A new technology for the reduction of particulate matter from diesel engines in ships

Proefschrift

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Summary

Particulate matter, in Dutch called “fijn stof”, influences weather and climate and has adverse health effects. The Netherlands is the European country with the largest loss of life expectancy due to the anthropogenic emission of particulate matter. Two third of the concentration of particulate matter in the Dutch atmosphere is emitted in a foreign country. This clearly indicates the trans-boundary nature of particulate matter, but also shows that emissions on sea may influence the particulate matter concentration on land. The contribution of shipping to the concentration of particulate matter in the Netherlands is as large as the contribution of the Dutch industry. It is estimated that worldwide 60 000 people per year die prematurely as a result of particulate matter emission from sea shipping. It is expected that this has increased by 40% in 2012.

Four different strategies can be applied to reduce the particulate matter emission of shipping: Less shipping, more efficient shipping, using alternative fuels or exhaust gas cleaning. The big advantage of exhaust gas cleaning over the other options is that it has few negative consequences and could in principal be applied relatively easy in existing ships. Unfortunately no existing exhaust gas cleaning technique is suitable for application in sea shipping with the presently used fuels, see chapter 2. Therefore, a new exhaust gas cleaning technique should be developed to reduce the particulate matter emission of ships, that functions for heavy fuel oil as well as distillate fuels. This is the main topic of this thesis.

In chapter 3 the differences with regard to particulate matter emission between an intermediate fuel oil and a distillate fuel are studied. The mass emitted particulate matter is 20 to 30% lower with a distillate fuel than with an intermediate fuel with 1.5% sulphur. The number of emitted particles is 60% lower with a distillate fuel.

In chapter 4 the development of SJAC is described. The idea is that if particulate matter is enlarged, it can be removed by conventional technology. The particles are enlarged by the condensation of steam. Steam is injected in cold, preferably saturated exhaust gas, which creates a supersaturation. The particles will act as nuclei for condensation. The conventional removal technique was a cyclone. Measurements showed that maximally 25% of the mass of particulate matter was removed. A simulation indicated that the removal efficiency could be improved, but more than 50% removal efficiency was improbable for particulate matter concentration in the exhaust gas typical for diesel engines. Therefore development of SJAC was not continued.

In chapter 5 the development of a new technology called SJAC-ESP is treated. It is a self-cleaning electrostatic precipitator, that is robust enough to be applied in ships. The idea is that particles get a small water coating, so that they do not stick to the precipitator, but flow off it. This will keep the precipitator clean, and no periodical cleaning is required. The water coating is created by injecting steam in cold, preferably saturated, exhaust gas. Up to 82% of particulate matter mass is removed by this technology. Measurements showed that in a 100 kg/h slipstream of a 350 kW engine between 41 and 70% of the particulate matter mass was removed by SJAC-ESP. In addition to this up to 34% of particulate matter mass was removed in the heat exchangers. In the entire installation between 57 and 78% of the particulate matter mass was removed. Between 70 and 83% of the number of particles
smaller than 1 micrometer are removed. It turns out that the SJAC-ESP is relatively insensitive to particle size and is thus very suitable to remove sub-micron particles. The SJAC-ESP also removes some SOx; approximately 50% for distillate fuels and 30% for an intermediate fuel oil with 1.5% sulphur.

An endurance test was performed. The SJAC-ESP was 142 hours operational over a 500 hour period. The most frequently occurring problem was fouling of a heat exchanger, which increased the pressure drop over the exhaust gas system over the maximally acceptable boundaries. In the end it turned out that the capacity of the cooler was insufficient. It is strongly recommended to do another endurance test, and focus on a particulate matter balance in the electrostatic precipitator, to ensure that no problematic build-up of particulate matter is occurring.

A computer simulation of the SJAC-ESP was made. The simulation, however, is not sufficiently accurate to predict all effects of changing parameters. The first improvement should be a better description of the charging section of the electrostatic precipitator.

Important for the application of the SJAC-ESP is whether the water-particulate matter mixture can be cleaned sufficiently to discharge it or not. Chapter 6 addresses the composition of the water streams from various parts of the SJAC-ESP, and design solutions for water treatment are outlined. Because the actual discharge limits are not known yet, no conclusive remarks can be made whether the water-particulate matter mixture can be discharged after water treatment. It seems feasible, however. Additionally in chapter 6 several devices are discussed that would combine well with the SJAC-ESP in the exhaust gas system. Those are a direct contact cooler, which will also act as a scrubber for SOx and making steam of 10 bar to generate electricity with the exhaust gas heat.

In chapter 7 the SJAC-ESP is compared with alternatives, with regard to financial implications. It can be concluded that the SJAC-ESP is not the most logic option for inland shipping. Using a fuel with road-quality and a diesel particulate matter filter seem better options. For sea shipping the SJAC-ESP is the best option. A wet scrubber is a cheaper option, also per kg removed particulate matter, but is not expected to be as efficient for sub-micron particles as the SJAC-ESP. For sea-shipping, use of a road-quality fuel and a diesel particulate matter filter is much more expensive than using SJAC-ESP.
Samenvatting

Fijn stof, in het Engels ook wel “particulate matter” genoemd, beïnvloedt klimaat en weer en heeft nadelige gevolgen voor de volksgezondheid. Nederland is het Europese land met het grootste verlies aan levensjaren ten gevolge van de menselijke emissie van fijn stof. Merk op dat de Nederlandse naam fijn stof wat ongelukkig is gekozen omdat ook in de lucht zwevende vloeistof onderdeel kan uitmaken van fijn stof. Tweederde van het fijn stof in de Nederlands lucht wordt in het buitenland uitgestoten. Dit geeft duidelijk aan dat fijn stof een grensoverschrijdend probleem is, maar ook dat emissies op zee invloed kunnen hebben op de fijn stof concentratie op land. De bijdrage van de scheepvaart aan de fijn stof concentratie in Nederland is net zo groot als de bijdrage van de Nederlandse industrie. Het wordt geschat dat wereldwijd 60 000 mensen jaarlijks vroegtijdig overlijden ten gevolge van de emissie van fijn stof door de zeescheepvaart. De verwachting is dat dit in 2012 met 40% is toegenomen.

Er zijn vier oplossingsrichtingen denkbaar om de emissie van scheepvaart te reduceren: minder scheepvaart, efficiëntere scheepvaart, gebruik van andere brandstof of rookgasreiniging. Het grote voordeel van rookgasreiniging boven de andere oplossingen is dat het weinig nadelige gevolgen heeft en dat het in principe relatief eenvoudig toepasbaar is voor bestaande schepen. Helaas is geen van de bestaande rookgasreinigingstechnieken erg geschikt om toe te passen in de scheepvaart in combinatie met de momenteel gebruikte brandstoffen, zie hoofdstuk 2. Daarom dient een nieuwe rookgasreiniging ontwikkeld te worden voor fijn stof van schepen, die zowel werkt voor zware scheepvaartbrandstoffen als voor schonere destillaatbrandstoffen. Dit is het belangrijkste onderwerp van dit proefschrift.

In hoofdstuk 3 wordt het verschil bestudeerd tussen het gebruik van een middelzware scheepvaartbrandstof en een destillaatbrandstof, wat betreft de emissie van fijn stof. De massa geëmitteerd fijn stof is 20 tot 30% lager met een destillaatbrandstof met 1,5% zwavel. Het aantal geëmitteerde deeltjes is ongeveer 60% lager met een destillaatbrandstof.

In hoofdstuk 4 wordt de ontwikkeling van de SJAC beschreven. De idee is dat, als de fijn stof deeltjes vergroot worden, ze met conventionele techniek afgevangen kunnen worden. De deeltjes worden vergroot door condensatie van stoom. Deze stoom wordt geïnjecteerd in koud, bij voorkeur verzadigd, uitlaatgas, waardoor een oververzadiging ontstaat en de deeltjes als groeikern dienen. In dit geval was de conventionele techniek een cycloon. Metingen gaven aan dat maximaal 25% van de massa fijn stof verwijderd werd. Een simulatie gaf aan dat dit percentage wel iets te verbeteren viel, maar dat meer dan 50% verwijderd fijn stof zeer onwaarschijnlijk is voor typische concentraties fijn stof in dieseluitlaatgas. Daarom werd de SJAC niet verder ontwikkeld.

Hoofdstuk 5 beschrijft de ontwikkeling van een nieuwe technologie, die SJAC-ESP heet. De idee is een zelfreinigend elektrostatisch filter, dat robuust genoeg is om toe te passen in schepen. De idee is dat de deeltjes worden voorzien van een waterlaagje waardoor ze niet blijven plakken aan het filter, maar van het filter stromen. Hierdoor houdt het filter zichzelf schoon. Het waterlaagje wordt gecreëerd door stoom te injecteren in koud, bij voorkeur verzadigd gas. Tot 82% van de massa fijn stof kan verwijderd worden met deze techniek.
Metingen toonden aan dat in een 100 kg per uur deelstroom van een 350 kW motor tussen de 41 en 70% van de massa fijn stof verwijderd werd door de SJAC-ESP. In de koelers werd daar bovenop nog maximaal 34% afgevangen. In de hele installatie werd tussen de 57 en 78% van de massa fijn stof verwijderd. Tussen de 70 en 83% van het aantal fijn stof deeltjes kleiner dan 1 micrometer werd verwijderd. De SJAC-ESP blijkt relatief ongevoelig voor de deeltjesgrootte, en is dus zeer geschikt om submicron deeltjes te verwijderen. Ook wordt er een klein percentage SOx afgevangen, voor destillaatbrandstoffen ongeveer 50% en voor de brandstof met 1.5% zwavel ongeveer 30%.

Een duurtest is uitgevoerd, waarbij de installatie 142 uur bedreven is over een periode van 500 uur. Het meest frequent operationele probleem was een koeler die na vervuiling een te hoge tegendruk veroorzaakte. Uiteindelijk bleek de koeler onvoldoende capaciteit te hebben. Het wordt sterk aanbevolen om nogmaals het duurgedrag te testen, met de focus op of er geen problematische opbouw van fijn stof op het elektrostatisch filter plaatsvindt.

Er is een simulatie gemaakt van de SJAC-ESP. De simulatie is echter nog niet voldoende precies om alle gevolgen van een verandering in parameters te voorspellen. De eerste verbetering zou een betere beschrijving van de oplaadsectie van het elektrostatisch filter moeten zijn.

Belangrijk voor daadwerkelijke toepassing van de SJAC-ESP is dat het fijn stof weer van het water gescheiden wordt en dat het water voldoende schoon is om te lozen. In hoofdstuk 6 wordt de watersamenstelling bekeken en worden een aantal oplossingsrichtingen voorgesteld voor waterreiniging. Daarnaast wordt in dit hoofdstuk besproken wat nog meer goed in het systeem zou passen. Zo zou een direct contact koeler goed in het systeem passen. Zo’n koeler heeft het voordeel dat het kan dienen als een natte wasser voor SOx. Daarnaast is er de mogelijkheid om hoge druk stoom te maken met de uitlaatgaswarmte. De stoom kan gebruikt worden om extra elektrisch vermogen op te wekken via een stoomturbine.

In hoofdstuk 7 wordt vervolgens gekeken hoe de SJAC-ESP zich verhoudt tot de alternatiefen, als het gaat om financiële inspanningen. De conclusie is dat voor de binnenvaart de SJAC-ESP niet de meest logische optie is. Het gebruik van brandstof met dezelfde kwaliteit als wegvervoer en een roetfilter lijkt hier een betere optie. Voor de zeescheepvaart is het een ander verhaal. Hier is de SJAC-ESP de beste optie. Een natte wasser is weliswaar goedkoper, ook per kg fijn stof verwijderd, maar het is de verwachting dat deze niet zo effectief is voor deeltjes die kleiner zijn dan 1 micrometer als de SJAC-ESP. Een roetfilter met een brandstof die weinig as bevat is duidelijk duurder dan de SJAC-ESP.
Nomenclature

Symbols:
A  
Area \( [m^2] \)
a  
Acceleration \( [m/s^2] \)
B  
Mechanical mobility \( [m/(Ns)] \)
b  
Number of collisions \([-]\)
C_c  
Cunningham correction factor \([-]\)
C_E  
Humidity correction break-down field \([-]\)
c  
Particle concentration \( [1/m^3] \)
\( \bar{c} \)  
Average concentration
\( c_p \)  
Heat capacity \( [J/(kgK)] \)
\( c_q \)  
Charge concentration \( [C/m^3] \)
D  
Diffusion coefficient \( [m^2/s] \)
d  
Derivative of the following variable
\( d \)  
Diameter (formula 2.2.14) \([m]\)
dbe  
Distance between electrodes \([m]\)
E  
Electric field \([V/m]\)
e  
Exponent (Mathematical constant, 2.71828...)
ec  
Elemental charge \( [1.6 \times 10^{-19} C] \)
F  
Force \([N]\)
FCI  
Fixed capital investment \([\text{€}]\)
FS  
Fuchs-Sutugin correction factor
f  
Probability density function \([-]\)
g  
Gravitational constant \( [9.81 m/s^2] \)
H  
Enthalpy \([J]\)
\( \dot{H} \)  
Enthalpy change \( [J/s] \)
h  
Specific enthalpy \( [J/kg] \)
I  
Current \([A]\)
i  
Interest \([-]\)
J  
Collision rate \( [1/(m^3s)] \)
j  
Molar flux \( [\text{mole/(m}^3\text{s}]] \)
\( j_q \)  
Charge flux \( [C/(m^3s)] \)
K  
Coagulation coefficient \( [m^3/s] \)
\( K_E \)  
Coulomb constant \( (=1/(4\pi\varepsilon_0)) [9.0 \times 10^9 N\text{m}^2/C^2] \)
\( K_Z \)  
Acid constant
k  
Thermal conductivity \( [J/(mKs)] \)
k_b  
Boltzmann’s constant \( [1.38 \times 10^{-23} J/K] \)
L  
Length \([m]\)
M  
Molecular weight \( [kg/mole] \)
m  
Mass \([kg]\) unless specified differently
\( \dot{m} \)  
Mass flow \([kg/s]\)
N  
Number of particles \([-]\)
\( \dot{N} \)  
Number per second \([-/s]\)
n  
Amount of moles \([\text{mole}]\)
ne  
Number of elemental charges \([-]\)
**Greek symbols:**

- $\alpha$: Accommodation coefficient [-]
- $\alpha_i$: Likelihood of sticking [-]
- $\beta$: Depreciation factor, defined in formula 7.3.4, [-]
- $\Delta$: Change in variable following $\Delta$
- $\delta$: Variable that indicates the size of the temperature gradient (see formula 4.4.34) [-]
- $\varepsilon_0$: Permittivity of vacuum [8.854 $10^{-12}$ F/m]
- $\varepsilon_r$: Permittivity of material relative to vacuum [-]
- $\zeta$: Time constant, see formula 5.4.15 [s]
- $\eta_{tot}$: Particle removal in total system [-]/[%]
- $\eta_{SJAC}$: Particle removal by SJAC [-]/[%]
- $\kappa$: Dimensionless parameter, see formula 5.4.19 [-]
- $\lambda$: Mean free path [m]
- $\mu$: Dynamic viscosity [Pa·s]
- $\xi$: Unit in calculation for coagulation coefficient [m]
- $\pi$: Mathematical constant ($3.14159...$)
- $\rho$: Density [kg/m$^3$]
- $\sigma$: Surface tension [N/m]
- $\tau$: Relaxation time [s]
- $\Phi$: Flow [m$^3$/s]
\[ \nabla \] Gradient (i.e. the sum of all partial derivatives)
\[ \partial \] Partial derivative

