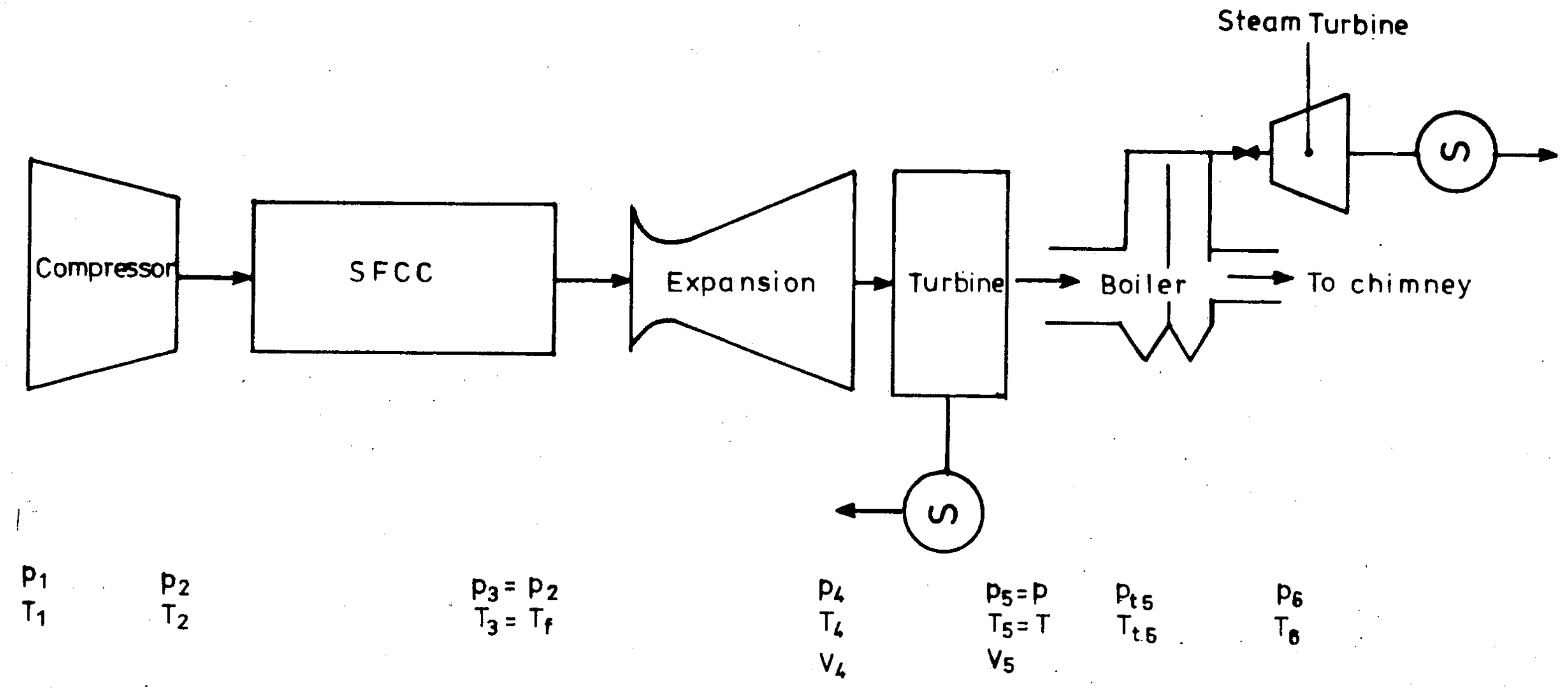

Fig. 1. Diagram of Electric Power Generator by an SFCC

The turbine efficiency, η_{turb}, is the product of three efficiencies:

conversion into electric energy η_{te}
mechanical efficiency η_{tm}
kinetic efficiency η_{tk}

The kinetic efficiency is a measure of how much kinetic energy of the gases is converted into kinetic energy of the turbine rotor. Hence, the kinetic energy of the gases, leaving the turbine is

$$\tfrac{1}{2} v_5^2 = \tfrac{1}{2} v_4^2 \, (1 - \eta_{tk}) \qquad (7)$$

and the total specific energy of the gases leaving the turbine, equals:

$$e = \tfrac{1}{2} v_5^2 + c_p T_5 = (c_p T_3 - c_p T_4)(1 - \eta_{tk}) + c_p T_4$$

as the turbine process is assumed to be isothermal. So after the turbine we are left with gases with a specific internal energy

$$e = c_p \left[T_3 (1 - \eta_{tk}) + \eta_{tk} T_4 \right] = c_p T_{t5} \qquad (8)$$

The total pressure, p_{t5}, follows from

$$p_{t5} = p_5 \left(\frac{T_{t5}}{T_5} \right)^{\frac{\gamma a}{\gamma_a - 1}} \qquad (9)$$

This total pressure should slightly exceed atmospheric pressure, as to ensure the ultimate outflow of the combustion gases through the chimney. This implies that p_5, the pressure at the end of the turbine may be substantial lower than atmospheric pressure. The pressure p_5 is found from solving

$$\left(\frac{p_{t5}}{p_5} \right)^{\frac{\gamma_a - 1}{\gamma a}} - \left(\frac{p_3}{p_5} \right)^{\frac{\gamma_a - 1}{\gamma a}} . \, (1 - \eta_{tk}) - \eta_{tk} = 0 \qquad (10)$$

The results are shown in Fig. 2 for combustion pressures between 15 bar and 25 bar and $0{,}75 \leq \eta_{tk} \leq 0{,}85$. It is seen that the allowable expansion ratio increases tremendously as compared to an expansion ratio p_3:1.

In the boiler there are gases of about atmospheric pressure and a temperature T_{t5}, where T_{t5} follows from (8).
It is assumed that the gases in the boiler cool down to 600 K, to heat steam which is driving a steam turbine. The power generated by the steam turbine is:

$$P_{steam}/m_a = \eta_{gen} \cdot \eta_{boiler} \left(1 + \frac{m_f}{m_a} \right) \cdot c_{p_g} \cdot (T_{t5} - T_6) \qquad (11)$$

All generated and required powers have been related to the mass flow of the air, m_a. So to compute the overall efficiency of the power plant, the heat of combustion also has to be related to the mass flow of air.

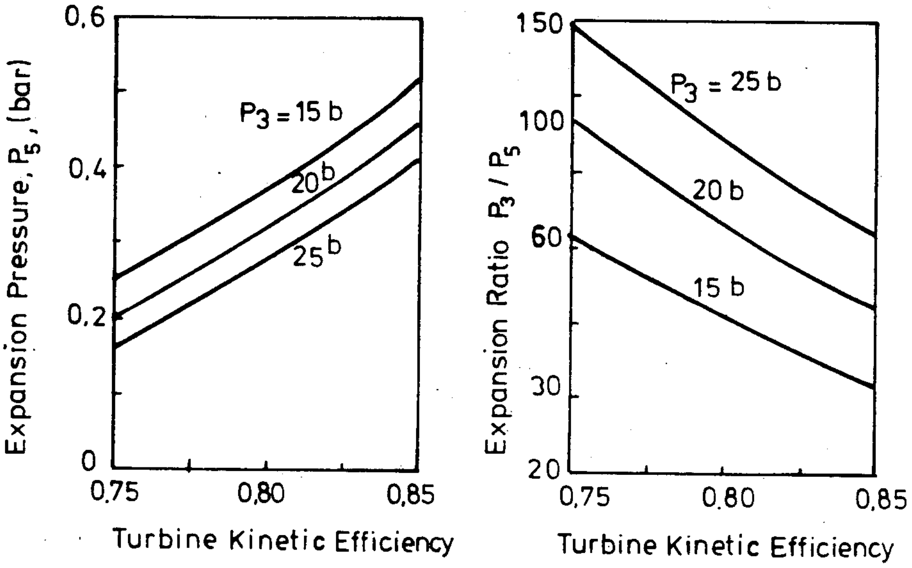

Fig.2. The effect of Turbine kinetic efficiency on the allowable expansion pressure and expansion ratio; γ_g = 1,25; P_{t5} = 1,01 bar.

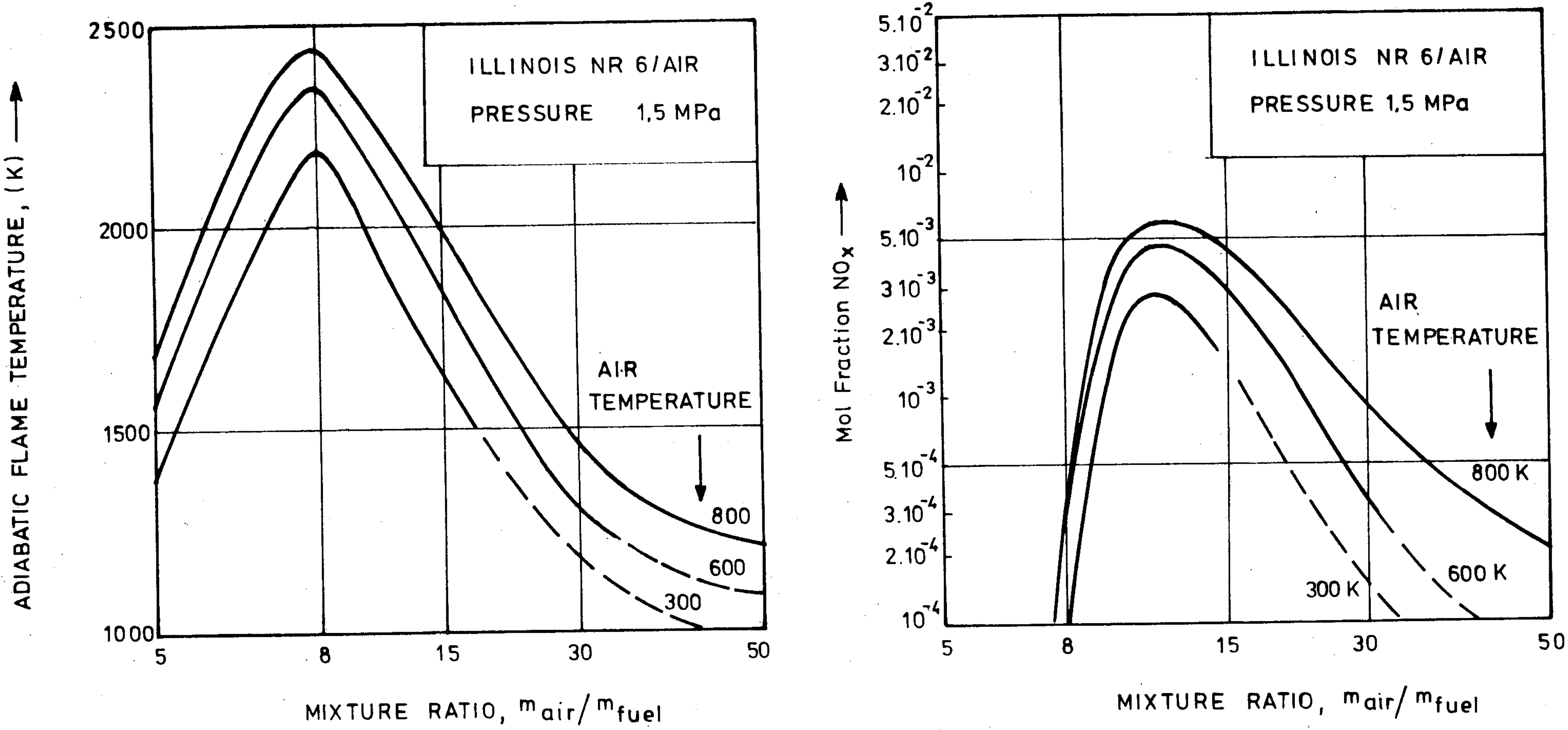

Fig.3. Flame temperature and amount of NO_x for Illinois no 6, for mixture ratios between 5 and 50 and inlet temperatures between 300 K and 800 K.

If the (specific) heat of combustion of the coal is Q_c, while there is a mass flow of air m_a, we have that for 1 kg of coal, m_a kg of air is required, so for 1 kg of air the heat generated is Q_c/m_a. So the total efficiency of the system follows from:

$$\eta_t = \frac{P_{turb/m_a} + P_{steam/m_a} - P_{compr/m_a}}{Q_c/m_a} \tag{12}$$

The efficiency of a power plant based on a combination of a compressor, solid fuel combustion chamber and a steam turbine has been calculated for two types of coal: Illinois no 6 and brown coal. The numerical data for the system that have been used, are listed in Table 1.

The thermal, and thermodynamic properties of the combustion gases depend on the mixture ratio m_a/m_f, the inlet temperature of the air, T_2, the composition of the coal and the pressure. For the pressure range of interest, the thermal and thermodynamic properties are only weak functions of the pressure. Therefore calculations have only been made for a pressure of 15 bar $^{(2)}$. For Illinois no 6, the results are presented in the Figs. 3 and 4. For this coal the calculations have not always been made for mixture ratios exceeding 15, which is indicated by the interrupted lines that have been extrapolated. Similar graphs are presented in the Fig. 5 and 6 for brown coal for mixture ratios between 4 and 16. The main characteristics of Illinois no 6 and brown coal are listed in the Tables 2 and 3.

Table 1: Numerical Data for the Powerplant System

Ratio of specific heats for air, γ_a	1,4
Heat capacity at constant pressure for air, cp_a	1013 J/(kg.K)
Compressor efficiency, η_{compr}	0,84
Total turbine efficiency, η_{turb}	0,70
Turbine kinetic efficiency, η_{tk}	0,75
Boiler efficiency, η_{boiler}	0,97
Efficiency of power generation by steam turbine, η_{gen}	0,30
Inlet pressure, p_1	1 bar
Exhaust pressure, p_6	1,01 bar

From the Figs. 3 and 5 it is seen that the maximum combustion temperature of this type of brown coal is about 150 to 200 K higher than for Illinois no 6. This is mainly because brown coal has a higher amount of H_2 than Illinois no 6 and hence requires less oxygen. Therefore a smaller amount of cold (inert) nitrogen has to be heated. On the other hand the ash content of Illinois no 6 is about 13 % while no ash contents were assumed for the brown coal.

The results of the calculations of the efficiency are presented in Fig. 7. The highest efficiencies are reached with brown coal and air at mixture ratios between 9 and 10. These efficiencies are in the order of magnitude of 45 %.
For Illinois no 6, the maximum efficiency is about 43 % at a mixture ratio 11. It is seen that the combustion pressure only weakly affects the total efficiency in the pressure range that has been investigated.