**Subscripts:**

0 \quad \text{Value at } t=0

110\degree C \quad \text{At a temperature of } 110\degree C

300\degree C \quad \text{At a temperature of } 300\degree C

A \quad \text{Aerodynamic}

ae \quad \text{At electrode}

after pre-cooling \quad \text{At a location after pre-cooling}

after SJAC \quad \text{At a location after the SJAC}

agg \quad \text{for agglomeration}

av \quad \text{Average}

before pre-cooling \quad \text{At a location before pre-cooling}

c \quad \text{Collection section}

cond \quad \text{Condensed/Condensation}

D \quad \text{Drag}

d \quad \text{Drift}

D-A \quad \text{According to Deutsch-Anderson equation}

deg \quad \text{Dry exhaust gas (i.e. excluding water vapour)}

diff \quad \text{Diffusion charging}

e \quad \text{Electric}

eg \quad \text{Exhaust gas (i.e. including water vapour)}

eq \quad \text{Equilibrium}

fc \quad \text{Field charging}

g \quad \text{Gas}

grav \quad \text{Gravitational}

H_2O \quad \text{Water (referring to properties that are not specifically linked to vapour or liquid)}

i \quad \text{for any subscript integer}

in \quad \text{of entering species}

int \quad \text{Total internal}

ion \quad \text{ions}

is \quad \text{ionisation section}

j \quad \text{for any subscript integer}

k \quad \text{for any subscript integer}

kin \quad \text{kinetic}

l \quad \text{liquid}

max,R \quad \text{Rayleigh limit (upper limit)}

mixed \quad \text{After mixing (and before condensation)}

n \quad \text{Normal conditions (T=273.15K, p=1.013 bar)}

ne \quad \text{Number of electrons}

onset \quad \text{Minimum for corona discharge}

out \quad \text{of exiting species}

p \quad \text{Particle (except for c_p, see symbols)}

part \quad \text{Particle (for concentration)}

pot \quad \text{Potential}
pp Per particle
r Radial direction
rel Relative
s At the surface
sat Saturation
set Settling
shaft Shaft
steam Injected steam
T Thermal
ta Terminal
v Water vapour, i.e. all water vapour present in the gas
volatile Volatile matter
wire High-voltage electrode in ionisation section
x In x-direction
y In y-direction
→ Towards
∞ At a location infinitely far away
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Chapter 1. Introduction
Air quality has become an important topic over the last decades. One of the air pollutants is particulate matter, which can be described as all non-gaseous pollutants. Particulate matter may have an effect on climate, by either enhancing or reducing global warming, dependant on the composition of particulate matter. Additionally it has an influence on the weather, because the particles will act as droplet condensation nuclei. This will result in less frequent, but heavier rainfall. However, the biggest reason for concern of particulate matter are the health effects. According to [Cofala et al., 2007], the Netherlands is one of the countries in Europe with the largest loss of life expectancy due to particulate matter emissions from anthropogenic sources. Approximately two third of the anthropogenic sources of particulate matter in the Netherlands is not emitted on Dutch territory, according to [Buijsman et al., 2005]. This indicates the trans-boundary nature of the particulate matter problem. Comparing the absolute emissions in the Netherlands including sea shipping on the Dutch continental shelf leads to the conclusion that 26% of the national particulate matter emission is stemming from traffic, excluding sea shipping, 23% from industry and 18% from sea shipping (based on data from [Van Dril et al., 2005]). Sea shipping is thus a significant source of particulate matter. [Hammingh et al., 2007] confirm this, by estimating that 5% of the particulate matter concentration in the Netherlands is stemming from sea shipping. This contribution is just as large as the contribution of the industry sector in the Netherlands to the particulate matter concentration. In contrast to the particulate matter emissions of the industry and transport sector, which are steadily decreasing, particulate matter emissions from sea shipping are expected to increase, because of the expected increase of shipping traffic. The importance of the particulate matter emissions of sea shipping is further underlined in [Cofala et al., 2007] and [Corbett et al., 2007]. [Cofala et al., 2007] show the influence of different measures to reduce the emission of particulate matter emissions from shipping on the average lost of life expectancy. From their data it can be seen that a significant reduction decreases the lost of life expectancy up to 20 to 50% for several regions. Figure 1.1, after [Corbett et al., 2007], shows the health effects of sea shipping over the world in absolute number of people that die annually prematurely, due to the particulate matter emission from sea shipping.

![Figure 1.1 Mortality due to sea shipping. Reprinted with permission from [Corbett et al., 2007]. Copyright (2008) American Chemical Society](image)

Especially large cities close to shipping routes experience the negative effects of the particulate matter emission from shipping. According to [Corbett et al., 2007] 60 000
people worldwide die annually prematurely due to particulate matter emissions from ships. This is expected to increase with 40% by 2012 if no measures are taken.

Therefore the particulate matter emission from shipping should be reduced. The problem with particulate matter emissions from sea shipping is that sea ships may use a fuel that contains a relatively large amount of sulphur and ash. Sulphur level may be as high as 4.5% and the ash level as high as 0.15% mass per mass fuel. Such a fuel is cheap, but poses serious challenges to the reduction of particulate matter emissions. The high ash content of the fuel indicates that a perfect combustion will still lead to a significant particulate matter emission.

Four different strategies can be applied to reduce the particulate matter emission from sea shipping. The first and most drastic strategy is to reduce shipping significantly. However, sea shipping is from fuel consumption point of view the most environmentally friendly means of transportation, expressed in ton fuel per ton goods transported over a kilometre, and therefore a modal shift, i.e. transport by truck or airplane instead of a ship, is undesirable. This would mean that the need for transportation should be reduced. However, this will have a major impact on the world economy, more specifically for those countries who export and import a lot of goods, or are big players in trans-shipment. The second strategy is to improve the efficiency of the transport of goods in ton fuel per ton goods per kilometre. This could be by building ships with less water resistance, by increasing the ship size, which generally leads to a more favourable ratio between fuel consumption and goods transported, by sailing slower, or by a more efficient propulsion system. A more efficient propulsion system can be accomplished by changes to the propeller or by changes to the engine. Changes to the engine could be the optimisation of the diesel engine, the useful application of exhaust gas and cooling water heat, by for example a steam turbine or a steam injected diesel (STID, see e.g. [Chomiak et al., 2004]) or different engine concepts, like diesel-electric propulsion, a combination of gas turbine and steam turbine, or fuel cell systems, although for the latter a different fuel is required. The third option is to use a different fuel than the heavy fuel oil. The present proposal of the international maritime organization is to use a fuel with maximally 0.5% sulphur in 2020 (or an equivalent emission in particulate matter and sulphur oxides), see [IMO, 2008]. It is likely that oil companies will have to refine (part of) their heavy fuel oil to obtain these sulphur levels, although blending of relatively low-sulphur heavy fuel oil with distillates may be an option as well. This will significantly increase the price of sea shipping, as a more expensive fuel needs to be used. Even cleaner fuels could be used, like road-quality diesel, petroleum gas, natural gas, hydrogen or biofuels. However, they come at a significantly higher price. Note that not every fuel will actually solve the particulate matter problem. The fuel proposed by IMO, for example will still require an additional improvement to reduce the particulate matter emission. The fourth and last option is to reduce the particulate matter concentration in the exhaust gas by an aftertreatment technique. This has the major advantage that in principal, it can be used in existing ships. It has little or no effect on the infrastructure, and could be the most cost effective option to reduce particulate matter. Several techniques are on the market to decrease the particulate matter emission from diesel combustion. Those are an oxidation catalyst, a particulate matter filter, a wet scrubber and an ESP. However, those technologies are less suitable for the presently used fuel, or impossible to use for shipping application, as will be discussed in more detail in chapter 2.
As discussed above, reduction of particulate matter from shipping is required, but reduction of shipping is less desirable because of the impact on the world economy. Improving the efficiency of shipping should be strongly encouraged, as it will reduce fuel consumption, and might even prove profitable. However, it is questionable whether this will alleviate the particulate matter problem sufficiently. Changing fuel may have a large impact on the particulate matter emissions, depending on the chosen fuel, but is expensive. Using an aftertreatment technique is interesting, as it has a limited impact on the present situation, and it is suitable for application in existing ships. The existing aftertreatment devices, however, each have their own drawbacks.

Therefore an aftertreatment technology should be developed to reduce the emissions of particulate matter from shipping. This aftertreatment technology should be fuel insensitive, and more importantly should work for heavy fuel oil as well as distillate fuels. In this thesis such a technology is developed. Additionally, the financial implications of this technology are investigated.

Chapter 2 discusses the composition and formation mechanisms of particulate matter from diesel engines, and the influence of the particle shape on the transport behaviour of particulate matter. It continues with discussing the health effects of particulate matter, a discussion on measuring particulate matter and a discussion on the present particulate matter reduction devices, that might be suitable for application in ships. Chapter 3 shows the results of an experimental study on the influence of different diesel fuel on the emission of particulate matter. Chapter 4 describes an experimental study and a model of a new technology to reduce particulate matter, called SJAC. In chapter 5 the SJAC-ESP concept is discussed. An experimental study is performed and a computer model is developed. Chapter 6 discusses the impact of the SJAC-ESP on exhaust gas system design. Chapter 7 investigates the market potential of the SJAC-ESP, based on a case for inland shipping and for a ferry. Lastly chapter 8 concludes with the conclusion and recommendations for further research.
Chapter 2. On particulate matter and its treatment
§2.1 Introduction

In this chapter background information on particulate matter emissions by diesel engines on ships is given as far as relevant for this thesis. The chapter starts with an explanation of what the composition of particulate matter is, and how it is formed. Subsequently the physical behaviour of particulate matter is explained. This information is necessary to understand the health effects of particulate matter, as well as to understand the issues involved in measuring particulate matter, which are discussed afterwards. Subsequently the legislation for the shipping business with regard to particulate matter is treated. Finally the state of development of aftertreatment devices is presented. That section is an updated and more generalised version of work performed by the author for the European project CREATING on inland navigation, performed in the framework of FP6 [Van Rens and De Wilde, 2005].

§2.2 What particulate matter is

§2.2.1 Composition of particulate matter

Particulate matter (or PM) is a general term for all non-gaseous pollutants. From this point on particulate matter will refer to all non-gaseous pollutants in the exhaust gas of internal combustion engines. Particulate matter consists of several components. The exact composition depends on fuel composition and measurement conditions. Particulate matter is composed of three main fractions. The first fraction is the insoluble fraction. This is the basis of particulate matter. It contains elemental carbon from incomplete combustion and ash. Ash is stemming from the fuel, burned lube oil and engine wear. The second fraction is called the soluble organic fraction (SOF). This is a complicated mixture of condensed organic compounds, either hydrocarbons, oxygenated hydrocarbons or nitro-polycyclic aromatic hydrocarbons. The third fraction consists of sulphates. Sulphates are formed by reaction of SO$_3$ with water. These sulphates can condense on the particulate matter. They can add significantly to the mass of emitted particulate matter.

The influence of fuel on the composition of particulate matter is illustrated in Figure 2.1 from data of [Gömalm, 1991]. The left figure shows the particulate matter composition for a marine gas oil (MGO), a relative clean, low-ash fuel which contains 0.1% sulphur; the right figure for a heavy fuel oil (HFO), or residual fuel, which can contain up to 0.15% ash and in this case contained 3% sulphur. It is crucial to realise that even if the combustion process is ideal, the engine would still be emitting particulate matter stemming from fuel ash and fuel sulphur.
§2.2.2 Formation of particulate matter and the resulting particle shape

The formation of particulate matter is related to its components. Therefore several mechanisms play a role in the formation of particulate matter. In this section it is opted to describe what is happening with particulate matter, starting from the moment of fuel injection until just after the exhaust gas leaves the tailpipe of the diesel engine.

For the description of the combustion process, the conceptual model of [Dec, 1997] is used, which is based on laser sheet imaging. This model is an improvement of the general understanding, with the major improvement that soot formation inside the flame is expected [Rente, 2003], as is found in measurements from e.g. [Dec, 1997] and [Ganippa, 2003], and simulations, e.g. [Tao, 2003]. The conceptual model describes the combustion process from the moment of fuel injection until just before the end of the diffusion controlled combustion. It does however not describe the end of the diffusion controlled combustion, which might be important for the actual emission of elemental carbon. The actual chemistry involved in soot formation is too complex to explain here in detail. Here the qualitative description of [Heywood, 1989] is used to explain the influence of the combustion model of [Dec, 1997] on soot formation in more detail. For further reading on the chemistry involved in soot formation, see e.g. [Tao, 2003].

Before and during the combustion process, liquid fuel is injected at high pressure in the cylinder as a liquid. The liquid stream breaks up in small droplets, which will subsequently vaporise by entrainment of hot air. As long as the fuel does not combust the fuel vapour air mixture will continue mixing with air, however, the fuel vapour air mixture is still rich of fuel before initial combustion. At some point initial combustion will take place and the fuel air mixture will combust volumetrically, i.e. over the entire volume of the fuel air mixture. This combustion is called pre-mixed combustion. Given the fact that this mixture is rich of fuel the combustion will be incomplete. During this incomplete combustion large hydrocarbons are formed. They mainly consist of alkynes and poly-aromatic hydrocarbon that are formed by pyrolysis and reactions of small hydrocarbon species, mostly acetylene. When these large hydrocarbons reach a certain size, they will condense. The condensation products are still very small, approximately 2 nanometres in diameter. At the edge of the combustion zone, more oxygen is present than in the core of the combustion. Shortly after the initial combustion, and before all oxygen inside the core is used, a diffusion controlled flame is developing along the edge of the combustion zone. On the air-rich side of the
flame the hydrocarbons and small soot particles will oxidise rapidly. On the fuel-rich side of the flame it was found that the particles are significantly larger and present in higher concentration than in the centre of the volumetric combustion. The temperature at the diffusion flame surface is very high and the fuel vapour at the fuel-rich side of the flame may continue to pyrolyse. The particles have grown, probably by surface growth with acetylene and by coagulation, i.e. the process where particles collide and merge into larger particles. Because the small particles of “young soot” are still quasi-liquid, they will merge in spherically shaped particles after collision. At some point the oxygen in the pre-mixed air-fuel mixture runs out and the remaining “fuel” should be combusted at the air-fuel interface in the diffusion controlled flame. This is the mixing-controlled combustion, already known from measurements of the heat-release in the cylinder. However, as long as fuel is injected, fuel and air will continue to mix close to the fuel injector. This fuel rich mixture first combusts incompletely in a pre-mixed flame according to the model of [Dec, 1997]. The products of incomplete combustion are subsequently combusted in the diffusion controlled flame. Note that the combustion in the mixing-controlled combustion phase is not volumetric throughout the entire flame. The flame front develops into a tadpole-shape. In the head of this tadpole shape a recirculating vortex is present, which contains a high soot concentration with large particles. This vortex circulates just underneath the flame front, which means it is subject to high temperatures and fuel pyrolysis and surface growth are expected to play a role. However collisions between particles will be frequent and particle enlargement by coagulation will be important. At this moment the model of [Dec, 1997] finishes, and the influence of flame quenching on particulate matter concentration is not incorporated in the model. When the small particles loose their quasi-liquid behaviour, the colliding particles will form chain-like structures of spherical particles. Such a particle may consist of up to 4000 spherules, in which case it would be approximately 1 μm big. These structures are quite irregularly shaped.

Note that soot oxidation has a big influence on final soot emission [Chomiak, 1993]. Another important thing to realise is that the more aromatics the fuel contains the more likely it is to form soot, [Karila et al, 2004] and [Ricardo]. This is most likely due to the fact that the aromatics are more difficult to break down during combustion and are more likely to form large poly-aromatic hydrocarbons.

The ash in the fuel goes through the same temperature regime as the rest of the fuel, which implies that the ash liquefies or volatilises in the high temperature of the flame and condenses and solidifies, when cooled down. [Lyyränen et al., 1999] hypothesise that fuel ash may act as condensation nuclei for carbonaceous material, although they do not distinguish between volatile organic compound and elemental carbon.

During the expansion stroke of the diesel engine the exhaust gas cools down. When the exhaust gas cools down below 500°C, gaseous hydrocarbons will start to condense on or are adsorbed on particulate matter, [Helmantel, 2006] and [Karila et al., 2004]. This fraction is called the soluble organic fraction. This process will continue in the exhaust gas pipe. The gaseous hydrocarbons are formed during the combustion process, in a process similar to soot formation, or stemming from unburned fuel and lubrication oil.

Sulphur oxides are formed from the combustion of sulphur in fuel and lubrication oil. The formation of sulphur oxides can only be prevented by taking sulphur out of the fuel and lubrication oil. Especially the SO3 in the sulphur oxides will react with water and will form sulphuric acid below a certain threshold temperature, which depends strongly on sulphur
content of the fuel. As the condensation of sulphuric acid will lead to excessive corrosion, it is generally avoided to have an exhaust gas temperature below the threshold temperature. For ships using heavy fuel oil, the exhaust gas temperature is not lowered below 180°C. However, in the atmosphere or in the measurement devices sulphuric acid may be formed by the reaction of water and SO₃. This condensation will prefer existing kernels, i.e. the existing particulate matter, but if the supersaturation is very high separate particles may be formed.

Since condensation is influenced by temperature and dilution of the exhaust gas, the composition, and hence size, of the particles in the exhaust gas pipe may be completely different from the composition and size during measurement or in ambient air.

When measuring the size distribution with devices with high solubility like an SMPS, see section §2.4.3, typically two particle modes are observed, according to [Mariq et al., 2002]. A so-called accumulation mode is always present. As the name indicates this is a mode of agglomerated soot particles possibly coated with hydrocarbons and sulphates, with a mean diameter typically between 50 and 100 nanometres for light-duty vehicles. Sometimes a nucleation mode is observed. This mode consists of small nucleated particles, with a mean diameter typically between 10 and 30 nanometres. According to [Mariq et al., 2002] the nucleated particles stem from the condensation of semi-volatile organic gases or sulphates, which would explain why this mode is not always observed. [Karila et al., 2004] state more general that this mode may not contain any elemental carbon.