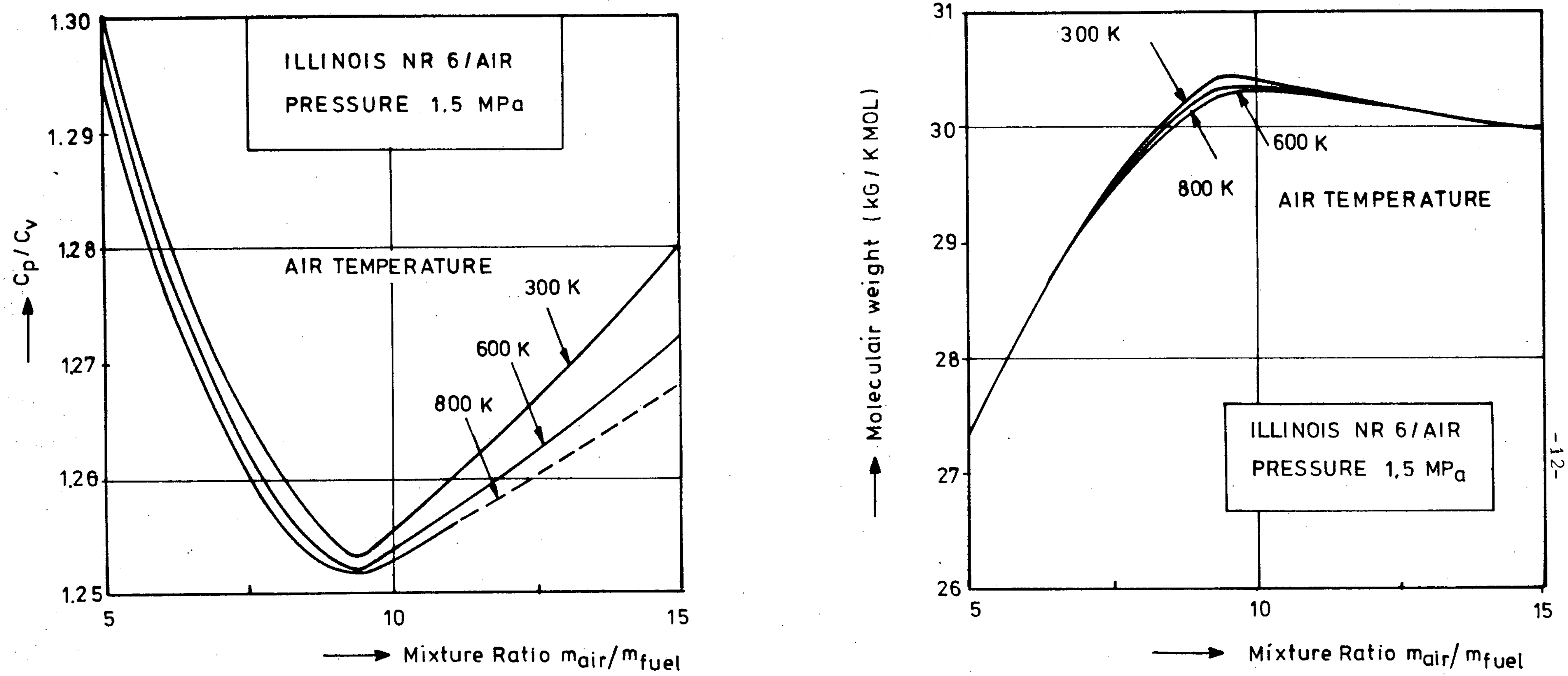

Fig.4. Properties of combustion gases of Illinois no 6 and air for some mixture ratios and inlet temperatures between 300 K and 800 K.

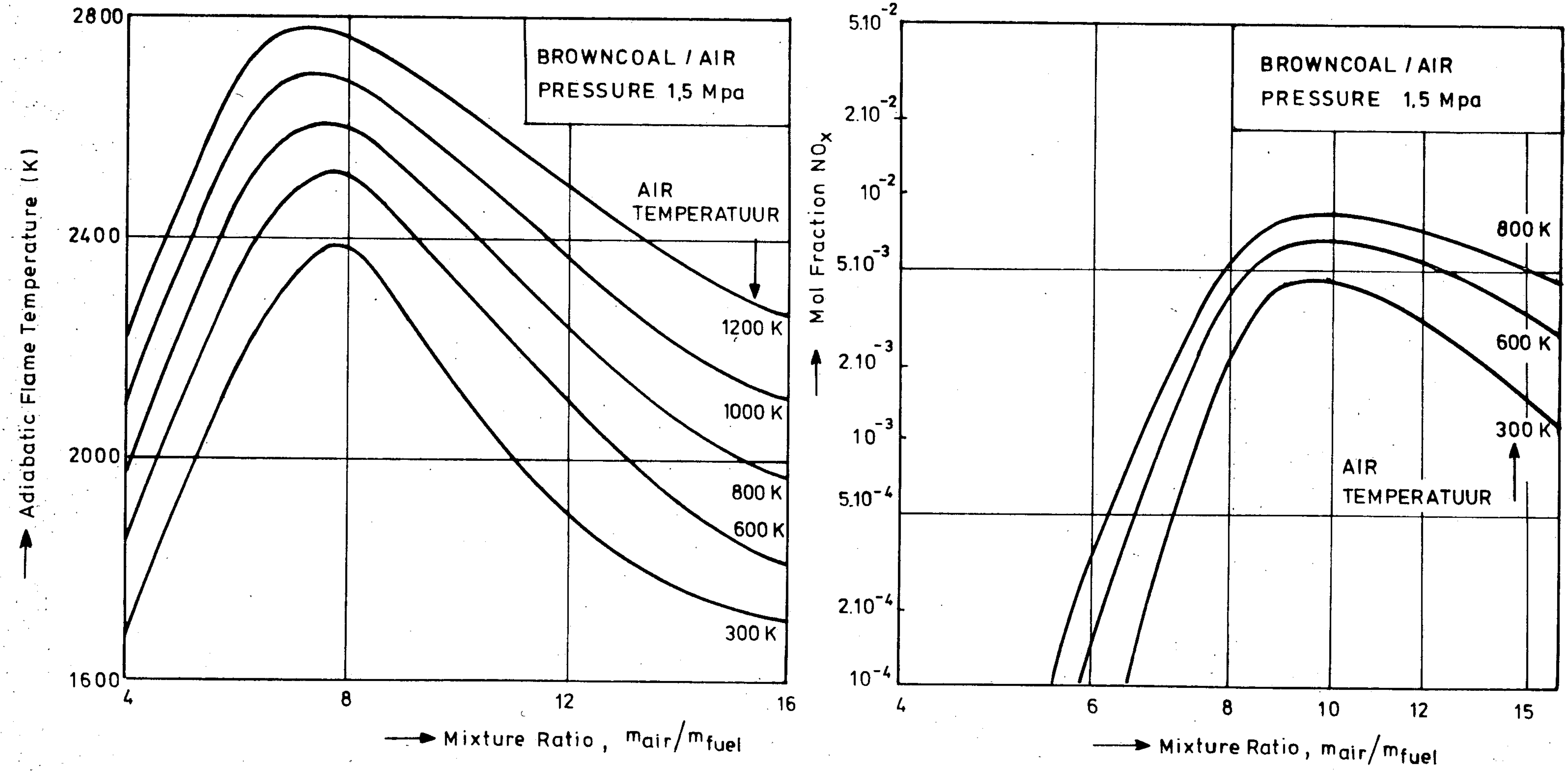

Fig.5. Flame temperature and amount of NO_x for Brown Coal, for mixture ratios between 4 and 16 and inlet temperatures between 300 K and 1200 K for the flame temperature and 300 K and 800 K for the amount of NO_x.

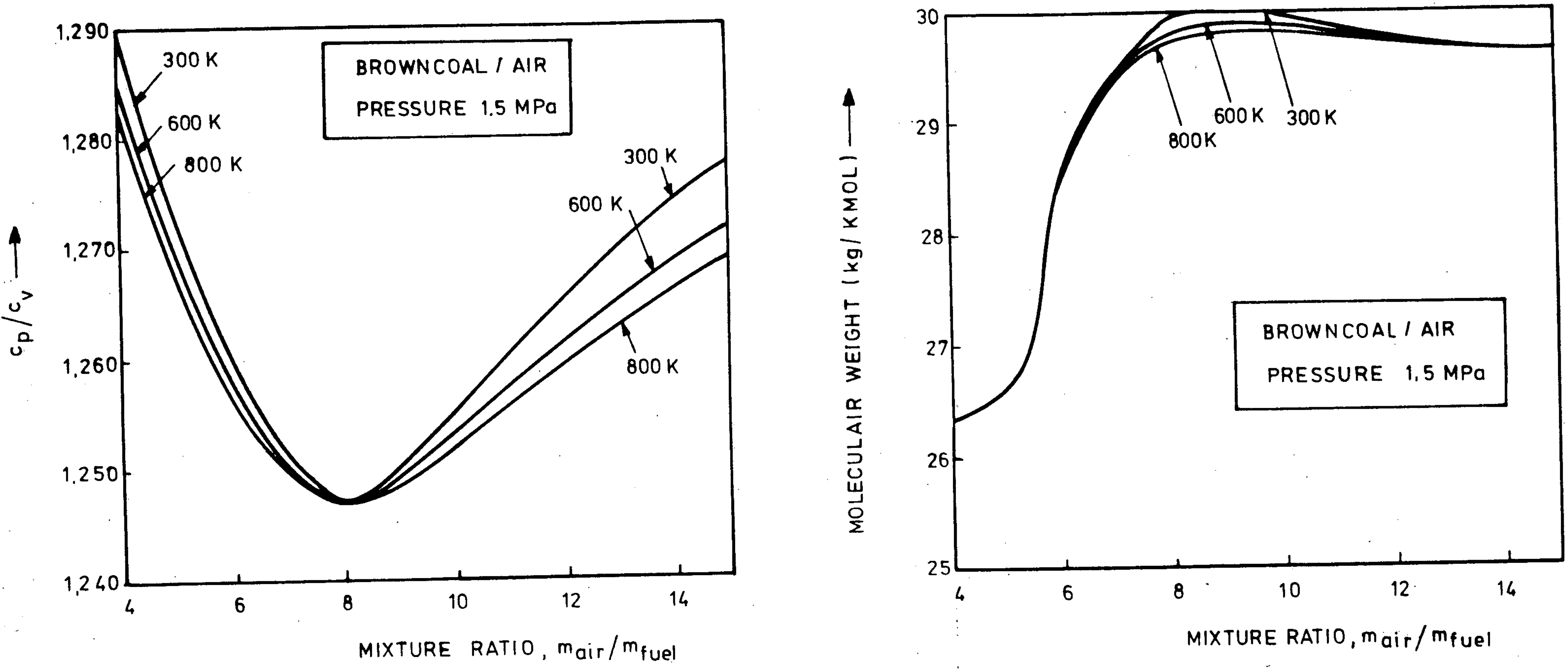

Fig.6. Properties of combustion gases of Brown Coal and Air for some mixture ratios and inlet temperatures between 300 K and 800 K.

Table 2: Properties of Illinois no 6, used in the analysis.

Composition	Percentage by weight	Standard heat of formation J/mol
$C_{132,23}H_{112,20}O_{13,32}N_{2,19}S_{1,06}$	87,20	- 8,87 . 10^6
SiO_2	2,99	- 8,59 . 10^5
Al_2O_3	5,79	- 1,67 . 10^6
Fe_3O_3	3,23	- 8,22 . 10^5
CaO	0,79	- 6,35 . 10^5
Heat of combustion	28,75 MJ/kg	

Table 3: Properties of brown coal used in the analysis.

Composition	Percentage by weight	Standard heat of formation J/mol
$C_{5,458}H_{5,1}N_{0,064}S_{0,006}O_{1,738}$	100	- 2,52 . 10^6
Heat of combustion	25,19 MJ/kg(3)	

A last important parameter is the turbine inlet temperature. This temperature is limited due to material strength and creep. It is assumed that the turbine inlet temperature should not exceed 1100 K. Figure 8 shows the turbine inlet temperature for Illinois no 6 and Brown Coal in relation to combustion pressure and inlet temperature. It may be concluded that it is possible to achieve maximum efficiencies at turbine inlet temperatures below 1100 K.

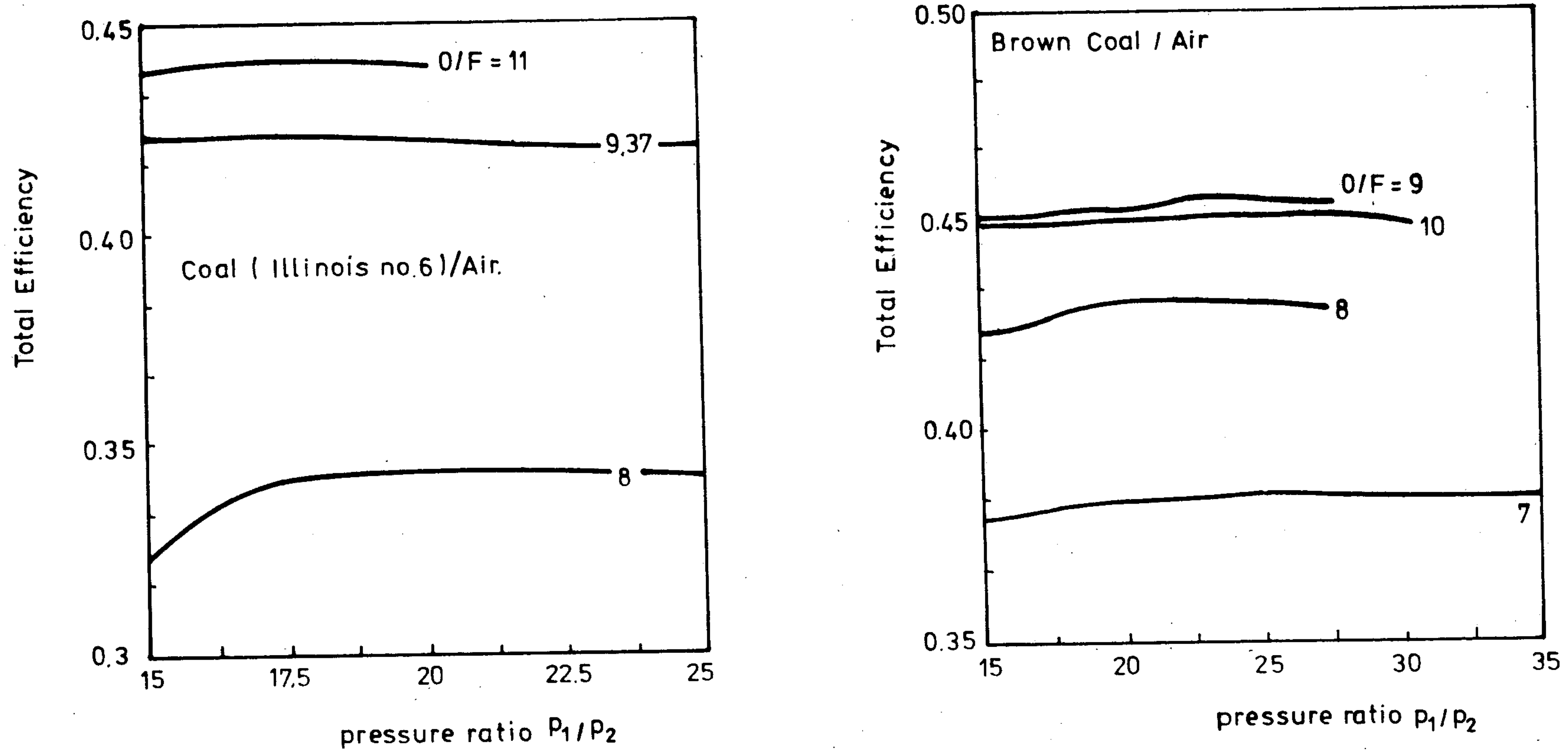

Fig.7. Calculated Total Efficiencies for a Power Plant System consisting of a Compressor, Solid Fuel Combustion Chamber, Impulse Turbine and Steam Turbine.