The influence of different fuels on the particle size distribution is treated in Chapter 3.

§2.2.3 Physical characteristics of (non-spherical) particles

As mentioned in §2.2.2 particulate matter can have an irregular shape. The particle shape has a big influence on the behaviour of the particles. In this study however, not the exact geometry of every particle is of interest, but the behaviour, and more in particular dynamic behaviour, of the particles under certain conditions. It is crucial to understand the behaviour of these particles as this behaviour is not only important for the health effects, but also for measuring and removing particulate matter. Theoretically it is possible to derive the behaviour of the particle from the exact geometry, but this is not particularly straightforward. In this section, therefore, a more phenomenological approach is used. The focus is on the behaviour of the particles, and from this behaviour appropriate properties in the form of a radius and density are defined. A more detailed overview can be found in e.g. [Schmid et al., 2007].

An important parameter is the velocity that a particle obtains after infinite time, when it is subject to a constant force. This is important for diffusion of particles, i.e. the movement of particles due to a concentration gradient or a charged particle in an electric field. After infinite time acceleration phenomena are non-existent and the constant force on the particle must equal the drag force of the particle. The relationship between the velocity of a particle after infinite time and the force on the particle is called the (mechanical) mobility. It is expressed in formula 2.2.1.

\[ B = \frac{u}{F} \]

Formula 2.2.1
With \( B \) the mechanical mobility in \( \text{m}/(\text{N} \cdot \text{s}) \), \( u \) the velocity of the particle relative to the gas velocity after infinite time in \( \text{m/s} \) and \( F \) the force on the particle in \( \text{N} \). As will be discussed in following sections, mechanical mobility is important for measuring devices and particulate matter removal devices. The results of those measuring devices are given as a mechanical mobility equivalent diameter or radius. This is the diameter or radius of a spherical particle with the same mechanical mobility as the irregularly shaped particle. For ease of use, and to distinguish it from diameters measured with different devices it is often shortened to the ‘mobility diameter’. The mechanical mobility is often shortened to ‘mobility’. How the mobility is related to the radius of spherical particles is explained below in formulae 2.2.2 to 2.2.4.

For round particles the drag force is expressed by Stokes’ law (with particle Reynolds number smaller than 1) in formula 2.2.2.

\[
F_D = \frac{6\pi \mu_g \cdot u \cdot r_p}{C_c} \quad \text{Formula 2.2.2}
\]

With subscript \( D \) for drag, parameter \( \mu_g \) the dynamic viscosity of the gas, \( r_p \) the particle radius, which is for round particles equal to the mobility radius, and \( C_c \) the Cunningham correction factor. The Cunningham correction factor corrects the assumption in Stokes’ law that the relative velocity at the surface is zero, which does not hold for sub-micron particles. The Cunningham correction factor is given in [Hinds, 1999] as formula 2.2.3.

\[
C_c = 1 + \left( 1.17 + 0.525 \cdot \frac{\lambda}{r_p} \right) \cdot \frac{\lambda}{r_p} \quad \text{Formula 2.2.3}
\]

With \( \lambda \) the mean free path of the gas, i.e. the average distance travelled by a molecule between successive collisions [Hinds, 1999].

Using formulae 2.2.1 to 2.2.3 a relationship between the mobility equivalent radius and the mobility is obtained; see formula 2.2.4.

\[
B = \frac{C_c (r_B)}{6\pi \mu_B} \quad \text{Formula 2.2.4}
\]

Subscript \( B \) is used to indicate mobility equivalent radius.

Note that the mobility radius is not dependent on the particle mass and particle density.

The electrical mobility is a derivative of the mechanical mobility. It is defined as the influence of an electric field on the velocity of a particle, see formula 2.2.5. Since the force on the particle by an external electric field is defined by the charge of the particle times the electric field, the electrical mobility can alternatively be described as the particle charge times the mechanical mobility of the particle.

\[
Z \equiv \frac{u}{E} = \frac{u}{F/\rho} = q_p B \quad \text{Formula 2.2.5}
\]

With ‘\( Z \)’ the electrical mobility in \( \text{m}^2/(\text{V} \cdot \text{s}) \), \( E \) the electric field in \( \text{V/m} \), and \( q_p \) the particle charge in \( \text{C} \).

Another important property of the particle is its inertia. The lower the inertia of a particle, the more it will behave like a gas. The higher the inertia the more the particle tends to deviate from the gas stream, when it is subject to accelerative forces. When a particle is
subject to an acceleration force, like gravity or a centrifugal force the velocity after infinite
time is given by formula 2.2.6, if the buoyancy force of the air is ignored.

\[ u_{ta} = F \cdot B = m_p \cdot B \cdot a \]  \hspace{1cm} \text{Formula 2.2.6}

With subscript ‘ta’ terminal velocity due to acceleration forces, \( m_p \) the mass of the particle
and ‘a’ the acceleration on the particle.
Note that \( m_p \cdot B \) is only dependent on the particle, and not on the device in which it
experiences the acceleration. In aerosol science this is called the relaxation time, which is
given by formula 2.2.7.

\[ \tau = \frac{u_{ta}}{a} = m_p \cdot B \]  \hspace{1cm} \text{Formula 2.2.7}

For a spherical particle formula 2.2.7 can be rewritten in the form of formula 2.2.8, and the
relaxation time is a function of gas properties and particle radius and density.

\[ \tau = \frac{4}{3} \pi \rho_p r_p^3 \cdot \frac{C_c}{6 \pi \mu_g r_p} = \frac{2 \rho_p r_p^2 C_c}{9 \mu_g} \]  \hspace{1cm} \text{Formula 2.2.8}

With \( \rho_p \) the density of a spherical particle in kg/m\(^3\).
The relaxation time is important for deposition. In aerosol science two relaxation time
dependent radii are defined for illustrative purposes. One is the Stokes’ radius, which is the
radius of a spherical particle with the same relaxation time as the particle and same density
as the bulk material of the particle. However, it is more common to use the aerodynamic
radius or diameter. The aerodynamic radius is defined as the radius of a spherical particle
with the same relaxation time as the original particle and an assumed particle density of
1000 kg/m\(^3\), and is expressed in formula 2.2.9:

\[ \tau = \frac{2 \rho_A r_A^2 C_c(r_A)}{9 \mu_g} \]  \hspace{1cm} \text{Formula 2.2.9}

With subscript ‘A’ for aerodynamic and \( \rho_A \) defined as 1000 kg/m\(^3\).
The mobility radius is related to particle mass by defining a mobility equivalent density of
the particle, which is simply the particle mass divided by the volume of a spherical particle
with the same mechanical mobility, see formula 2.2.10.

\[ \rho_B = \frac{3 m_p}{4 \pi r_B^3} \]  \hspace{1cm} \text{Formula 2.2.10}

Note that for spherical particles, the mobility equivalent density is the actual particle
density, and if additionally the particle has no inclusions, it is equal to the density of the
bulk material.
The aerodynamic and mobility radius can be related to each other by expressing the
relaxation time based on mobility radius and setting this equal to the relaxation time based
on the aerodynamic radius, leading to formula 2.2.11.

\[ r_A^2 C_c(r_A) = r_B^2 C_c(r_B) \]  \hspace{1cm} \text{Formula 2.2.11}

Note that formula 2.2.11 also means that for spherical particles, the mobility and aerodynamic
radius are not equal, unless the mobility equivalent density is equal to 1000 kg
/m\(^3\).
The mobility equivalent density for non-spherical particles is not easily determined. It is either determined by measuring both the mass of a particle and the mobility radius, or determining both the mobility equivalent radius and the aerodynamic radius.

The main problem in describing the mobility equivalent density is that particulate matter is a collection of different “materials” which might have coagulated with each other and might have condensation of foreign material. This means that there is not a single density which appropriately describes the variety of densities. The general approach is to describe an average density for every mobility equivalent radius. Because a cluster of spheres has a larger frontal area in comparison to its volume than one large sphere, it is expected that the cluster of spheres has a lower density in comparison to its frontal area. In addition to this, the shape of a sphere is quite optimal in relation with the drag coefficient. Because drag is related to frontal area and particle shape, it is expected that particles with a larger particle mobility radius have a lower density than particles with a lower particle mobility radius.

For the case of diesel particulate matter quite some studies are performed with regard to how mobility equivalent density depends on the particle mobility radius. Examples are [Van Gulijk et al., 2004], [Maricq and Xu, 2004] and [Park et al., 2003]. In all three studies empirical formulae were derived to convert the particle mobility diameter into particle mass. They all have in common that particle density decreases with increasing particle diameter.

Within this thesis the conversion formula for high loads as found by [Park et al., 2003] is applied for all loads whenever the mobility equivalent radius is converted to particle mass. In common SI-units this formula is expressed in formula 2.2.12.

\[
mp = 3.75 \cdot 10^{-2} \cdot r_B^{2.33}
\]

Formula 2.2.12

With \(m_p\) the mass of a particle in kg and \(r_B\) the mobility equivalent radius in metres.

Alternatively this formula can be expressed as a formula for the mobility equivalent density, using formula 2.2.10.

\[
\rho_B = \frac{2.82 \cdot 10^{-2}}{\pi \cdot r_B^{0.66}}
\]

Formula 2.2.13

From formula 2.2.13 it can be found that the mobility equivalent density equals 1000 kg/m\(^3\) for particles with a mobility radius of 22.5 nm. This means that particles with a mobility radius of 22.5 nm have an aerodynamic radius of 22.5 nm too. Particles smaller than 22.5 nm have a smaller mobility radius than aerodynamic radius, whereas particles with a radius larger than 22.5 nm have a larger mobility radius than aerodynamic radius. Note that the results from this formula can only be used as an indication, as the actual conversion factor is engine, fuel and load specific.

§2.3 Health effects of particulate matter

The health effects of particulate matter are mainly found by epidemiological studies. However, as indicated by [Neubert, 1999] it is not possible to do a purely epidemiological study because the exact exposure is unknown, the exact composition of particulate matter in ambient air is uncertain and varying, and the exposure is never to particulate matter alone. So results of the epidemiological studies, and results of studies that estimate health effects,
like [Cofala et al., 2007] and [Corbett et al., 2007], as were presented in Chapter 1, should be treated with great care.

This section focuses on the expected effects of particulate matter on the lungs, based on the physical approach in [Sher, 1998] and [Hinds, 1999] and on the physiological effects of large exposure to similar components, like coal dust or cigarette smoke. The hazards of particulate matter depend on its composition and on where it ends up. For particles larger than 10 nanometres one can say that the smaller the particle, the further it will penetrate in the lungs. This is due to the way the protective system of the lungs works. Figure 2.2 illustrates the different parts of the respiratory tract.

![Figure 2.2 Schematic representation of respiratory tract [Sher, 1998]](image)

Large particles with an aerodynamic diameter larger than 7 μm are removed by inertial impaction in the nasal septum and turbinates. Particles between 0.7 and 7 μm are mainly removed by impaction in other parts of the airways when the flow direction is suddenly changed. Smaller particles are filtered by settling. This occurs when the air flow is so low that particles deposit due to gravity in the moist lining of the airways. Mainly particles with an aerodynamic diameter in the range of 0.5-0.7 μm deposit this way. Very small particles are mainly deposited by diffusion. Diffusion is governed by the mobility diameter of the particle and not the aerodynamic diameter, see section §2.2.2. As a general rule one can say that mainly particles with an aerodynamic diameter smaller than about 0.3-0.5 μm are deposited by diffusion. However, most inhaled particles larger than 100 nanometres leave the lungs when exhaling. A significant part of the particles smaller than 10 nanometres are captured in the nasal septum and turbinates. Although the small particles, between 10 and 100 nanometres are removed by diffusion throughout the entire lung system, the influence of diffusion is most pronounced in the alveoli, i.e. small lung sacs, in the acinus, see Figure 2.2.

Water soluble gases, like SO₂ and SO₃, are likely to be completely removed in the upper airways, and will not penetrate in the smaller airways. However, if SOx reacted to H₂SO₄ before it is inhaled, it may penetrate more deeply in the respiratory tract.

Particles that are deposited in the medium airways and before are captured in mucus, which is transported out of the lungs by little hairs that move the mucus upwards. The particles that are deposited in the small airways and the alveolar region cannot be removed this way because they do not have any mucus secreting cells and no cilia (i.e. the little hairs that
move the mucus upwards). Particles in the lower region of the airways can be removed by macrophages. When the body is working as it should, the particles are expelled in the mucus of the higher airways or through the lymphatic system [Richards van Zyl and Obenour, 2007]. The particles from the bronchial system are removed within a few days, but the particles in the alveolar region have a half-life of about 500 days [Neubert, 1999].

The effects of particulate matter emissions are not clearly described. Therefore it is opted to describe the health effects of two very different compounds, who are both similar to particulate matter; in this case coal dust and cigarette smoking. Note that the dose of the pollutant will play an important role in the actual effects of particulate matter. For exposure to coal dust the main threat is pneumoconiosis, also known under the name “black lung disease”. Accumulation of particulate matter in lungs is found in all urban dwellers to some extent. If the body is able to cope with this dose this is called anthracosis, and no symptoms will arise. The exposure becomes a problem if the natural defence becomes overwhelmed due to a high dose. The macrophages with dust will deposit in the alveolar region and may trigger an immune response. The macrophages will be coated with tissue. If the dust-laden macrophages partly entered the lymphatic system and then become coated with tissue they will slowly block the lymphatic system and arteries close by, which may ultimately lead to dying lung tissue due to restrained blood supply [Richards van Zyl and Obenour, 2007].

If the effects of particulate matter are similar to exposure of cigarette smoke, two effects are expected. It may cause inflammation of the respiratory tract leading to COPD, a chronic inflammation leading to reduced lung capacity, and it may cause lung cancer. The latter is related to the composition of particulate matter and most likely related to the amount and species of PAH adsorbed on the particle. Some polyaromatic hydrocarbons emitted by diesel engines are known carcinogens, other are probable or possible carcinogens.

It is questionable if particle mass is the determining factor, when it comes to health effects. For health effects the number of particles or the number of particles within a certain size range might be the determining factor. However, at the moment particle mass is legislated, as is shown in §2.5.

§2.4 Measuring particulate matter

§2.4.1 Introduction

The big challenge in measuring particulate matter is in the changing nature of particulate matter, with respect to temperature and dilution ratio. Because of this changing nature it is important to know beforehand what one wants to learn from the measurements, as it is crucial to adapt the measurements to the purpose. For estimating the health effects the particle size distribution in the exhaust gas pipe may not be of any interest and a measurement after cooling and dilution may be preferred, as this might simulate atmospheric processes. For studying the particulate matter removal of a removal device the particulate matter concentration in the exhaust gas pipe is of more interest from an engineering point of view. In this section only measurement technology is treated that was used in this research.
§2.4.2 Filter measurement

Particulate matter mass was not determined by dilution of exhaust gas, as described in ISO-8178-1 [ISO, 1996]. Although the method is sufficiently proven for fuels up to 0.8% sulphur in fuel it is still debated for fuels with higher sulphur content, due to the possibility of excessive condensation of H₂SO₄. The occurrence of this event will depend on dilution ratio.

In this study particulate matter mass was determined in undiluted exhaust gas. This way the measurement is only sensitive to sample temperature. In this thesis the filter temperature was kept at 383 K (110°C), unless noted otherwise. Note that the measured mass in this study can not be compared to measurement results according to ISO-8178-1, as mentioned in this method [ISO, 1996].

The gas was sampled isokinetically by J-shaped tubes. Isokinetic conditions were ensured by a vacuum compressor. In order to protect the compressor, water was removed from the sampled gas by a cooling bath and a silicagel dryer. The entire sample set-up is illustrated in Figure 2.3.