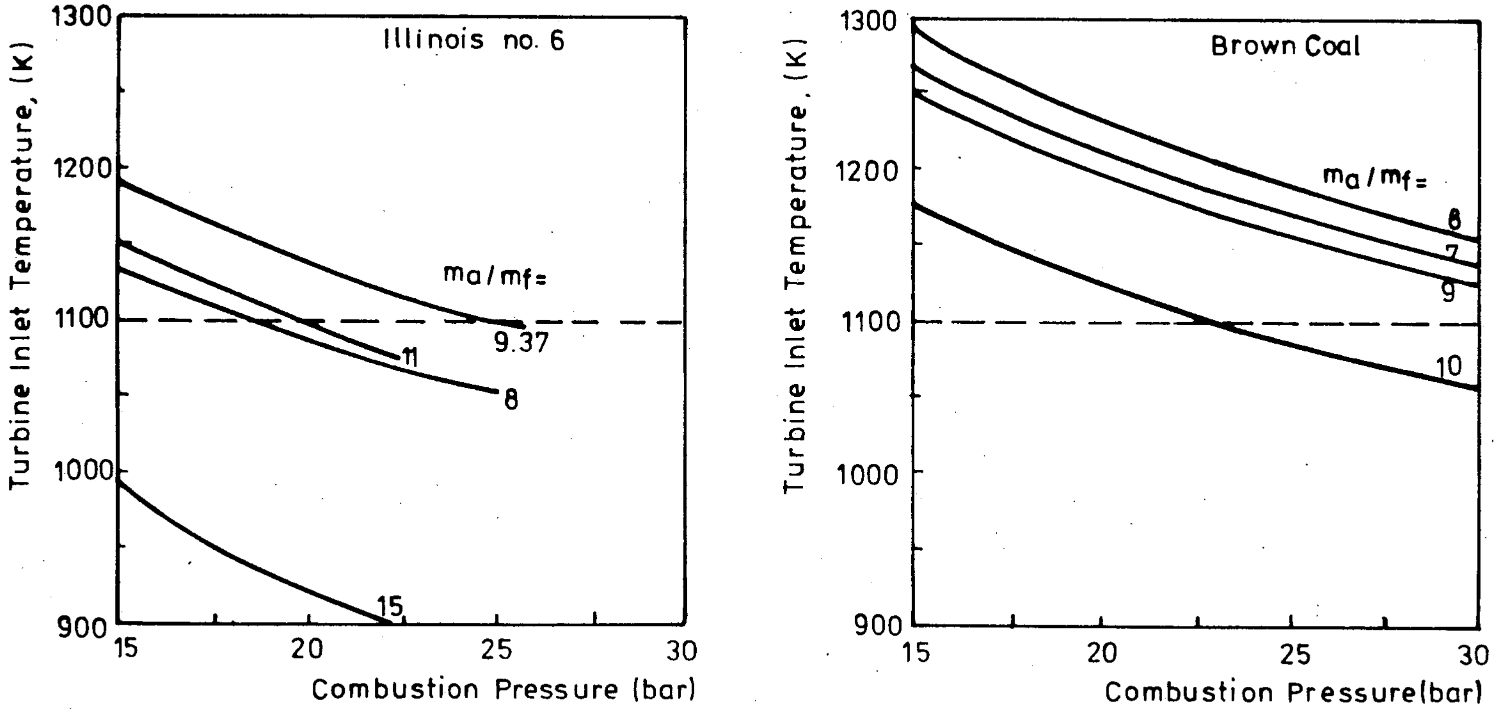

Fig.8. The Turbine inlet temperature in relation to mixture ratio and combustion pressure.

5. Discussion and Results ; Application of SFCC's for Power Generation.

In the previous Section engineering calculations have been made to estimate the performance of a Power Plant that is based on the combination of a compressor, a solid fuel combustion chamber, an impulse turbine and a classical steam turbine system.

The calculations were based on two different types of coal: Illinois no 6 and an ash-free brown coal. The flame temperatures for brown coal are significantly higher than for Illinois no 6.
The heat of combustion for the brown coal was calculated with an expression taken from Van Krevelen (3). This expression yielded a heat of combustion for Illinois no 6, that agreed very well with the value that was used for the Illinois no 6 calculations and which was taken from ref. 4. On the other hand Illinois no 6 contains ~ 13 % ash while no ash contents were assumed for brown coal. On the other hand brown coal requires less air for a complete combustion, therefore less nitrogen has to be heated, and therefore higher flame temperatures might be possible. If this is true brown coal may be an attractive fuel for high flame temperature applications such as is the case with the SFCC or MHD power generation.

It is seen from the calculations, presented in the previous Section, that overall efficiencies between 40 % and 45 % may be expected. It should be noted that the efficiency of the steam cycle is rather low (0,291) and that the temperature of the combustion gases, when they are exhausted is fairly high (600 K). If an overall efficiency of the steam cycle of 38 % is assumed and additionally the gases are allowed to cool down to 500 K, the total efficiency is raised to 45 % to 51 % for the complete Power Plant.

If the SFCC concept can be realized for coal or brown coal combustion, this may perhaps be an attractive alternative for the generation of electric power.

It should be noted that even if large scale operational SFCC's with coal and/or brown coal can be realized, there are still severe technical problems that have to be overcome. To mention the two most obvious ones:

- removal of solid particles from the combustion gases
- development of impulseturbines.

At present, however, the concept in itself may be attractive, because of rather favorable looking overall power plant efficiencies.

6. Coal Gasification

SFCC's may also be used for the production of combustible gases. Two different approaches may be followed. The first one is to feed the SFCC with pure oxygen in such a way that a fuelrich mixture results. The main gaseous combustion products are: CH_4, CO, H_2, CO_2 and H_2O. If the mixture becomes too fuelrich, the ash may contain a substantial fraction unburned solid carbon. The second approach is to feed the SFCC with a mixture of oxygen and steam. At the elevated temperatures the water will partly be reduced by the coal leading to a higher H_2 and possible CH_4 content in the combustion products, raising the total heat content of the gasified coal and reducing the combustion temperature. In both cases the combustion temperature is high enough to use the available heat of the combustion products (ash and gases) for electric power generation. This may be done by a conventional steam cycle. After that the gases have cooled to ambient temperature the solids and water may be removed from the gas. In this way one may combine an SFCC-coal gasification plant with electric power generation. Figure 9 is a schematic of such an installation.

6.1. Coal Gasification with Pure Oxygen

Some sample calculations have been made with Illinois nr. 6 as a reference coal. This coal contains 87,2% combustibles (by weight) and 12,8% ash. Its heat of combustion is 28,75 MJ/kg. Calculations have been made for various mixture ratios m_{O_2}/m_{fuel} by weight. The fuel is the coal, including ash. The results are shown in the Figs. 10 and 11. As can be seen from Fig. 10, the heat of combustion of the gasified coal is at a maximum at m_{O_2}/m_{fuel} mixture ratios between 0,8 and 0,85. On the other hand the amount of unburned carbon increases with decreasing mixture ratio's. This has also been plotted in Fig. 10. From this graph it follows that at a mixture ratio m_{O_2}/m_{fuel} = 0,85 the amount of unburned carbon is negligible while the dry gas has a heat of combustion of 13 MJ/kg. The heat of combustion of the wet gas is somewhat lower, but it is assumed that most of the water (17 g per kg coal) will be removed. A second measure to judge which mixture ratio is the most attractive one, is to consider the efficiency of the cycle. As the primary product is gas, the heat of combustion of the gas is compared with the heat of combustion of the coal. Every kg coal produces g kg gas with a specific heat of combustion q_{gas}. So the total heat of combustion of the gas, per kg coal is found from $Q_{gas} = q_{gas} \cdot g$, and the efficiency follows from

$$\eta = Q_{gas}/Q_{coal} \tag{13}$$

This efficiency has been plotted versus the mixture ratio in Fig. 11. It is seen that a maximum efficiency of ~ 75% may be achieved at $m_{O_2}/m_{fuel} = \sim 0,85$.
To estimate the usefulness of the application of FSCC's for coal gasification with electric power generation, a mixture ratio of 0,85 will be assumed.
With a steam cycle electric power may be generated from the hot combustion products (including the hot ash) in a conventional way. Assuming, like in the previous sections, a boiler exit temperature of 600 K and an overall efficiency of the steam cycle of 29,1%, 600 kJ electric power may be obtained from every kg coal. Assuming a boiler exit temperature of 500 K and an overall efficiency of the steam cycle of 38% raises the total amount of electric power to 900 kJ for every kg coal. Compressing the oxygen from 1 bar to 10 bar requires 302 kJ per kg oxygen, and as 0,85 kg oxygen is used per kg coal the required compressor power is 257 kJ, which has been calculated by Eq.(2) where $\eta_{comp} = 0.84$.

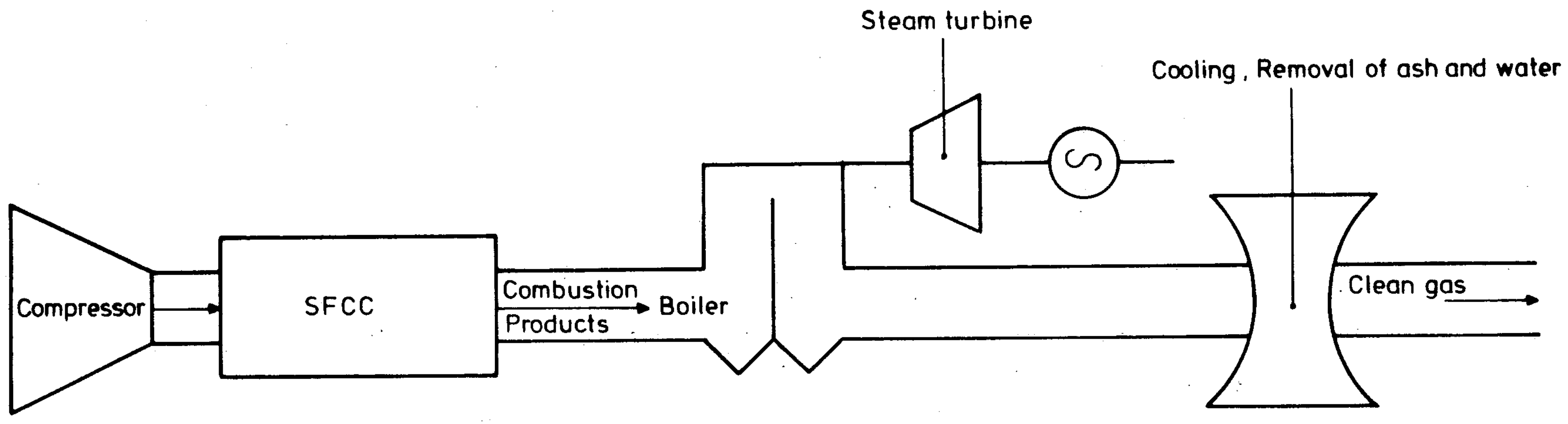

Fig. 9: Schematic of a combined SFCC Coal Gasification/
Electric Power Plant.

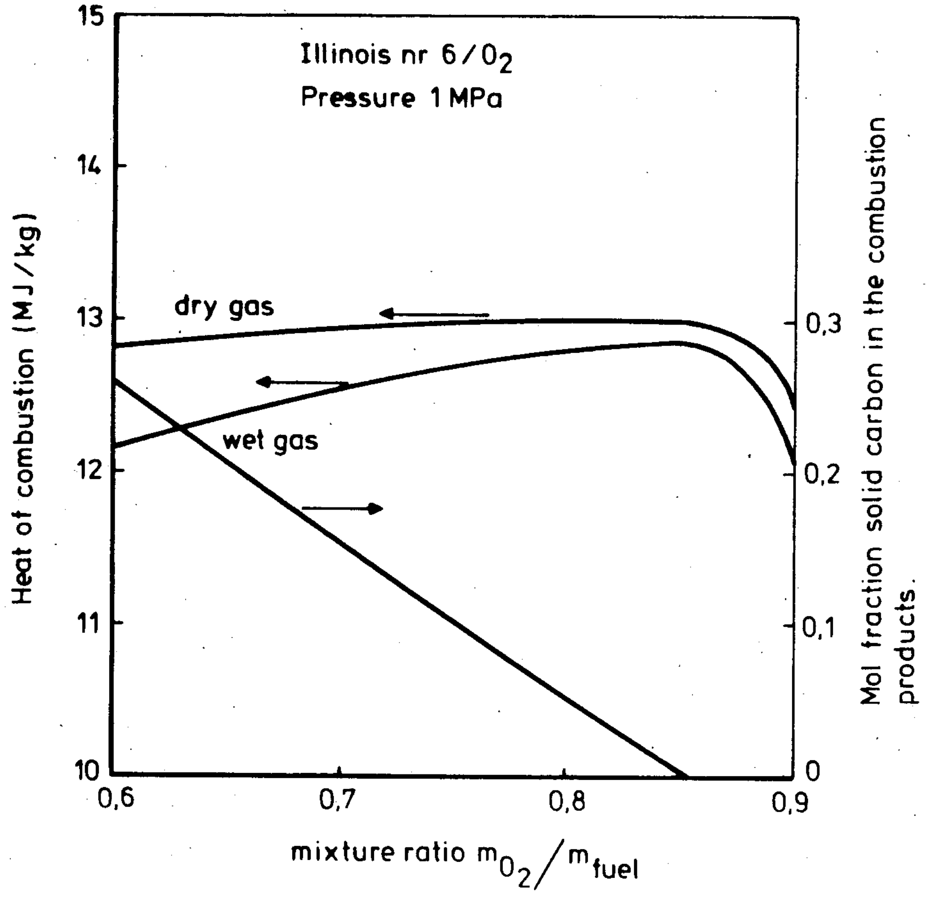

Fig. 10: Heat of combustion of gasified coal and the amount of unburned carbon for various mixture ratio's.

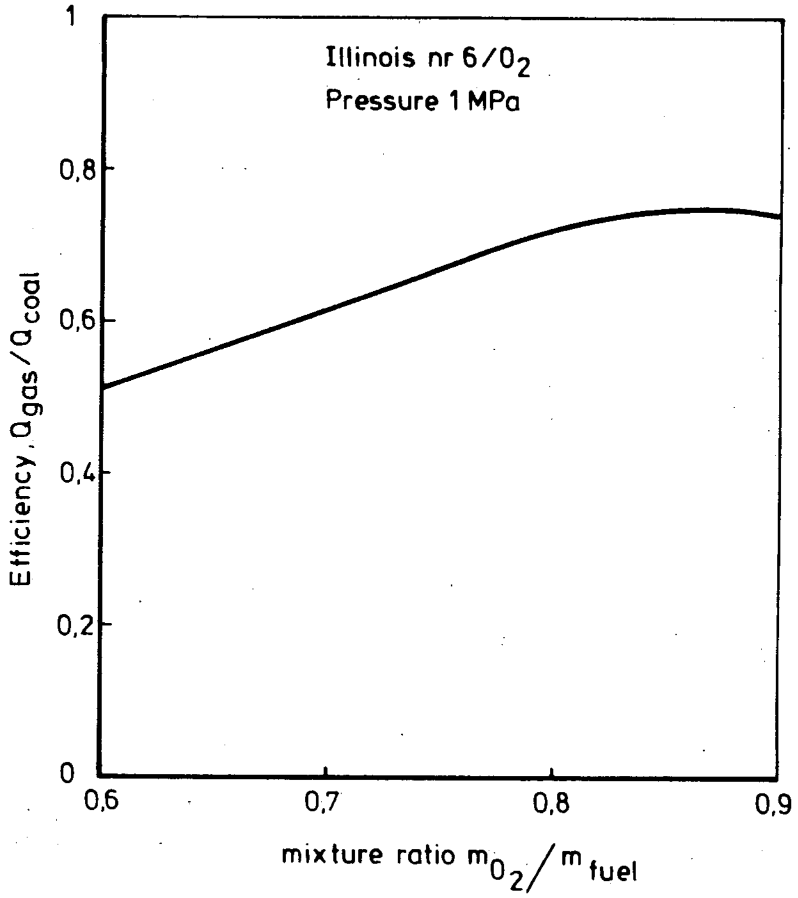

Fig. 11: Efficiency of gasified coal versus mixture ratio.