![Figure 2.3 Sample set-up for mass measurement of particulate matter](image)

The filter medium was a Whatmann QMA quartz fibre filter with a 99.95% retention efficiency for particles with a diameter of 300 nm. The filter was 50 mm in diameter. Before the measurement and the initial weight determination, the filter was preconditioned in an oven at the sample temperature of 110°C. Before determining the end weight, the filter was again heated in an oven to 110°C. The filter was placed in a filter holder in an oven during sampling. The pressure drop over the filter and volume of exhaust gas through the filter were measured. The weight of particulate matter and the volume through the filter were combined for an emission in mg/m³. Together with the temperature at the volume meter the emission was converted to an emission in mg/m₉. The emission can be converted to an emission in g/kWh by using the power consumption and exhaust gas flow.
§2.4.3 Scanning mobility particle sizer

The scanning mobility particle sizer (SMPS), or sometimes called scanning electrical mobility spectrometer is described in [Wang and Flagan, 1990]. In this section shortly the measurement principle is described. The SMPS consists of two parts, an ‘electrostatic classifier’ (EC) and a ‘condensation particle counter’ (CPC), schematically represented in Figure 2.4. Before the measurement of the particulate matter, the gas is dried and if necessary cooled down to approximately room temperature. Additionally large particles are removed by an impactor. The gas needs to be dried to avoid water condensation in the cooling process, which would negatively impact the functioning of the electrostatic classifier. The cooling is necessary for the condensation particle counter. Particles that are larger than the measurement window should be removed, because they might influence the measurement result. The dried and cooled exhaust gas with particles passes through a bipolar Krypton-85 charger, which will give the particles a known charge distribution. The charged particles subsequently enter a cylinder with an electric field. At the entrance of this cylinder, the exhaust gas is shielded from the central electrode by so-called sheath air, which in this thesis is cleaned and recycled exhaust gas. The charged particles are attracted to a central electrode under the influence of an electric field that is applied in the cylinder. Particles with certain electrical mobility exit through the central hole at the bottom of the cylinder. By changing the field strength particles with different electrical mobility are sampled. The particles that exit through the central hole go to the condensation particle counter. The exhaust gas is saturated with butanol, and subsequently the butanol condenses on the particles, thereby enlarging the particles. These particles are subsequently “counted” by the refraction of light due to the particles present. This way the number of particles with certain electrical mobility can be determined. Software converts the electrical mobility to corresponding particle radii, with the help of the transfer function of the device; see [Wang and Flagan, 1990] for more information. In a time period of three minutes the particle distribution is measured once. To be more accurate, the number of particles in a small bandwidth around a number of central diameters, also called midpoint diameters, was determined. The bandwidth increased exponentially, with increasing central diameters. Therefore the central diameters are plotted logarithmically. Generally a bandwidth independent number concentration density is calculated from the number of particles around a central diameter by formula 2.2.14 for every central diameter. This way the surface under a logarithmically plotted curve is representative for the total particle concentration.

\[
\frac{c}{10 \log(d)} = \frac{c_{\text{bandwidth}}}{10 \log\left(\frac{d_{\text{max}}}{d_{\text{min}}}\right)}
\]

Formula 2.2.14

With ‘c’ the concentration of particles in the bandwidth, \(d_{\text{max}}\) the maximum mobility diameter of the bandwidth around the central diameter, \(d_{\text{min}}\) the minimum mobility diameter of the bandwidth around the central diameter.


Figure 2.4 Schematic drawing SMPS

§2.5 Legislation on particulate matter

Particulate matter emissions in shipping are only directly limited for inland shipping. For sea shipping, particulate matter emissions are not limited. However, because ash and sulphur content in fuel are legislated, legislation has an indirect effect on the particulate matter emission. Present legislation is elaborated below, first for inland shipping and subsequently for sea shipping, followed by future emission limits for sea shipping.

For inland shipping a number of regulations are in place with regard to fuel specification and engine emissions. The regulations from the CCNR are summarised in Table 2.1, whereas the regulations for the European Union are summarised in Table 2.2.

<table>
<thead>
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<th>Nominal power [kW]</th>
<th>n [rev/min]</th>
<th>CO [g/kWh]</th>
<th>HC [g/kWh]</th>
<th>NOx [g/kWh]</th>
<th>PM [g/kWh]</th>
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<td>18≤P&lt;37</td>
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<td>5.5</td>
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<td>8.0</td>
<td>0.8</td>
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<td>37≤P&lt;75</td>
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<td>1.3</td>
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<td>1.0</td>
<td>6.0</td>
<td>0.3</td>
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<td></td>
<td>≥3150</td>
<td>3.5</td>
<td>1.0</td>
<td>6.0</td>
<td>0.2</td>
</tr>
</tbody>
</table>
Table 2.2 Maximum engine emissions inland shipping European union [EC, 2004]

<table>
<thead>
<tr>
<th>Engine displacement</th>
<th>Entry into force date</th>
<th>CO [g/kWh]</th>
<th>HC+NOx [g/kWh]</th>
<th>PM [g/kWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>D&lt;0.9, P≥37 kW</td>
<td>01.2007</td>
<td>5.0</td>
<td>7.5</td>
<td>0.40</td>
</tr>
<tr>
<td>0.9≤D&lt;1.2</td>
<td>01.2007</td>
<td>5.0</td>
<td>7.2</td>
<td>0.30</td>
</tr>
<tr>
<td>1.2≤D&lt;2.5, 37&lt;P&lt;75</td>
<td>01.2007</td>
<td>5.0</td>
<td>7.2</td>
<td>0.20</td>
</tr>
<tr>
<td>2.5≤D&lt;5</td>
<td>01.2009</td>
<td>5.0</td>
<td>7.2</td>
<td>0.30</td>
</tr>
<tr>
<td>5≤D&lt;15</td>
<td>01.2009</td>
<td>5.0</td>
<td>7.8</td>
<td>0.27</td>
</tr>
<tr>
<td>15≤D&lt;20, P≤3300 kW</td>
<td>01.2009</td>
<td>5.0</td>
<td>8.7</td>
<td>0.50</td>
</tr>
<tr>
<td>15≤D&lt;20, P&gt;3300 kW</td>
<td>01.2009</td>
<td>5.0</td>
<td>9.8</td>
<td>0.50</td>
</tr>
<tr>
<td>20≤D&lt;25</td>
<td>01.2009</td>
<td>5.0</td>
<td>9.8</td>
<td>0.50</td>
</tr>
<tr>
<td>25≤D&lt;30</td>
<td>01.2009</td>
<td>5.0</td>
<td>11.0</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Table 2.2 is derived from American legislation and already entered into force for inland shipping in the United States of America. The maximum sulphur level in fuel for inland shipping in Europe is determined in [EC, 2005], and summarised in Table 2.3.

Table 2.3 Fuel specification inland shipping with regard to fuel sulphur [EC, 2005]

<table>
<thead>
<tr>
<th>Entry into force</th>
<th>Sulphur content in fuel [mass/mass]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>present</td>
</tr>
<tr>
<td></td>
<td>From 01.2010</td>
</tr>
<tr>
<td></td>
<td>0.2%</td>
</tr>
<tr>
<td></td>
<td>0.1%</td>
</tr>
</tbody>
</table>

The prescribed measurement method for particulate matter in shipping is based on ISO 8178. The cycle to be used is described in ISO 8178-4 [ISO, 2007]. The measurement method is defined in directive 2004/26/EC, but is for particulate matter over a cycle for marine diesel engines similar to ISO 8178-1:1996 [ISO, 1996]. According to the measurement method the exhaust gas should be diluted and cooled to a maximum temperature of 52°C. Particulate matter should be measured at or below this maximum temperature. Water condensation during the dilution process should be avoided. Some serious objections can be made to this measurement method. First and foremost it does not simulate the atmospheric processes, as in reality water condensation may occur, and for shipping, where the source is relatively far from the immission, the temperature of 52°C after dilution is too high. Secondly the particulate matter mass may not be the correct parameter for health effects. The last objection to this method is that it does not contribute to a good understanding of the emission, because it contains a mixture of which a part is not represented well. For a better understanding, and modelling purposes, it would have been better, if only unchangeable components were measured. The other components could then be derived from modelling condensation from the gas phase during a typical dilution phase. Note that in practice the exhaust gas pipe geometry and velocity have an influence on the particle size distribution.

For sea shipping the amount of allowed fuel ash is dictated in ISO-8217 [ISO, 2005]. For the heaviest fuel the maximum fuel ash content is 0.15% mass of ash per mass of fuel. The limits get tighter with lighter fuels. Note that the ash in the heaviest fuel alone would lead to an emission of approximately 0.27 g PM/kWh. The sulphur in fuel is limited by the international maritime organization (IMO) to 4.5% mass sulphur per mass fuel. Some areas are designated as sulphur (oxide) emission control areas (SECAs). At the moment the Baltic Sea and North Sea, including English Channel are SECAs. In these areas the maximum allowable emission of SOx is equivalent to using a fuel of 1.5% sulphur. In
practice virtually all ships will fulfil this legislation by switching to a fuel with maximally 1.5% sulphur. From 2010 onwards, sea ships at berth in a harbour in Europe should use a fuel that maximally contains 0.1% sulphur [EC, 2005].

The annex that limits emissions of SOx and NOx is being reviewed. It is expected that the total text is available shortly after this thesis is being printed. The broad outlines, however, are already clear, and are summarised in Table 2.4. Note that the future limits for both SECA areas as well as global sulphur cap can also be fulfilled by an aftertreatment device that delivers an SOx-emission which is equivalent to using a fuel with the sulphur percentage as listed in Table 2.4.

<table>
<thead>
<tr>
<th>Now until end 2009</th>
<th>1.5%</th>
<th>4.5%</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010 until end 2011</td>
<td>1.0%</td>
<td>4.5%</td>
</tr>
<tr>
<td>2012 until end 2014</td>
<td>1.0%</td>
<td>3.5%</td>
</tr>
<tr>
<td>2015 until end 2019</td>
<td>0.1%</td>
<td>3.5%</td>
</tr>
<tr>
<td>From 2020 onwards</td>
<td>0.1%</td>
<td>0.5%</td>
</tr>
</tbody>
</table>

## §2.6 Available technologies for removing particulate matter

### §2.6.1 Introduction

In this section only technologies for the reduction of diesel particulate matter are discussed that are on the market or are likely to go on the market within a reasonable time-frame. The following sections are an updated and generalised version of a report, called “Pre- and aftertreatment techniques for inland shipping”, made for the European project CREATING in the framework of FP6 [Van Rens and De Wilde, 2005].

### §2.6.2 Oxidation catalysts

#### §2.6.2.1 Introduction

Diesel oxidation catalysts are very effective in reducing the emissions of carbon monoxide (CO) and gaseous hydrocarbons (HC). The removal efficiency depends on catalyst composition, but up to 90% is possible for CO and HC [Clean air systems, 2005]. The effect of oxidation catalysts on particulate matter emissions is somewhat more complicated, however. This strongly depends on fuel and catalyst composition as will be explained below.

#### §2.6.2.2 Working principle

Carbon monoxide and hydrocarbons are oxidised by the excess oxygen in the exhaust gas. This reaction is catalysed by precious metals that are present in the catalyst, like platinum and palladium. The precious metals are coated on a substrate material, either metallic or ceramic. The oxidation of carbon monoxide and gaseous hydrocarbons is catalysed from a certain threshold temperature, called the light-off temperature of the catalyst. In fact several light-off temperatures exist; one for carbon monoxide and one for every different hydrocarbon species. The light-off temperature depends on the catalyst formulation but roughly lies between 150 and 200°C [Eastwood, 2000], [Stein et al., 1995]. During a part of
the load cycle the exhaust gas temperature may lie below the light-off temperature, especially after a cold-start.

An oxidation catalyst may affect every component of particulate matter besides the ash. Due to the honeycomb structure, which is generally used for oxidation catalysts, the catalyst traps no particles. This means that oxidation catalysts have no risk of clogging, ensuring trouble-free operation. The downside is that the residence time of the particle is not long enough to oxidise the carbonaceous part of the particle by large amounts. It is in fact not entirely clear if a decrease in the carbonaceous part is achieved [Eastwood, 2000], yet a 5-15% reduction in the carbonaceous part seems realistic.

The soluble organic fraction (SOF), which contains carcinogenic material like Poly-Aromatic Hydrocarbons (PAH), is removed from the exhaust gas in a different way than gaseous hydrocarbons. Four different stages can be identified, during catalyst warm-up [Eastwood, 2000]. First a storage period can be observed, where hydrocarbons adsorb or condense onto the catalyst surface. Secondly a temperature regime is present in which these adsorbed or condensed hydrocarbons are released. In the third regime the catalyst has finished releasing the hydrocarbons, but the light-off temperature has not yet been reached. The fourth regime is the actual oxidation regime, where the catalyst temperature exceeds the light-off temperature. These four phases do not need to occur consecutively. They might also occur simultaneously. In fact as SOF consists of several hydrocarbons every hydrocarbon might be in a different regime at the same temperature.

The main problem of particulate removal by means of an oxidation catalyst is the oxidation of sulphur dioxide to sulphur trioxide, which forms sulphates that may contribute significantly to particle mass. Sulphur oxide emissions consist approximately for 5% of SO₃ and 95% of SO₂ [Götalm, 1991]. Normally, when SO₃ is removed at typical exhaust gas temperatures barely no new SO₃ is generated, because the equilibrium value for this temperature is strongly towards SO₂. The higher the exhaust gas temperature, the more the reaction is towards the formation of SO₃. The oxidation catalyst enhances this. In fact an upper threshold temperature is present that represents the temperature at which the additional particle mass due to the conversion of SO₂ to SO₃ and sulphates equals the reduction of particle mass due to the conversion of the volatile organic fraction and elemental carbon. Above this threshold temperature the oxidation catalyst creates additional particle mass. The key to a well functioning oxidation catalyst for PM removal is to find the catalyst composition that has a threshold temperature that is as high as possible. The sulphur level of the fuel influences this threshold temperature. The higher the fuel sulphur level, the lower the threshold temperature is.

§2.6.2.3 Requirements
Besides the influence of the sulphur level in fuel on the particulate matter emissions, fuel sulphur can poison a catalyst. Most oxidation catalysts are quite sulphur tolerant. It is claimed that fuel with more than 500 ppm sulphur will not damage the catalyst coating or the ceramic substrate [Clean air systems, 2005]. It will however not reduce the particulate matter emission significantly. For a comparison the presently used inland navigation fuel contains approximately 2000 ppm. If particulate matter reduction is one of the reasons to
use an oxidation catalyst it is necessary to use a fuel with a lower sulphur level than presently required for inland shipping. For optimum performance the exhaust gas temperature needs to be in the right window.

§2.6.2.4  State of development
Diesel oxidation catalysts are used commercially in cars and some trucks. The performance of oxidation catalysts does decrease during time. Deterioration of each catalyst formulation will be different. An example from [Stein et al., 1995] gives a deterioration of 8% for PM, 13% for CO and 21% of HC after 2200 hours, meaning that the removal efficiency after 2200 hours is 92% of the original removal efficiency for PM etc. Oxidation catalysts that replace mufflers are designed in a way that they do not require any additional volume. The price of an oxidation catalyst is rather modest, and it is especially in combination with low-sulphur fuel a cheap and trustworthy solution to reduce particulate matter emissions. As discussed above the removal efficiency of an oxidation catalyst with regard to particulate matter may be rather modest.

§2.6.3 Particulate matter filter

§2.6.3.1  Introduction
A diesel particulate matter filter (DPF), also referred to as a particulate trap, is a rather simple device. Particles are trapped in the device, so that almost no particles leave the filter. Over 80% of particulate matter mass can be removed this way, depending on filter type. Whether or not a particulate trap removes the soluble organic fraction of particulate matter depends on the exhaust gas temperature and the type of regeneration used, which will be treated in the next section. In principal a particulate trap does not reduce the emission of hydrocarbons that are still volatile at the temperature of the trap. The trapped particles will result in an increasing backpressure on the engine. As the backpressure influences fuel consumption, a penalty in the form of larger fuel consumption can be expected. Unacceptably high levels of backpressure might be obtained quite quickly. Therefore it is necessary to remove the trapped particles periodically or continuously by a so-called regeneration technique. The available techniques are presented below, preceded by different varieties of traps.

§2.6.3.2  Filter types
Wall-flow monoliths consist of channels with porous walls that are alternately plugged, as is illustrated in Figure 2.5. The exhaust gas is forced to stream through these porous walls leaving the particles behind at the wall.
This results in the formation of a particle cake that increases the backpressure on the engine. An important factor in the resulting backpressure on the engine is the pressure drop over the particle cake [Eastwood, 2000]. This leads to the somewhat unexpected conclusion that a high initial pressure drop over the wall-flow monolith leads to a lower pressure drop, when it has a higher particle loading. The removal efficiency of a wall-flow monolith is high, 90% is achievable [Davies], with efficiency depending on particle loading.

A ceramic foam filter is a porous fixed bed with macroscopic holes, where gas is forced through. Particles are removed by diffusion, impaction and interception [Van Gulijk, 2002]. Therefore particulate matter removal is less efficient than a wall-flow monolith trap, with a removal efficiency ranging from 50 to 80% [Davies], [Karila et al., 2004]. Ceramic foams are generally made of aluminium oxide or silicon carbide [Karila et al., 2004]. Due to the fact that particulate deposition is less concentrated on single spots, less risk of excessive temperatures during trap regeneration is present, compared to wall flow monoliths [Van Gulijk, 2002].

A ceramic fibre trap consists of a perforated metal tube closed at one end, which acts as a support for layers of ceramic fibre that are wrapped around the tube. Gas generally enters the open side of the metal tube and is forced to stream through this filter bed. Approximately 70 to 80% of the particles are removed [Davies], [Karila et al., 2004]. Fibres are relatively thick with diameters of 10-12 mm [Karila et al., 2004]. Every fibre is composed of approximately 400 filaments with a diameter of 11μm [Davies].

Sintered metal filters consist of metal fibres that are baked together at a high temperature. Generally plates are made of them, although it is very well possible to manufacture them in different shapes. According to [Karila et al., 2004] it is a surface-type filter, meaning that particles are retained at the surface of the filter. A manufacturer of sintered metal filters claims that it is a deep-bed type filter [Bekaert, 2005], meaning that particles are trapped inside the filter. This discussion is mainly important for the storage capacity of the filter, and thus time between regenerations and lifetime. A deep-bed filter has a larger storage
capacity than a surface-type filter. Due to the high porosity of 85% of the filter from [Bekeart, 2005] the claim, that it is a deep-bed filter, seems plausible.

§2.6.3.3 Regeneration

Typical temperatures for (non-catalysed) particulate matter combustion are 550 to 600°C [Eastwood, 2000], [Davies]. This temperature is almost never reached during typical load cycles. Therefore it is necessary to apply a regeneration strategy. A large number of regeneration strategies are possible. Active and passive regeneration can be discerned. A particulate trap with active regeneration has the pressure drop over the particulate filter monitored continuously. When a certain threshold pressure drop is measured, regeneration will start. Active regeneration methods are engine throttling, fuel injection in the exhaust gas, electrically heated regeneration, regeneration by microwave irradiation and regeneration by pressurised air. Passive regeneration methods make use of a catalyst or oxidation by NO₂. Regeneration by non-thermal plasma is also possible [Karila et al., 2004].

One way to obtain regeneration is by increasing the exhaust gas temperature by periodically letting the engine run hotter. The moments for regeneration are determined by a Δp-sensor that gives a signal to the engine management. With engines with flexible fuel injection timing this is achieved by post-injection of fuel [Karila et al., 2004]. A significant increase in fuel consumption occurs with post-injection.

Another means of increasing the exhaust gas temperature is by adding a fuel burner in the exhaust pipe, or injecting fuel in the exhaust gas, which is oxidised at a catalyst upstream of the trap, thereby releasing heat. Caterpillar showcased this last option on a 2007-prototype [Dieselnet, 2005a]. Filter temperature is monitored to minimise fuel consumption during regeneration.

Catalyst-enhanced regeneration can be achieved by incorporating a catalyst in the trap material or by adding a catalyst in the fuel. The advantage of adding a catalyst in fuel is that it not only aids the regeneration of the trap; it will also reduce engine-out emissions, because it will catalyse soot oxidation in the engine as well. This will lead to less frequent regeneration, which saves energy. The drawbacks of adding a catalyst in the fuel are a constant need for an additive together with a small loss of catalyst, which will be emitted in air, and an additional ash build-up in the trap. The catalyst reduces the temperature at which soot will start to combust. The combustion of soot may now occur with an exhaust gas temperature, which is achieved during normal operation. If only short distances are travelled, meaning that the exhaust gas stays cool, a large build-up of particulate matter in the filter is unavoidable. This may result in engine damage if the backpressure becomes too high. If the combustion temperature of the soot is reached with high particle loading it might lead to an uncontrolled combustion, with temperatures as high as 1000°C. This might seriously damage the particulate trap. Therefore it is wise to control this with an active regeneration technique such as engine throttling. In fact this is the strategy PSA (Peugeot and Citroën) uses in their cars [Karila et al., 2004], [PSA, 2005]. Besides the effect the catalyst has on particulate matter emissions it also reduces the emissions of volatile organic compound and carbon monoxide.
CRT\textsuperscript{TM} stands for continuously regenerating technology (it used to mean continuously regenerating trap) and is a registered trademark of Johnson Matthey. Instead of oxygen, nitrogen dioxide is used to oxidise soot, reducing nitrogen dioxide to nitrogen monoxide. Nitrogen dioxide is only a small portion of the nitrogen oxides emission. Therefore a very active platinum based catalyst is applied before the trap, which oxidises, besides carbon monoxide and volatile organic compound, nitrogen oxide to nitrogen dioxide [JM, 2005a]. Hereby the soot oxidation temperature is lowered to approximately 250°C, enabling continuous regeneration. Engines that will operate at low loads for long periods of time might need an additional means of active regeneration [Karila et al., 2004]. Low-sulphur fuel (<50 ppm sulphur) is required in order to convert enough NO to NO\textsubscript{2} in the catalyst for soot oxidation [JM, 2005b], [Dieselnet, 2005b]. The very active catalyst will increase particle emissions for sulphur levels higher than approximately 150 ppm over the ESC cycle by converting sulphur dioxide into sulphates [Dieselnet, 2005b].

The minimum NO\textsubscript{x} to PM ratio by weight is reported as 20:1-25:1 in literature [Dieselnet, 2005b]. This means that NO\textsubscript{x} reduction cannot take place upstream of the diesel particulate filter, although Johnson Matthey recently designed a combination of EGR with a CRT, called EGRT, which reduces NO\textsubscript{x} by 40\% and PM by 90\% [JM, 2005c]. For engines with low exhaust gas temperatures or low NO\textsubscript{x}/PM-ratio Johnson Matthey advises a Catalysed CRT, CCRT\textsuperscript{TM}, where the trap itself is catalysed as well [JM, 2005b].

Particulate traps that are electrically conducting can easily be heated by applying an electrical current on them, when regeneration is required [Bekaert, 2005]. Electrically conducting traps are metal filters or filters from silicon carbide. Accumulated soot burns due to the elevated filter temperature. Exhaust gas temperature should be monitored (together with pressure drop over the particulate trap) in order to prevent overheating of the trap. It is possible to apply heating elements on the upstream face of ceramic wall-flow monoliths as well, but it relies on propagation of soot combustion through the trap [Davies]. Energy consumptions can be significant, with reported fuel efficiency penalties of 3 to 5\% [Davies].

Another way to remove particles captured by a particle trap is by means of microwave irradiation. Microwave irradiation is directly absorbed by the particle, thereby heating the particle only, when ceramic filter materials are used. Metals reflect microwaves and can this way be used as wave-guides for the microwaves [Karila et al., 2004]. A complication in microwave regeneration is the non-homogenous and therefore not complete combustion of the particles [Karila et al., 2004]. To overcome this problem special coatings are being developed that convert microwave energy to heat energy at the surface of the filter, thereby creating a more uniform temperature distribution [Elzinga et al., 2004]. Care should be taken not to exceed electromagnetic radiation limits.

The most basic approach is cleaning the filter with pressurised air. Pulses of pressurised air dislodge the trapped particles. The pulses are directed opposite to the exhaust gas flow. The big advantage of this system is that it can be operated at cool exhaust gas temperatures, meaning that it is possible to trap a part of the soluble organic fraction and that all components of particulate matter are removed from the trap. Problem with pressurised air regeneration is that air seeks the way of least resistance thereby cleaning only a part of the trap surface. The dislodged particulate matter needs to be separated in some way from the
pressurised air and exhaust gas stream. One strategy is to bypass the particle filter temporarily and let the particles settle in a “dead-flow” system. Another strategy is to burn the particles on an electrical heater, which requires less energy due to the fact that the entire trap does not have to be heated.

§2.6.3.4 Requirements

The requirements when using a particle trap differ for each regeneration technology, but every active technique requires a control, which generally consists of a \( \Delta p \) sensor and a temperature sensor. Only pressurised air regeneration does not need a temperature sensor. The only passive technology for which it seems feasible to operate without the aid of an active regeneration technology is the CRT-filter. The filter needs a low-sulphur fuel, as do all filter which are catalytically active. This is compensated by the fact that other regeneration technologies require additional fuel, which equals approximately 1-2% of the fuel consumption. Note that a low-ash fuel is required for every regeneration type except for pressurised air. This means that a fuel change for sea shipping is inevitable.

§2.6.3.5 State of development

Especially in car and truck applications a lot of experience is obtained with particulate matter filters. The big difference is that in this market low-sulphur and low-ash fuel is used, in contrast to sea shipping and to a lesser extent inland shipping. Some inland ships are nowadays being fitted with particulate matter filters. In the European project Cleanest ship, see [Cleanestship.eu, 2008], an inland navigation ship is being fitted with a particulate matter filter with a diesel burner for regeneration. The ship is using a low-sulphur fuel (<50 ppm). The harbour of Rotterdam was in the process of commissioning three ships with particulate matter filters in 2007. They will also be using low-sulphur fuel (<50 ppm) [Port of Rotterdam, 2007].

§2.6.4 Wet scrubber

§2.6.4.1 Introduction

Wet scrubbers are capable of removing SOx, NOx, hydrocarbon and particulate matter emissions. Which emissions are reduced and how efficiently they are removed is strongly dependent on the configuration of the scrubber and the scrubbing liquid used. Wet scrubbers are widely used in the power industry, especially for the reduction of the emission of sulphur oxides. Usually water is used as the scrubbing liquid. More than 90% of sulphur oxides can be removed by means of a wet scrubber with water as a scrubbing liquid [Davies], [Haase&Koehne, 1999], [Trivett et al., 1999]. Approximately 15% of NOx emissions and 15-27% of particulate number emissions, with a potential up to 60%, are removed with pilot-scale set-ups [Haase and Koehne, 1999], [Van Rens, 2004]. The device presented in [Trivett et al., 1999] has been commercialised by Marine Exhaust Solutions under the trade name EcoSilencer [Lantz, 2005]. Up to 90% SOx, 7% NOx and up to 80% PM removal is claimed with this technique [MES, 2005a], with a sustainable SOx-removal level between 72 and 80% [MES, 2005b]. Krystallon claims SOx-removal over 97% (in fact they claim 100%) and claim 80% PM removal [Krystallon, 2008]. However, it is unlikely that scrubbers remove significant amounts of sub-micron particles.
§2.6.4.2 Working principle

As mentioned above SOx removal efficiencies of over 90% are possible by a suitable type of wet scrubber. In an experimental study [Ives and Klokk, 1993] showed a removal efficiency of 71-73% for SOx from the exhaust gas of a marine diesel engine using heavy fuel oil.

The main reaction involved is the reaction of SO2 with water after it is absorbed in the water:

\[ \text{SO}_2 + \text{H}_2\text{O} \leftrightarrow \text{H}_2\text{SO}_3 \]

The reaction product is in equilibrium with hydrogen sulphite and sulphite. Sulphite might react to sulphate by means of a redox reaction [Haase and Koehne, 1999].

[Götmalm, 1991] however says that a desulphurisation plant on every ship is hardly desirable from an environmental point of view, referring to the use of energy and natural resources to manufacture those devices. This is even more true for inland shipping, when considering that [Götmalm, 1991] made his comment looking at sulphur oxide removal from engines using heavy fuel oil, which emit more sulphur oxides because of the higher sulphur content in the fuel in comparison with diesel fuel oil used in inland shipping. The effluent of the scrubber can be quite acidic; [Ives and Klokk, 1993] measured a pH of 2.7. Therefore it might be necessary to neutralise the effluent before discharge of the scrubbing water.

NO2 can easily be absorbed in water [Davies], and therefore a scrubber reduces some NOx. Experimental investigation of [Haase and Koehne, 1999] showed that more than 15% removal of NO2 by means of a wet scrubber requires relatively big devices. NO cannot be reduced by a wet scrubber itself. Unfortunately over 90% of the NOx in exhaust gas is in the form of NO [Niven, 1993], and therefore NOx-reduction is limited. However, it is possible to oxidize NO to NO2 before the wet scrubber by means of an oxidation catalyst. In itself this does not sound very attractive, because the removal efficiency of NO2 for a wet scrubber is still not high. However with this combination it is possible to bypass one of the problems of the oxidation catalyst, i.e. the formation of SO3 that will form sulphates when the exhaust gas cools down. The formed SO3 can easily be removed in the wet scrubber, especially if it is still in the gas phase, and oxidation selectivity is no longer an important issue for the choice of oxidation catalyst. It also facilitates the use of oxidation catalysts for heavy fuel oil, without increase in mass of particulate matter.

Wet scrubbers also remove particulate matter. This is sometimes referred to as a problem, because it might be necessary to treat the scrubbing liquid additionally, however it can also be seen as an opportunity to reduce the emission of particulate matter as well. Recall that particulate matter consists of elemental carbon and ash, in the form of metal oxides, and condensed hydrocarbons and reacted sulphates, although the exhaust gas composition at the entrance of the scrubber may be different. When entering the scrubber the associated sulphates might still be gaseous in the form of SO3 and the same goes for hydrocarbons. In this way a first quick win comes from the removal of SO3. However scrubbers can be optimised to remove the solid particles as well. The most suitable scrubber for this goal is a venturi scrubber. Unfortunately a pressure drop of 15 kPa is necessary to remove the small particles effectively. This pressure drop is higher than the pressure drop for which engines normally are designed. A high pressure drop also results in a higher fuel consumption. [Trivett et al., 1999] designed a scrubber that had a particulate matter removal efficiency of
70-80% for particles larger than 1 \( \mu \text{m} \) in diameter, which is only a fraction of particulate matter number emissions. [Van Rens, 2004] showed 15-27% particulate removal, measured with a smoke meter for a pilot plant wet scrubber behind a diesel engine. Scaled up and extrapolated, it is estimated that 60% of particulate emissions can be reduced. [Cofala et al., 2007] indicate that the amount of removed particulate matter based on data from the sludge from the waste water of the MES scrubber is approximately 25%. [Krystallon, 2008] claim 80% particulate matter removal, which seems realistic based on the amount of sludge produced (0.2 kg PM per 100 kg fuel, or alternatively approximately 0.4 g/kWh).

A wet scrubber will always absorb some hydrocarbons when the exhaust gas is cooled below the dew point temperature of the hydrocarbons. This will result however in a mixture of water and hydrocarbons that requires additional wastewater treatment.

§2.6.4.3 Requirements

Although a scrubber has a significant pressure drop and as a result gives a higher backpressure on the engine, pressure drops do not exceed engine manufacturers demands, if carefully looked after. However a small increase in pressure drop, even if it is within the limits of an engine manufacturer may lead to an increase in fuel consumption.

No special requirements for the fuel are necessary, although for fuels with high sulphur content, it might be necessary to add a base to the scrubbing water in order to maintain an acceptable acidity. One of the problems of a scrubber is the possible necessity for treatment of the scrubbing water. In that case recycling of the scrubbing water might be preferable.

Marine exhaust solutions Inc. shows that treatment is possible to within the EPA water quality limits [MES, 2005b]. Approximately 0.6T soot sludge per week is produced during on-board use with 4800 kW installed electrical power. It was handled together with the regular onshore waste disposal.

A problem with wet scrubbers might be that they are rather voluminous, especially when accounted for the additional space for wastewater treatment, but Marine exhaust solutions show for a 200-250 kW engine a package of approximately 2 m\(^3\) [MES, 2005c]. SOx removal will not be the major reason to implement a wet scrubber for inland shipping, due to the sulphur level in the used fuel. Particulate matter removal will be the governing reason to implement wet scrubbers in inland shipping.

§2.6.4.4 State of development

Wet scrubbing is frequently used in the power generation industry. Demonstrations of wet scrubbers on ships on pilot-scale are shown in for example [Trivett et al., 1999], [Ives and Klokk, 1993]. Marine Exhaust Solutions is able to deliver an entire system, which includes treatment of the scrubbing liquid, with the trade name EcoSilencer. It also acts as a muffler, as indicated by the name, reducing noise levels by 35dB. The first full-scale system has been build on a RoRo-ferry, running on a fuel with 2.5 % sulphur. A trial report [MES, 2005b] shows that wet scrubbers are reliable and durable. Regular maintenance consisted of boroscopic investigation of the silencer, level measuring probe cleaning and water circulation pump maintenance. The main problem from durability point of view seems to be the wastewater treatment, and more specifically the wastewater circulation pump, rather than the EcoSilencer itself. Krystallon offers a sea water scrubber commercially as well. It is installed in the exhaust gas system of a diesel generator on board of a cruise ship.
§2.6.5 Electrostatic precipitator

§2.6.5.1 Introduction
An electrostatic precipitator (ESP) is often used to clean the exhaust gas of power plants efficiently from fine particles. It is also used to reduce particle emissions from large stationary diesel engines and is commercially offered by Wärtsilä amongst others. With unlimited size, over 99% particle removal is achievable. Therefore it seems a possible solution to reduce the particle emissions of diesel engines on ships by an ESP.