So from 1 kg coal we obtain

Heat of combustion of the gas	
$Q_C = g.q_C = 1{,}701 \times 12{,}988 =$	22,09 MJ
Electric Power (low efficiency cycle)	0,6 MJ
Electric Power (high efficiency cycle)	0,9 MJ
Compressor power	- 0,26 MJ
+	
Total Available Energy,	E = 22,43 (22,73) MJ

and the overall efficiency is $E/Q_{coal} = 0{,}78$ (0,79).

No account has been made for the energy necessary to produce the oxygen. This amount of energy has to be subtracted from the total available energy to obtain the net energy output.

If the oxygen is produced by electrolysis of water, much of the energy for electrolysis may be regained by adding the hydrogen that is also produced to the gasified coal. As one kg of coal requires 0,85 kg of oxygen for gasification, simultaneously 0,10625 kg H_2 is produced with a heat of combustion of 120,913 MJ/kg. In this way a gas results with a heat of combustion of 19,34 MJ/kg, which is rather near to the heat of combustion of natural gas (24,3 MJ/kg). If oxygen is obtained in a different way, or if the hydrogen is not added to the gasified coal, a gas results with a heat of combustion of 13 MJ/kg. The composition of the gasified coal is listed in Table 4.

Table 4: Composition and specific heat of combustion of dry gasified coal (percentage by weight) (dry process).

Constituent	without H_2 addition	with H_2 addition
CH_4	0,35	0,33
CO	93,74	88,22
CO_2	3,21	3,02
H_2	2,70	8,43
Q (MJ/kg)	13	19,34

6.2. Coal gasification with an Oxygen/Water mixture

If a mixture of oxygen and water is used as oxidizer, the water will partly be reduced to H_2 and more CH_4 will be formed. Simultaneously the flame temperature will be lowered as compared to the case that the same amount of pure oxygen is used as oxidizer.

Some sample calculations have been made at various pressures, mixture ratios $m_{(O_2+H_2O)}/m_{fuel}$, (the fuel again is Illionois nr. 6) and various ratios of oxygen and water. The pressure has only a secondary effect. Therefore, the results are only given for combustion pressures at 1 MPa; they are shown in Fig. 12. The two horizontal axes represent the mixture ratio $m_{(O_2 + H_2O)}/m_{fuel}$ and the weight percentage oxygen in the oxidizer. The efficiency, as defined in Eq. (13) is plotted along the vertical axis. Only efficiencies > 50% have been plotted. The efficiency for 100% oxygen agrees with the case that has been discussed in the previous Section, and hence is the same as in Fig. 11. It is seen that the maximum efficiency increases with decreasing oxygen percentages in the oxygen/water mixture. Only a limited number of cases has been calculated, but we see from the results that the highest calculated efficiency is achieved at $m_{(O_2 + H_2O)}/m_{fuel} = 2$, with 30% oxygen and 70% water. The results of the obtained maximum efficiencies are listed in Table 5.

Table 5: Maximum efficiencies for wet coal gasification.

weight percentage oxygen	oxygen mixture ratio m_{O_2}/m_{fuel}	mixture ratio $m_{(O_2+H_2O)}/m_{fuel}$	efficiency $\eta=Q_{gas}/Q_{coal}$
100	0,85	0,85	76,8
75	0,825	1,1	74,5
50	0,70	1,4	80,0
30	0,60	2	89,1

It may well be that it is even possible to achieve a still higher efficiency, but as it is not the purpose of these calculations to find the ultimate optimum efficiency, this has not been pursued. Therefore, the case of wet coal gasification with 30% O_2 at a mixture ratio $m_{(O_2+H_2O)}/m_{fuel} = 2$ will be considered as the sample case.

In this case 1 kg of coal (Illinois nr.6) produces 2,07 kg of dry gas with a heat of combustion of 12,8 MJ/kg. The wet combustion products contain (per kg coal) 128 g ash and 802 g water which have to be removed. The combustion products (gas, water and ash) have a temperature of 920 K and a heat capacity C_p = 1909 J/(kg.K). By means of a conventional steam cycle this heat may be used for the generation of electric power. Depending on whether one assumes a low or a high efficiency steam cycle (i.e. boiler exit temperature 600 K or 500 K and an overall efficiency of 29,1% or 38%) one finds for the electric power output:

$$P_{electric(low)} = 533 \text{ kJ/kg coal} ,$$

$$P_{electric(high)} = 914 \text{ kJ/kg coal}$$

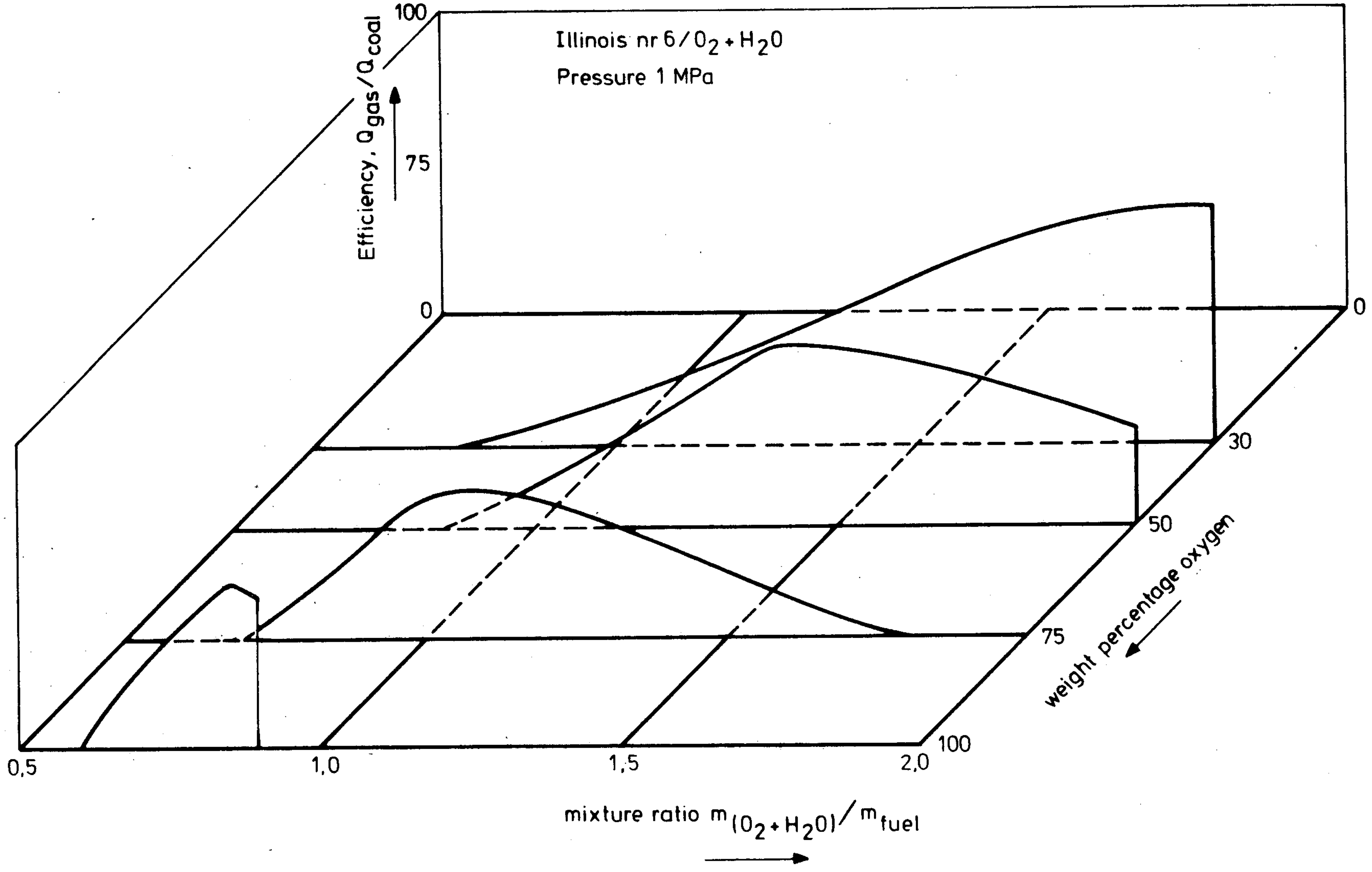

Fig. 12: Efficiency of a wet coal gasification process.