§2.6.5.2 Working principle
A high voltage creates a corona discharge, which creates a lot of ions. Particles are charged by these ions. The applied voltage can be negative as well as positive. The overall-charge of the gas remains neutral. The charged particles are subsequently attracted towards the electrode of opposite polarity. If an ESP is operated dry, the particles will form a cake, which has to be dislodged periodically. This is done by hammers or by ultrasound. Another option is to operate the ESP with additionally supplied water. The big advantage is that the electrodes are cleaned continuously. This will also lead to lower power consumption, because the resistance of the particle cake is absent.

§2.6.5.3 Requirements
The most important requirement for an ESP is the required space. Commercially available ESPs are rather large. A 1 MW engine produces approximately 8100 kg/h exhaust gas, assuming a typical 8.1 kg/kWh. This equals approximately 6200 m$^3$/h. An example for a suitable ESP, in this case a wet ESP, has the following dimensions 7.62*1.80*1.80 metres [CGS, 2005]. Data from [Van Paasen et al., 2004] show that an upper-boundary for power consumption is given by equalling the volume flow in m$^3$/h to the required energy in Watts. This leads to the conclusion that the required energy is rather modest, with less than 1% of engine power. It is required to dispose the collected dust in a safe and environmentally acceptable way. No special fuel is required.

§2.6.5.4 State of development
An ESP is demonstrated behind a stationary diesel engine and is marketed by Wärtsilä. It is frequently used in power plants. No publications of demonstration on board of a ship were found, but a removal efficiency of 90% seems reasonable. The construction of the presently used one-stage ESP is not deemed robust enough for application on sea by Wärtsilä, which markets these ESPs for diesel engines on land. The reason is that that type of ESPs have very long (7m) and thin (~1 cm) electrodes hanging from the top, which, if they move 10 cm at the bottom, will short-circuit the ESP violently. This will most likely lead to ESP malfunction. [Ariana et al, 2007] present a different design of an ESP for reduction of particulate matter intended for use on sea on a 14 kW-scale.

§2.6.6 Non-thermal plasma
In contrast to the technologies treated above, non-thermal plasma is not an established technology yet, but an emerging technology. It can reduce both NOx, gaseous hydrocarbons and particulate matter emissions. The working principle is that a plasma is created by a high-voltage discharge. The process is not unsimilar to an electrostatic precipitator. In this
case however, the goal is to create as much O- and OH-radicals as possible to oxidise all the pollutants, and therefore the corona-region needs to be larger. As a result, a higher potential is required, as well as a higher current. In some applications NO is converted to NO₂ by the radicals and NO₂ is subsequently removed by selective catalytic reduction with hydrocarbons, reducing nitrogen dioxide to nitrogen. It is theoretically possible that harmful substances are created by non-thermal plasma. The emission of ozone is expected to increase.

Non-thermal plasma is in one application combined with a diesel particulate filter with the trademark Electrocat. In that application it is solely used to start the regeneration of the particulate filter. 90% particulate matter removal was shown with successful regeneration [McAdams et al., 2003]. A pilot-scale set-up showed NOx reduction potential of 30 to 40%, whereas a set-up with a particle filter in front of the non-thermal plasma showed approximately 50-70% removal efficiency. Power consumption was assumed to be 5% of engine power [McAdams et al., 2003]. In another application it is a combination of an electrostatic precipitator with oxidation by the plasma [Creyghton and Schilt, 2007]. It is claimed that energy consumption is less than 1% of engine power.

Note that ash cannot be oxidised and the ash will either be emitted, or in case of the Electrocat and the nameless application from [Creyghton and Schilt, 2007], accumulate in the filter.
Chapter 3. Influence of fuel type on particulate matter emissions for a medium-speed marine diesel engine
§3.1 Introduction

The maximum emissions from engines in sea shipping are legislated by the International Maritime Organization by way of Marpol 73/78 Annex VI. In this treaty the maximum NOx-emission is limited together with the maximum sulphur emission. At the moment this Annex is being reviewed. Possibly particulate matter emissions are limited too. During the review process INTERTANKO, an organisation of independent tanker owners, proposed to reduce the emissions of shipping by banning the use of heavy and intermediate fuel oil, and using distillate diesel oils instead. It was proposed that the distillate fuels would initially contain 1.0% sulphur in fuel (on mass basis), which is later reduced to 0.5% sulphur [Intertanko, 2007]. The international maritime organization (IMO) announced that it intends to limit the maximum sulphur amount to 0.5% in 2020, although it does not state that the fuel should be a distillate fuel [IMO, 2008].

It is known that switching to distillate fuels with lower sulphur content will lower the emissions of sulphur oxides, as the majority of sulphur oxide in the exhaust gas stems from the sulphur in fuel. It is also known that it will reduce the emissions of mass of particulate matter, see for example [Tsukamoto et al., 2002].

The influence of this switch on particle size distribution is less known. Most studies on particle size distributions are performed for road-going vehicles. The engines from road-going vehicles are notably different from ship engines, due to engine size and engine speed. Particle size distributions with heavy fuel oils were studied by [Lyyränen et al., 1999] and [Okada et al., 2007] for four-stroke turbocharged engines. However, they did not compare results from their measurement, with measurements with distillate fuels in the same engine. [Kasper et al., 2007] do compare the particle size distributions of heavy fuel oil with particle size distributions from distillate fuel for 2-stroke engines at 1% load and at 100% load.

This study addresses the influence of a switch to distillate fuels on particle size distribution by testing an intermediate fuel oil and two distillate fuel oils on the same engine. In addition to this the emitted particulate matter mass is measured.

§3.2 Experimental set-up

§3.2.1 Experimental conditions

All experiments were performed on a 4-stroke turbocharged research engine in a land-based test site at the Netherlands Defence Academy. The engine specifications are described in Table 3.1. The engine was fed with 3 different fuels, as specified in Table 3.2. Two of the fuels were distillate fuels (MGO, Marine Gas Oil). They were comparable in composition, except for the fuel sulphur level. The third fuel was an intermediate fuel oil. This fuel was fed to the engine at an elevated temperature of 70°C in order to decrease the viscosity of the fuel.
Table 3.1 Specifications of test engine

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine Name</td>
<td>MAN 4L 20/27</td>
</tr>
<tr>
<td>Engine type</td>
<td>4-stroke in-line turbocharged engine</td>
</tr>
<tr>
<td>Number of cylinders</td>
<td>4</td>
</tr>
<tr>
<td>Bore/stroke [mm/mm]</td>
<td>200/27</td>
</tr>
<tr>
<td>Total displacement [l]</td>
<td>34</td>
</tr>
<tr>
<td>Maximum engine power at maximum speed</td>
<td>350 kW @ 1000 rpm</td>
</tr>
<tr>
<td>Maximum engine power during experiments</td>
<td>210 kW @ 1000 rpm</td>
</tr>
</tbody>
</table>

Table 3.2 Specifications of fuels

<table>
<thead>
<tr>
<th>Element</th>
<th>Fuel</th>
<th>MGO 0.1%</th>
<th>MGO 0.16%</th>
<th>RMA-30</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>%-%wt</td>
<td>86.2</td>
<td>86.2</td>
<td>85.6</td>
</tr>
<tr>
<td>H</td>
<td>%-%wt</td>
<td>13.7</td>
<td>13.6</td>
<td>12.8</td>
</tr>
<tr>
<td>N</td>
<td>%-%wt</td>
<td>&lt;detection limit</td>
<td>&lt;detection limit</td>
<td>&lt;detection limit</td>
</tr>
<tr>
<td>O</td>
<td>%-%wt</td>
<td>&lt;detection limit</td>
<td>&lt;detection limit</td>
<td>&lt;detection limit</td>
</tr>
<tr>
<td>S</td>
<td>%-%wt</td>
<td>0.1</td>
<td>0.16</td>
<td>1.5</td>
</tr>
</tbody>
</table>

The engine is tested over the propeller curve, in accordance to ISO-8178-4 mode E3 [ISO, 2007] and over the constant engine speed curve, in accordance with ISO-8178-4 mode E2 [ISO, 2007]. The experimental programme is described in Table 3.3.

Table 3.3 Measurement programme

<table>
<thead>
<tr>
<th>Test day</th>
<th>Fuel</th>
<th>Measurements</th>
<th>Load points</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>MGO 0.16%</td>
<td>Filter, SMPS</td>
<td>E3: 100, 75, 50%</td>
</tr>
<tr>
<td>2</td>
<td>MGO 0.16%</td>
<td>Filter, SMPS</td>
<td>E2: 100, 75, 50, 25% and E3: 25%</td>
</tr>
<tr>
<td>3</td>
<td>MGO 0.16%</td>
<td>Filter</td>
<td>E3: 100, 75, 50, 25%</td>
</tr>
<tr>
<td>4</td>
<td>MGO 0.16%</td>
<td>Filter</td>
<td>E2: 100, 75, 50, 25%</td>
</tr>
<tr>
<td>5</td>
<td>MGO 0.1%</td>
<td>Filter, SMPS*</td>
<td>E3: 100, 75, 50, 25%</td>
</tr>
<tr>
<td>6</td>
<td>MGO 0.1%</td>
<td>Filter, SMPS</td>
<td>E2: 100, 75, 50, 25%</td>
</tr>
<tr>
<td>7</td>
<td>MGO 0.1%</td>
<td>Filter, SMPS*</td>
<td>E3: 100, 75, 50, 25%</td>
</tr>
<tr>
<td>8</td>
<td>MGO 0.1%</td>
<td>Filter</td>
<td>E2: 100, 75, 50, 25%</td>
</tr>
<tr>
<td>9</td>
<td>RMA-30</td>
<td>Filter, SMPS</td>
<td>E3: 100, 75, 50, 25%</td>
</tr>
<tr>
<td>10</td>
<td>RMA-30</td>
<td>Filter</td>
<td>E2: 100, 75, 50, 25%</td>
</tr>
</tbody>
</table>

*with SMPS only load points E3: 50 and 25%  
#with SMPS only load points E3: 100 and 75%

Since the engine was not tested over the constant engine speed curve with RMA-30, the measurements over the constant engine speed curve are only mentioned, if they have additional value for the comparison between MGO and intermediate fuel oil.

The experiments described in this study have been performed in conjunction with tests of an emission reduction device. For the experiments presented in this study it has one major consequence. The engine was operated with a backpressure of maximally 7 kPa. This is higher than the 3 kPa, defined as the maximum backpressure on the engine. In order not to overheat the engine, maximum power during the tests was limited to approximately 210 kW at the maximum engine speed of 1000 rpm. Points at lower loads are related to this maximum.

Emission samples are taken from a slipstream of the main exhaust gas stream. Exhaust gas is pressurised in this slipstream by a valve that throttles the main exhaust gas stream. The slipstream is taken from the middle of the exhaust gas stream. The slipstream was not 100%
isokinetical, but given the low Stokes number (<0.002 for particles smaller than 1 micrometer in diameter) the particle concentration is still representative.

§3.2.2 Measurement of particulate matter mass
Particulate matter mass was not determined by dilution of exhaust gas, as described in ISO-8178-1 [ISO, 1996]. Although the method is sufficiently proven for fuels up to 0.8% sulphur in fuel it is still debated for fuels with higher sulphur content, due to the possibility of excessive condensation of H$_2$SO$_4$. The occurrence of this event will depend on dilution ratio.

In this study particulate matter mass was determined in undiluted exhaust gas. This way the measurement is only sensitive on sample temperature. In this study the filter temperature was kept at 383 K (110°C). Note that the measured mass in this study can not be compared to measurement results according to ISO-8178-1, as mentioned in this method [ISO, 1996].

The gas was sampled isokinetically by J-shaped tubes. Isokinetical conditions were ensured by a vacuum compressor. In order to protect the compressor, water was removed from the sampled gas by a cooling bath and a silicagel dryer. The entire sample set-up is illustrated in Figure 3.1.

![Sample set-up for mass measurement of particulate matter](image)

Figure 3.1 Sample set-up for mass measurement of particulate matter

The filter medium was a Whatmann QMA quartz fibre filter with a 99.95% retention efficiency for particles with a diameter of 300 nm. The filter was 50 mm in diameter. Before the measurement and the initial weight determination, the filter was preconditioned in an oven at the sample temperature of 110°C. Before determining the end weight, the filter was again heated in an oven to 110°C. The filter was placed in a filter holder in an oven during sampling. The pressure drop over the filter and volume of exhaust gas through
the filter were measured. The weight of particulate matter and the volume through the filter were combined for an emission in mg/m$^3$. Together with the temperature at the volume meter the emission was converted to an emission in mg/m$^3$. The emission can be converted to an emission in g/kWh by using the power consumption and exhaust gas flow. The sample time was 15 minutes. At every measurement condition two samples were taken. The samples were taken on different days (see Table 3.3).

### §3.2.3 Measurement of particle size distribution

An SMPS (Scanning Mobility Particle Sizer), sometimes called scanning electrical mobility spectrometer, was used to determine the number particle size distribution; see section §2.2.3 and [Wang and Flagan, 1990]. The SMPS used in this study consists of two parts, an 'electrostatic classifier' (EC) from TSI Inc. of type 3071 and a 'Condensation Particle Counter' (CPC) from TSI Inc., model 3022. With the SMPS the number of particles in a small bandwidth around a central diameter, also called midpoint diameter, was determined for a number of central diameters. The bandwidth increased exponentially with increasing central diameters. From these data a number concentration density, or, in other words, bandwidth independent number distribution, was calculated. The measured midpoint diameters ranged from 16.5 to 523 nanometres. The calculated number concentration density ranged between 15.4 and 562 nanometres.

Sampling of particulate matter for the particle size distribution was done counter-current. This had little influence on the measurement results, as the measurement device in this study only measured particles up to 562 nanometre in diameter. Sampled exhaust gas was dried by a silica-gel dryer and subsequently filtered by an impactor with a cut-off diameter of 1000 nm. This ensured accurate measurements of the SMPS.

The SMPS is rather sensitive to the sample flow. It is also sensitive to sample pressure, because the flow is controlled by a critical orifice. The pressure was first equalised with the atmospheric pressure by a sample system, shown in Figure 3.2. Measurements have confirmed that flow from the sample point was higher than the required sample flow for the SMPS.

![Figure 3.2 Simplified drawing of sample system used in tests at Royal Netherlands Naval College](image)

Presented data in this study is averaged SMPS-data over at least 3 valid SMPS-scans. The SMPS-scans showed good reproducibility. An entire scan was rejected if one data point of that scan was more than 2 standard deviations away from the average of this data point from other scans.
§3.3 Results and discussion

§3.3.1 Mass measurements

The results of the mass measurements over ISO-8178-4 cycle E3 [ISO, 2007] are shown in Figure 3.3 and Figure 3.4. The measurement results with both MGOs do not statistically differ from each other. The trends in mass for the different loads are similar for the two gas oils, whereas the trend with intermediate fuel oil is totally different. For 25 and 50% load the particle emission with intermediate fuel oil is different from the particle emission with MGO.

In fact according to the measurements the concentration of particulate matter mass for intermediate fuel oil is load independent. Note that the emission over the cycle for marine gas oils is only 69-81% of the emissions for intermediate fuel oil, see Figure 3.4. [Tsukamoto et al., 2002] found a larger reduction of particulate matter mass for two-stroke engines. The trend in emission is totally different, as well. [Tsukamoto et al., 2002] observed higher particulate emissions at high engine loads, whereas in this study higher particulate matter emissions were observed at low engine loads.

Figure 3.3 Influence of fuel type on mass concentration particulate matter in exhaust gas at different engine loads and for the weighted average over the E3 duty cycle. Error bars indicate the standard deviation.
Figure 3.4 Influence of fuel type on mass emission particulate matter per kilowatt engine output per hour in exhaust gas at different engine loads and for the weighted average over the E3 duty cycle. Error bars indicate the standard deviation.

The average emissions with MGO are in accordance with values from the Dutch emission registration and monitoring for shipping, a.k.a. EMS, (0.3-0.5 g/kWh), whereas the emission with intermediate fuel oil is slightly lower than values reported for heavy fuel oil in EMS (0.7-0.8 g/kWh). The latter has to do with the fact that the used fuel oil is an intermediate fuel oil and contained only 1.5% sulphur. Derating of the engine may have had some influence as well.

§3.3.2 Particle size distribution

Figure 3.5 shows the particle size distribution that is measured for the MGO fuel containing 0.16% sulphur. The particle size distribution is a distribution that is typically found for diesel particulate matter as described in [Maricq et al., 2002]. Especially at high loads a so-called accumulation mode is visible at particle diameters of approximately 100 nanometres. According to [Maricq et al., 2002], the accumulation mode arises from coagulated carbon structures, possibly coated with adsorbed carbons and sulphates, which are formed as a consequence of the diffusion combustion inherent to diesel engines. At 50% load a small nucleation mode becomes visible, that is much more pronounced at 25% load. At 25% load the mode at 100 nanometres becomes partly covered by the nucleation mode. According to [Maricq et al., 2002] a nucleation mode stems from semivolatile organic gases and sulphates that nucleate and condense when the exhaust gas cools down. Typically the mean diameter of the nucleation mode is at 10-30 nanometres.
The particle size distribution for MGO with 0.1% sulphur shows a particle size distribution that is similar to the particle size distribution for MGO with 0.16% sulphur for high loads; see Figure 3.6. At low load the distribution is notably different; especially the point at 25% load. It seems that a significant part of the nucleation mode at 25% load with MGO 0.1% is just outside the measurement window. Extrapolation of the data shows that it is an important number of particles. Therefore the number of particles at this load-point is not used in the overview picture of measured particulate matter number concentration. Note that the obtained distributions are quite different from distributions with MGO as measured by [Kasper et al., 2007] for a two stroke engine. [Kasper et al., 2007] found a maximum particle concentration density at 40 nm, but the particle concentration distribution they found had a very distinct shape.
The number size distribution for RMA-30 is very different from the distribution obtained from both marine gas oils over the propeller curve as is illustrated in Figure 3.7.

![Particle size distribution for RMA-30](image)

**Figure 3.7 Particle concentration distribution over propeller curve for intermediate fuel oil**

The shape obtained here is much more similar to measurements of [Kasper et al., 2007] for marine diesel oil with 0.155% sulphur. With RMA-30 the maximum number of particles is visible at approximately 50 nanometres. A separate mode at 100 nanometres, as was the case with MGO is not visible at first glance. However, the particle number distribution does not look log-normally distributed. A log-normal distribution with a main mode at 50 nanometres is manually fitted to the measured particle concentration distribution, and is subsequently subtracted from the original data, leading to the size concentration distribution in Figure 3.8. Figure 3.8 reveals a second mode at approximately 120 nanometres. This mode is not caused by spread in the measurement. This indicates that the actual distribution is (at least) bimodal, containing a large nucleation mode and a small nucleation mode with approximately the same particle concentration density as MGO 0.1%.
The measured distribution is actually quite similar to what is obtained by [Lyyränen et al., 1999], but is notably different from what was obtained by [Okada et al., 2007], who measured a mode at approximately 20 nanometres. What strikes is that the distribution does not seem to change much in shape, nor in total concentration for different engine loads. The peculiar shape of the distribution is however not limited to the intermediate fuel oil. A similar shape has been found at 25 percent load with both marine gas oils when testing the same test engine over the constant engine speed curve; curve E2 of ISO-8178-4 [ISO, 2007], see Figure 3.9. With marine gas oil the number of emitted particles was much lower.

Figure 3.8 Particle concentration distribution RMA-30 at 75% load after subtraction of a log-normal distribution with a mode of 50 nm.

Figure 3.9 Comparison of particle concentration density RMA-30 propeller curve 25% load with MGO over constant engine speed 25% load
The total number concentrations as measured by SMPS are compared in Figure 3.10. It is clear that an intermediate fuel oil results in significant higher emissions of the number of particles. When the engine runs on MGO 0.16% it produces at high load more particles than with MGO 0.1%. The number of emitted particles can be reduced by 56% by switching to these distillate fuels. Figure 3.5 to Figure 3.7 indicate that at high engine loads especially smaller particles are reduced by a switch to distillate fuels.

![Influence fuel on particle number concentration](image)

**Figure 3.10 Influence of fuel type on particle number concentration**

### §3.3.3 Estimated mass from number distribution measurements

From the number distribution it is possible to approximate the actual mass distribution, see section 2.2.3. In Table 3.4 the results obtained from filter measurements are compared to conversions of the SMPS-measurements by the conversion factor of [Park et al., 2003], formula 2.2.12. As a reference SMPS-measurements are also converted by assuming spherical particles with unit density (1000 kg/m³). When comparing the mass obtained from SMPS measurements with the measurement from a filter it is crucial to realise that an SMPS measures only a part of the actual particle spectrum. This should lead to an underestimation of the particle mass. On the other hand the exhaust gas temperature during SMPS measurements was lower than during filter measurements. This means that it is possible that more particle mass is present during the SMPS measurements because of condensation of matter.
<table>
<thead>
<tr>
<th>Table 3.4 Comparison between mass emissions expressed in mg/m₃³</th>
</tr>
</thead>
<tbody>
<tr>
<td>MGO 0.1% Filter</td>
</tr>
<tr>
<td>SMPS, (Park et al., 2003)</td>
</tr>
<tr>
<td>SMPS, spherical ρ=1000 kg/m³</td>
</tr>
<tr>
<td>RMA-30 Filter</td>
</tr>
<tr>
<td>SMPS, (Park et al., 2003)</td>
</tr>
<tr>
<td>SMPS, spherical ρ=1000 kg/m³</td>
</tr>
<tr>
<td>RMA-30 Filter</td>
</tr>
<tr>
<td>SMPS, (Park et al., 2003)</td>
</tr>
<tr>
<td>SMPS, spherical ρ=1000 kg/m³</td>
</tr>
<tr>
<td>RMA-30 Filter</td>
</tr>
</tbody>
</table>

In order to be able to compare the calculated mass concentrations from SMPS measurements with filter measurements it is necessary to know if the calculated mass from SMPS measurements contains all the mass. Therefore, a mass concentration distribution is calculated. It is shown in Figure 3.11. The mass concentration distribution indicates that a significant amount of particle mass is not included in the mass obtained from SMPS measurements, because at the end of the measurement window the mass concentration density is still high. Figure 3.11 seems to indicate that the actual mass is approximately 66% higher for MGOs and 25% higher for RMA-30. From Figure 3.11 it can be concluded that the combination of an SMPS in the present set-up and present mass conversion factors does not lead to a good approximation of the actual mass. Given the already low particle density of 200 kg/m³ from the formulae of [Park et al., 2003] for particles of 500 nm in diameter, it seems that either the measurement error in the results, the measurement window or the conversion factor is to blame. It seems fair to conclude that the assumption that the particle is spherical and has a density of 1000 kg/m³ is unsuitable for high loads with engines running on marine gas oils.
§3.4 Conclusion and recommendations

If sea ships would use distillate fuels as tested in this study instead of intermediate fuel oils the emissions of particulate matter would decrease by 20 to 30% on mass basis and 56% on number basis. The main decrease in particulate matter emissions is found at low loads. The particles that are not emitted by a shift to marine gas oil are particles with a mobility diameter of 50 nanometres. It needs to be stressed that the distillate fuels in this study have a sulphur-content that is lower than the maximum proposed in the Intertanko proposal. This study indicates that the nucleation mode shifts towards larger particle diameters if a heavier fuel is used. The accumulation mode found during the experiments with the two different gas oils is still present when using intermediate fuel oil. However, this mode gets almost completely covered by the nucleation mode.

The present combination of mass conversion factors and SMPS number measurements does not lead to trustworthy mass results, because the mass concentration distribution indicates that a significant amount of particulate matter mass is present outside the measurement window of the SMPS. Whether this is caused by the measurement error or the measurement window, or the mass conversion factors should be subject to further research. The SMPS remains a good tool for measuring the number of particles present in exhaust gas and is used as an estimation of the mass smaller than the measurement window, in this case 592 nanometres.
Chapter 4. SJAC-technology

Sections §4.2 and §4.3 have been published in [Van Rens et al., 2007]
§4.1 Introduction
In Chapter 2 it was discussed that shipping contributes significantly to combustion related emissions of particulate matter. The composition of particulate matter and exhaust gas led to the conclusion that, especially for sea shipping, a physical removal technique has a bigger potential than catalytic options. Diesel particulate matter filters as used in road transport are also capable to remove large quantities of particulate matter from shipping. The problem with these filters lies in cleaning those filters. They are cleaned by burning off the particulate matter. As the ash does not burn, the ash will accumulate in the filter. This will lead to operational problems, especially in sea shipping, where fuels are allowed to contain up to 0.15% ash. A device is needed that is capable of reducing particulate matter emissions regardless of the used fuel.

A new device is developed to reduce the diesel particulate matter emissions of shipping. This device is the Steam Jet Aerosol Collector, from hereon abbreviated as SJAC.

This chapter describes the suitability of SJAC as a particulate matter reduction technique for diesel engines on board of ships. The concept and realisation of SJAC are described in §4.2. The measured particulate matter reduction efficiency is treated in §4.3. In §4.4 the theoretical efficiency is calculated and compared to the measured reduction efficiency. Options to further increase the removal efficiency of SJAC are numerically studied in §4.5. Finally in §4.6 it is concluded if SJAC is suitable as a particulate matter removal device for shipping.

§4.2 Concept of SJAC-technology

§4.2.1 General concept
The concept behind the SJAC is to apply a water coating on the particles by condensation of steam. The coated particles are formed by injecting steam in cooled (20 to 30°C), saturated exhaust gas. The necessary low-pressure steam is generated by a steam generator. The steam could be generated by the heat dissipated in the cooler. Boiler feed water could be made by a fresh water generator based on reverse osmosis, or the water could be distilled (and thus creating steam) with use of exhaust gas heat. Due to supersaturation, condensation will take place. As condensation on kernels is favoured, the injected steam will condense on particulate matter. This allows the particles to grow to a size that can be captured by conventional removal devices. With a constant amount of condensing steam and a constant size spectrum, a larger number of particles will result in reduced outgrowth of particles, as the condensed water needs to be divided over more particles. This reduces the particle removal efficiency in a system that contains a size selective removal device, like a cyclone.

This concept was first described by [Sun, 1992]. The development of the SJAC at ECN started as a measurement technique [Khlystov et al., 1995]. The conclusion of this work was that 99% of the aerosols could be captured with an initial particle concentration of $6 \times 10^5$ #/cm$^3$. The work of [De Wilde et al, 2004] shows the experimental results of a small
SJAC with a capacity of 0.25 l/s, using only a part of the exhaust gas from a diesel engine. The first measurements with this set-up with ten to twenty times diluted exhaust gas led to an efficiency of 85 to 90% removal of particle mass. A measurement with undiluted exhaust gas showed a number efficiency of 57%. Based on these results it was decided to investigate the concept of SJAC in conjunction with a 15 kW diesel engine.

§4.2.2 Implementation

The pilot-scale SJAC was designed as an after-treatment device for an engine with a rated power of 15 kW. The pilot-scale set-up is schematically shown in Figure 4.1.

![Figure 4.1 Schematic structure pilot-scale set-up](image)

The diesel engine used, was an ONAN 12.0 MDJF generator set delivering 12 kW of electric power at full load. The generator set was running on commercially available automotive diesel fuel, which contains maximally 50 mg sulphur per kg fuel (50 ppm). The exhaust gas flow was approximately 100 kg/h (72 m$_3$/h, i.e. volume at normal conditions, being 273K and 1.013 bar). The pre-cooling is realised by two spiral-type coolers. The used steam generator was of the make and type “MK 5 Visual 10”. The droplet removal device was a so-called coalescer, i.e. a filter that is kept clean by a continuous water stream formed by the retention of water by the filter. Because of the short lifetime of 15-20 hours before reaching an unacceptably high pressure drop across the filter, it was decided not to determine the efficiency of this droplet removal device.

![Figure 4.2 Schematic structure SJAC](image)

The SJAC itself, schematically represented in Figure 4.2, consisted of a steam-injection chamber, followed by a mixing zone, which contained a static mixer. The residence time was prolonged by 0.8 s in a specially designed chamber. An after-cooler was present during all the experiments. It was intended to investigate the influence of cooling on the particulate matter removal efficiency. The influence of this cooler turned out to be small and the effect will not be shown separately. The realisation of SJAC with pre-coolers is shown in Figure 4.3.
§4.3 Measurement results

§4.3.1 Measurement set-up

In order to investigate the efficiency of the SJAC several operating parameters were changed. The most important one was the temperature after the pre-cooler, which is the temperature just in front of the SJAC. Another parameter that was changed was the amount of injected steam. All experiments were performed at full load, after the engine had stabilised at a constant exhaust gas temperature and cooling water temperature. Table 4.2 lists the experimental conditions under which the tests were performed. The steam temperature was not measured.

Table 4.2 Measurement conditions

<table>
<thead>
<tr>
<th>Temperature after pre-cooler [°C]</th>
<th>Amount of injected steam [kg/h]</th>
<th>Measurement methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>8.3</td>
<td>SMPS</td>
</tr>
<tr>
<td>20</td>
<td>10</td>
<td>SMPS</td>
</tr>
<tr>
<td>25</td>
<td>10</td>
<td>absolute filter</td>
</tr>
<tr>
<td>30</td>
<td>8.3</td>
<td>SMPS, absolute filter</td>
</tr>
</tbody>
</table>
Two important efficiencies are distinguished. The first is the particle removal efficiency of the total system (\(\eta_{\text{tot}}\)):

\[
\eta_{\text{tot}} = 1 - \frac{x_{\text{after SJAC}}}{x_{\text{before pre-cooling}}}
\]

with \(x_{\text{after SJAC}}\) and \(x_{\text{before pre-cooling}}\) the number or (calculated) mass concentration of particles at sample point 3 and 1 respectively, indicated in Figure 4.1.

The second is the efficiency of the SJAC itself (\(\eta_{\text{SJAC}}\)):

\[
\eta_{\text{SJAC}} = 1 - \frac{x_{\text{after SJAC}}}{x_{\text{after pre-cooling}}}
\]

with \(x_{\text{after SJAC}}\) and \(x_{\text{after pre-cooling}}\) the number or (calculated) mass concentration of particles at sample point 3 and 2 respectively, indicated in Figure 4.1.

§4.3.2 SMPS measurement

The first experiments of SJAC were performed with an SMPS to determine the particle number distribution. From the distribution the mass of particles can be calculated. See for more reading on the SMPS and the conversion of the particle number distribution sections §2.4.3 and §2.2.3. The first set-up tested was with a temperature before the SJAC of 20°C and 8.3 kg/h steam injection. The cut-off diameter of the impactor in front of the SMPS was 800 nm, the silicagel-dryer and the cyclone were present at sample point 1. The orientation of the flow through the sampling points was counter-current to the exhaust gas flow. The sample-flow through the EC and CPC was 0.3 l/min. The midpoint diameters of the small bandwidths ranged from 19.8 to 626 nm.

<table>
<thead>
<tr>
<th>Measurement no.</th>
<th>Efficiency total system (mass)</th>
<th>Efficiency SJAC (mass)</th>
<th>Efficiency total system (number)</th>
<th>Efficiency SJAC (number)</th>
<th>No. of particles at sample point 1 [#/cm³]</th>
<th>Mass of particles at sample point 1 [mg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>49%</td>
<td>-</td>
<td>44%</td>
<td>-</td>
<td>1.5x10⁷</td>
<td>25</td>
</tr>
<tr>
<td>2</td>
<td>-</td>
<td>43%</td>
<td>-</td>
<td>34%</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

A slight difference in efficiency between the SJAC and the total system can be noted. This means that there is an apparent retention of particles in the coolers before the SJAC. Also the number of particles removed is somewhat smaller than the mass removed, but that was to be expected; bigger particles, which contribute more to the total particle mass, will remain bigger, and are therefore more easily removed than smaller particles.

In Figure 4.4 the resulting particle size distribution of dry particles at sample point 3 when the SJAC is working is compared with the particle size distribution at sample point 3 when the SJAC is not working, showing the effect of the SJAC.

A large mode is clearly visible at a radius of approximately 35 nm, while the end of a small mode seems to be present at approximately 10 nm. This small mode is associated with so-called secondary aerosol, like condensed hydrocarbons or sulphuric acid formed by homogeneous nucleation [Andersson and Wedekind, 2001], [Vaarashahti et al., 2004].
During the second set-up the temperature after the pre-cooler was 30°C and 8.3 kg/h steam was injected. The sample-flow through the EC and CPC was 0.2 l/min. The measured midpoint diameters ranged from 19.8 to 897 nm. The impactor had a cut-off diameter of 1000 nm. Sampling was co-current, besides the samples at sample point 1, which were counter-current. Table 4.4 shows the results of this measurement.