The water has to be injected at a pressure at least equalling the combustion pressure of 1 MPa. If, for vaporization and spraying, an additional water pressure of 0,5 MPa is required, then the required power for water injection follows from

$$P_{water} = m_{H_2O} \cdot \frac{\Delta P}{\rho} / \eta_{pump} \qquad (14)$$

With $m_{H_2O} = 1{,}4\ kg/kg_{coal}$,

$\Delta P = 1{,}4\ MPa$,

$\rho = 1000\ kg/m^3$,

and $\eta_{pump} = 0{,}84$, the power required for water injection is 2,33 kJ/kg coal. The power necessary for the compression of oxygen follows from Eq. (2), P_{comp} = 181,4 kJ/kg coal, and the total power for the injection of oxidizer is

$$P_{inj} \approx 0{,}185\ MJ/kg\ coal.$$

All data are now available to make an energy yield balance for the wet cycle per kg coal:

Heat of combustion of the gas	
$Q_c = g \cdot q_c = 2{,}07 \cdot 12{,}8 =$	26,50 MJ
Electric Power (low efficiency cycle)	0,53 MJ
Electric Power (high efficiency cycle)	0,91 MJ
Power for oxygen and water supply	- 0,19 MJ
	+
Total available energy per kg coal,	P_t = 26,84(27,22)MJ ,

which yields an overall efficiency P_t/Q_{coal} = 93,3%(94,7%).

If oxygen is produced by the electrolysis of water, the hydrogen that is also produced may be added to the gasified coal. As in this case 0,6 kg O_2 is required for the combustion of 1 kg of coal, the electrolysis of water would produce 0,075 kg H_2 per kg coal. Adding this to the gas raises the specific heat of combustion from 12,8 MJ/kg to 16,59 MJ/kg. The composition and specific heat of combustion of the gas is given in Table 6.

Table 6: Composition and specific heat of combustion of dry gasified coal by the wet process (30% O_2, 70% H_2O) (percentages by weight).

Constituent	without H_2 addition	with H_2 addition
CH_4	11,16	10,77
CO	14,46	13,95
CO_2	71,52	69,02
H_2	2,86	6,26
Q_{gas} (MJ/kg)	12,801	16,59

In comparison with the dry process, there is a large difference in composition (see Table 4). Also the specific heat of combustion of the gas from the wet process is lower, especially after H_2 addition. The overall efficiency of the process, however, has been raised from 78% to 93%. The main difference in the composition is that with the wet process, the CO_2 contents is ~ 71% versus ~ 3% for the dry process. Subsequently the CO contents has gone down from ~ 90% for the dry process to ~ 14% for the wet process. The amount of CH_4, however, has been raised from ~ 0,3% for the dry process to ~ 11% for the wet process.

6.3. Removal of Water, Ash and Carbondioxide

If the combustion products are brought to rest in a cooling tower (schematically indicated in Fig. 9), where the gas is cooled to ambient temperature (~ 300 K) the water will condense. As the vapor pressure of water at 300 K is 3,58 kPa, this means that the combustion gases from the pure oxygen process will contain 2,3 g H_2O per kg gas and those obtained from the wet process will contain 1,7 g H_2O per kg gas.

Now much of the ash particles will serve as condensation nuclei for the water, and therefore much of the ash may drip down with the condensed water. The remainder may be removed by means of cyclones and sieves.

If one wants to take out (part of) the CO_2, this might be accomplished by expanding the gas after that most of the water and all ash has been removed in the cooling tower.

Now CO_2 freezes at ~ 216 K, while its sublimation point lies at ~ 195 K. The boiling points of Methane and Carbonmonoxide lie much lower, ~ 109 K and 82 K, respectively. So by expanding the gas through cyclones will allow to remove most of the CO_2. For the gasified coal, obtained by the wet process, the ratio of specific heats, $\gamma = 1,43$, while for the gasified coal obtained by the dry process, $\gamma = 1,4$. If for simplicity the heat of sublimation of CO_2 is neglected, the necessary expansion ratio p_1/p_2, to achieve the temperature where CO_2 will freeze, follows from

$$p_1/p_2 = (T_1/T_2)^{\frac{\gamma}{\gamma-1}} \tag{15}$$

Taking $T_2 = 300$ K (ambient temperature), $T_1 = 200$ K to accomodate for neglecting the heat of sublimation one finds

$$(p_1/p_2)_{\text{dry process}} = 0,24 \quad ,$$

$$(p_1/p_2)_{\text{wet process}} = 0,26 \quad .$$

After that the CO_2 has been frozen and collected for example in cyclones, the remaining gas has a Machnumber of 1,566 for the dry process and 1,19 for the wet process.

As the Mach numbers remain small, there is hardly any pressureloss. Removal of the CO_2 results in a pressure loss of 0,006 MPa so that after CO_2 removal a total pressure of 0,994 MPa remains. For the dry process there is a slightly larger pressure loss after a straight shock, $\Delta p \approx 0,1$ MPa, so that after recovery a total pressure of 0,908 MPa is obtained. After that all CO_2 has been removed, gasified coal with a higher specific heat of combustion results.

Its composition and specific heat of combustion are listed in Table 7.

Table 7: Composition and specific heat of combustion of gasified coal after removal of water, ash and carbon dioxide.

constituent	Dry process without H_2 addition	 with H_2 addition	Wet process without H_2 addition	 with H_2 addition
CH_4	0,36	0,34	39,18	34,76
CO	96,85	90,98	50,77	45,03
H_2	2,79	8,68	10,05	20,21
Q_{gas} (MJ/kg)	13,42	19,93	44,95	53,54

7. Discussion and Results; Application of SFCC's for Coal Gasification

A dry and a wet coal gasification process for application in Solid Fuel Combustion Chambers have been discussed in the previous Section. The discussion has been limited to a feasibility level; i.e. efficiencies for power conversion were estimated, and no attention has been paid to details of the technical realization. It has been assumed that water and ash can be removed from the combustion products by cooling these products until most of the water has been condensed. Probably, much of the solids present in the combustion gases will serve as condensation nuclei and can be removed together with the water. The remainder of the ash will have to be removed by means of cyclones and sieves or other means. The energy, necessary for cleansing the gas has not been accounted for in the calculation of the efficiency.

If it is possible to remove carbondioxide from the gases, especially in the case of wet coal gasification, a very high specific heat of combustion may be achieved for the residual gasmixture. One possible way to remove carbondioxide has been indicated but other processes may be more practicable.

It has also been indicated that one possible way to obtain the oxygen for coal gasification is by electrolysis of water. In that case the hydrogen gas that is produced simultaneously may be added to the gasified coal. As no information was available about the efficiency of the electrolysis of water, the energy necessary for the production of oxygen has not been included in the calculated overall efficiencies. Overall efficiencies have only been given for the cases without hydrogen addition.

A remark of a different nature, concerning coal gasification should also be made at this point. For very low oxygen/fuel ratios, the ash may contain large fractions of unburned carbon. Although the specific heat of combustion of the gases may be fairly high, the overall efficiency decreases strongly in those cases. The cases that have served as sample cases for the calculations were free of unburned carbon. Of course, all results have to be regarded with some care, as they are based on chemical equilibrium calculations(2), and the actual situation in SFCC's may or may not deviate from that assumption.

The present studies show that SFCC's may be interesting means for coal gasification, either with a wet or a dry gasification process as rather high overall efficiencies, in combination with a simple and compact combustion process may be achieved.

8. References.

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