<table>
<thead>
<tr>
<th>Measurement no.</th>
<th>Efficiency total system (mass)</th>
<th>Efficiency SJAC (mass)</th>
<th>Efficiency total (number)</th>
<th>Efficiency SJAC (number)</th>
<th>No. of particles at sample point 1 [#/cm³]</th>
<th>Mass of particles at sample point 1 [mg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>64%</td>
<td>30%</td>
<td>34%</td>
<td>15%</td>
<td>3.3 (10^7)</td>
<td>82</td>
</tr>
<tr>
<td>2</td>
<td>59%</td>
<td>29%</td>
<td>35%</td>
<td>31%</td>
<td>4.6 (10^7)</td>
<td>105</td>
</tr>
</tbody>
</table>

An increase in measured particle emissions of the engine as compared to the number of particles shown in Table 4.3, both in number as in mass, is notable. The slightly larger measurement range in the measurement shown in Table 4.4 cannot explain the difference. The initial low values might be due to run-in effects of the exhaust gas pipe. Also evident is the increase in total system-efficiency in the second set-up compared to the first set-up, while the SJAC-efficiency decreases in comparison to the first set-up. The decrease in
SJAC-efficiency was expected, because the second set-up is less beneficial to SJAC than the first set-up, due to the higher temperature before steam injection. This also means that the difference between the measured concentration at sample point 1 and 2 has increased over time.

The third condition that was measured was expected to be the most beneficial condition with a temperature before the SJAC of 20°C and 10 kg/h steam injection, as most steam is expected to be condensed. The experimental set-up is the same as during the second condition.

Table 4.5 SMPS measurement with a temperature of 20°C and 10 kg/h steam injection

<table>
<thead>
<tr>
<th>Measurement no.</th>
<th>Efficiency total system (mass)</th>
<th>Efficiency SJAC (mass)</th>
<th>Efficiency total system (number)</th>
<th>Efficiency SJAC (number)</th>
<th>No. of particles at sample point 1 [#/cm³]</th>
<th>Mass of particles at sample point 1 [mg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>58%</td>
<td>43%</td>
<td>31%</td>
<td>33%</td>
<td>3.1 \times 10^7</td>
<td>70</td>
</tr>
<tr>
<td>2</td>
<td>66%</td>
<td>-</td>
<td>42%</td>
<td>-</td>
<td>3.6 \times 10^7</td>
<td>80</td>
</tr>
<tr>
<td>3</td>
<td>66%</td>
<td>-</td>
<td>48%</td>
<td>-</td>
<td>3.6 \times 10^7</td>
<td>73</td>
</tr>
</tbody>
</table>

Table 4.5 shows that a maximum system efficiency of 66% by estimated mass was achieved. The efficiency of the SJAC is slightly lower than during the first condition (20°C with 8.3 kg/h steam injection), which can be explained by the larger number of particles at the former measurement condition. If more particles are present than normal, the condensing water is divided over more particles, which will lead to smaller particles and subsequently to a lower particle removal.

The efficiencies according to SMPS measurements are summarised in Figure 4.5 and Figure 4.6.
The difference in measured value between sample point 1 and 2 has gradually increased from the first condition to the third condition. This ostensible retention of particles between sample point 1 and 2 is in fact a real retention in the pre-cooler (for position see Figure 4.1). After 40 hours of operation the decrease of performance of the first pre-cooler became a problem; the temperature after the first pre-cooler had gradually increased during testing by approximately 50°C. After this temperature rise cleaning of the cooler was necessary because the second cooler of the pre-cool-section could no longer compensate for it. The used cooler is of a spiral type in which gas is forced to stream between the windings, as illustrated in Figure 4.7. The pitch of this specific spiral is rather small, limiting the space between the windings of the pipe.

Opening the cooler revealed an entirely black interior; no clean surface for heat exchange was visible anymore, which was not surprising. The remaining space between the windings
was reduced so much that there was barely any space left between the first windings, making them virtually useless and forcing most gas to stream at higher than normal velocity through the last windings. 

Using a design of a cooler, which is less prone to fouling or does not have such a critical passage, can avoid this complication.

§4.3.3 Absolute filter measurement

In order to verify the mass-results as measured by an SMPS, absolute filter measurements were performed, see section §2.4.2 for more details. First the influence of the orientation of the sample tube was investigated, as not all probes were oriented the same way during the SMPS-measurements. In particular larger particles might be sampled less effectively, when the sample flow is counter-current to the gas flow. Therefore the influence of the orientation of the sample point was investigated. The results of these measurements are shown in Table 4.6.

Table 4.6 Result measurement influence of sample point direction at 110°C

<table>
<thead>
<tr>
<th>Measurement 1 [mg/m³]</th>
<th>Measurement 2 [mg/m³]</th>
<th>Average [mg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample co-current</td>
<td>37</td>
<td>45</td>
</tr>
<tr>
<td>Sample counter-current</td>
<td>44</td>
<td>41</td>
</tr>
</tbody>
</table>

The mass of accumulated dust can be determined with an accuracy of 0.4 mg. The volume during sampling can be determined with an accuracy of 2%. The sampled volume of these measurements differed slightly but is approximately 0.27 m³. For the measurement conditions in this chapter the maximum measurement error is ±2 mg/m³.

The distribution of the measured values and the lack of statistical difference between the measurements indicate that an error due to the other orientation of the sampling point at sample point 1 is negligible. This does not come as a surprise, because submicron particles are known to behave just like a gas, and are therefore sampled with counter-current sampling as well as with co-current sampling. This is supported by a statement in ISO 8178-1 section 16.1.1 [ISO, 1996].

Note that the mass-concentration of particles measured with the absolute filter measurement is smaller than the mass-concentration calculated from SMPS-measurements. Other measurements, presented in Table 4.7 and Table 4.8, show mass concentrations of the same order as those in Table 4.6. Measurement number 5 at the inlet of the pre-cooler in both Table 4.7 and Table 4.8 was treated as an erroneous measurement as this measurement is larger than the average plus two standard deviations.

Table 4.7 Measurements absolute filter at 110°C, between brackets sample point number

<table>
<thead>
<tr>
<th>Position</th>
<th>Sample point</th>
<th>measurement</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet pre-cooler (engine out)</td>
<td>1</td>
<td>mg/m³</td>
<td>37</td>
<td>45</td>
<td>44</td>
<td>41</td>
<td>(56)</td>
<td>42</td>
</tr>
<tr>
<td>After pre-cooler with cyclone</td>
<td>2</td>
<td>mg/m³</td>
<td>37</td>
<td>40</td>
<td></td>
<td></td>
<td></td>
<td>38</td>
</tr>
<tr>
<td>After pre-cooler without cyclone</td>
<td>2</td>
<td>mg/m³</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>After SJAC, 25°C, 10 kg/h steam</td>
<td>3</td>
<td>mg/m³</td>
<td>29</td>
<td>35</td>
<td></td>
<td></td>
<td></td>
<td>32</td>
</tr>
<tr>
<td>After SJAC, 30°C, 8.3 kg/h steam</td>
<td>3</td>
<td>mg/m³</td>
<td>34</td>
<td>37</td>
<td></td>
<td></td>
<td></td>
<td>35</td>
</tr>
</tbody>
</table>
Table 4.8 Measurements absolute filter at 300°C, between brackets sample point number

<table>
<thead>
<tr>
<th>Position</th>
<th>Sample point</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet pre-cooler (engine out)</td>
<td>1</td>
<td>34</td>
<td>43</td>
<td>(58)</td>
<td>38</td>
<td></td>
<td></td>
</tr>
<tr>
<td>After pre-cooler with cyclone</td>
<td>2</td>
<td>33</td>
<td>37</td>
<td>35</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>After pre-cooler without cyclone</td>
<td>2</td>
<td>39</td>
<td>34</td>
<td>37</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>After SJAC, 25°C, 10 kg/h steam</td>
<td>3</td>
<td>22</td>
<td>30</td>
<td>26</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>After SJAC, 30°C, 8.3 kg/h steam</td>
<td>3</td>
<td>32</td>
<td>34</td>
<td>33</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

During SMPS-measurements a cyclone was used at sample point number 2. It could be argued that the decrease in particle mass observed between sample point number 1 and sample point number 2 is (partially) caused by the cyclone. Comparing the weight on the filters after residing in an oven at 300°C from sampling after the pre-cooler with each other shows that 96% of the particle mass measured without a cyclone is also measured with the cyclone. The difference between these measurements is statistically not relevant, and cannot explain the large removal of particles between sample point 1 and 2 that was found with the SMPS-measurements.

The share of volatile components on the filter after the measurement can be determined by comparing the weight of the particulate matter at 110°C with the weight after evaporating the volatile components. The volatile components are evaporated by placing the filters in an oven of 300°C for a period longer than an hour. Change in weight of the absolute filter is incorporated. The share volatile can be calculated with formula 4.2.3.

\[
\text{share}_{\text{volatile}} = \frac{m_{\text{part,110°C}} - m_{\text{part,300°C}}}{m_{\text{part,110°C}}} \quad \text{Formula 4.2.3}
\]

The values are calculated by first computing the share of volatile components for each measurement and subsequently averaging these for each condition. The alternative approach, i.e. averaging first and subsequently calculating the share, will lead to the same average share, but it will overestimate the standard deviation, because it accounts for the changes in absolute emissions too. The measurement error in the share of volatile components is approximately ±5% (absolute). It can be concluded that volatile components are present on the particles when measured at 110°C, but in relatively small amounts, as is shown in Figure 4.8.
The efficiency of the SJAC and the total system can be calculated at 110°C and 300°C, using the same efficiency definitions as with SMPS measurements. The results are shown in Figure 4.9; all efficiencies are mass efficiencies. It can be clearly seen that the removal efficiency as measured by an absolute filter is considerably smaller than the removal efficiency by mass according to the calculation from SMPS measurements. From Figure 4.9 and Table 4.9 it can be concluded that the removal efficiency in the present set-up is lower than 25%. Measurements showed that the number removal of the SJAC is not as high as observed during the measurements done in [De Wilde et al., 2004]. Therefore, it is useful to investigate the theoretical potential of the SJAC by a simulation. This is the subject of §4.4. With the help of this simulation further system improvements are studied in §4.5.

**Table 4.9 Results from filter measurements at 110°C**

<table>
<thead>
<tr>
<th>Steam Flowrate</th>
<th>Mass efficiency total</th>
<th>Mass efficiency SJAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.3 kg/h steam in exhaust gas of 30°C</td>
<td>17%</td>
<td>8%</td>
</tr>
<tr>
<td>10 kg/h steam in exhaust gas of 25°C</td>
<td>24%</td>
<td>16%</td>
</tr>
</tbody>
</table>
§4.4 Simulation of SJAC with cyclone

§4.4.1 Introduction
While preparations for the measurements, reported in §4.3, were made, development of a simulation of the SJAC-technology was started. This simulation gained importance, when measurements showed that the number removal of the SJAC is not as high as observed during the measurements done in [De Wilde et al., 2004]. One explanation could be that the conditions in [De Wilde et al., 2004] were more favourable. Another explanation could be that something went wrong when scaling up the installation to 100 kg/h exhaust gas. In order to find out if the measurement results of §4.3 can be explained by theory, the results of the simulation will be compared with the measurements by SMPS in §4.4.5.

§4.4.2 Macroscopic considerations
Starting point of the simulation of the SJAC are the typical engine parameters, shown in Table 4.10. Inlet air of the engine is considered to be dry, unless it is stated differently. This assumption mainly has influence on the amount of water that condenses in the cooler, before steam injection. The exhaust gas contains particles. For the macroscopic consideration only one parameter is used to describe the particles and that is particle concentration. This parameter is generally varied. When it is not varied a value of $2.5 \times 10^{13} \#/m_0^3$ is used, see Table 4.10.

Table 4.10 Engine and SJAC parameters used in the calculations of SJAC, unless noted otherwise

<table>
<thead>
<tr>
<th>Engine and SJAC parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine power</td>
<td>14 kW</td>
</tr>
<tr>
<td>CH-ratio of fuel [mass/mass]</td>
<td>5.5</td>
</tr>
<tr>
<td>Air excess ratio [-]</td>
<td>1.5</td>
</tr>
<tr>
<td>Temperature of exhaust gas</td>
<td>330°C</td>
</tr>
<tr>
<td>Mass flow exhaust gas</td>
<td>100 kg/h</td>
</tr>
<tr>
<td>Temperature of exhaust gas after cooling</td>
<td>30°C</td>
</tr>
<tr>
<td>Mass flow injected steam</td>
<td>10 kg/h</td>
</tr>
<tr>
<td>Temperature of injected steam</td>
<td>110°C</td>
</tr>
<tr>
<td>Particle concentration</td>
<td>$2.5 \times 10^{13} #/m_0^3$</td>
</tr>
</tbody>
</table>

The calculation follows the steps in Figure 4.1. From CH-ratio, and air excess ratio the composition of the exhaust gas from the engine is determined. The next step in the calculation is cooling of the exhaust gas. For virtually all operating conditions the exhaust gas is supersaturated after the cooler, and condensation will take place in the exhaust gas cooler. It is assumed that condensation occurs on the actual heat exchanging surface, and not on the particles. The condensing water is assumed to be separated from the exhaust gas completely before the exhaust gas enters the steam injection zone. Note that a temperature of 30°C is assumed after cooling of the exhaust gas, because 20°C cannot be reached for all weather conditions. In fact even the temperature of 30°C cannot be achieved for tropical conditions, but under most conditions 30°C can be achieved.

The exhaust gas that enters the steam injection zone is, due to the assumptions, either unsaturated or saturated. When steam is injected in the exhaust gas, a number of things happen. The amount of water vapour in the gas mixture will increase. At the same time the
temperature of the exhaust gas will increase due to the temperature and heat capacity of the injected steam. At the moment of steam injection a supersaturation is created. Condensation will take place during and immediately after steam injection. This reduces the amount of water vapour, but increases the temperature, as heat is released during condensation of water vapour. For the sake of calculation it is assumed that steam and exhaust gas will mix entirely (both a uniform concentration profile and a uniform temperature profile), before condensation takes place. This assumption makes it easier to illustrate the process. The assumption does not have any influence on the calculation based on macroscopic conditions. It does, however, influence the dynamical calculation of particle growth, as performed in section §4.4.3.

The mixing process can be described by an energy balance. The general energy balance is given by formula 4.4.1

\[ \Delta U_{\text{int}} + \Delta U_{\text{kin}} + \Delta U_{\text{pot}} = Q + W \]  

Formula 4.4.1

With \( \Delta \) the difference between the condition out and the condition in, \( U_{\text{int}} \) the internal energy of the system, \( U_{\text{kin}} \) the kinetic energy of the system, \( U_{\text{pot}} \) the potential energy, \( Q \) the heat transferred out of the system and \( W \) the work transferred out of the system.

Formula 4.4.2

For a steady-state steady-flow process the work \( W \) is the sum of the “shaft work” and the work done by pushing the volume of liquid in and out of the system [Smith et al., 1996], or in form of a formula:

\[ W = W_{\text{shaft}} + p_{\text{in}} Vol_{\text{in}} - p_{\text{out}} Vol_{\text{out}} = W_{\text{shaft}} - \Delta(p \cdot Vol) \]

With \( p \) the pressure and \( Vol \) the volume of the medium. Substituting formula 4.4.2 in formula 4.4.1 leads to formula 4.4.3.

\[ \Delta U_{\text{int}} + \Delta U_{\text{kin}} + \Delta U_{\text{pot}} = Q + W_{\text{shaft}} - \Delta(p \cdot Vol) \]  

Formula 4.4.3

By definition (a.o. [Smith et al., 1996]) the enthalpy is defined as:

\[ \Delta U_{\text{int}} + \Delta(p \cdot Vol) \equiv \Delta H \]  

Formula 4.4.4

It is assumed that no heat is transferred out of the system and no shaft work is done. Additionally it is assumed that the kinetic and potential energy are constant. Under these circumstances the energy balance reduces to formula 4.4.5.

\[ \Delta H = 0 \]  

Formula 4.4.5

In order to calculate the effect of mixing the hot steam with the cold exhaust gas (before condensation) formula 4.4.5 is used. Additionally the two media are regarded as ideal gases, i.e. that the enthalpy of mixing equals zero. This leads to the formula shown in formula 4.4.6.

\[ \Delta H_{\text{eg}} + \Delta H_{\text{steam}} = 0 \]  

Formula 4.4.6

With \( \Delta H \) the total enthalpy for exhaust gas (including water vapour) and injected steam respectively. Since continuously new steam and gas is entering the process the enthalpy balance can be written as formula 4.4.7.

\[ \Delta H_{\text{eg}} + \Delta H_{\text{steam}} = 0 \]  

Formula 4.4.7

If formula 4.4.7 is written explicitly, formula 4.4.8 is obtained for a constant pressure process.
With \( \dot{m} \) the mass flow, \( c_p \) the heat capacity, and \( T \) the temperature. Note that since steam and exhaust gas are mixed, they obtain the same temperature after mixing (\( T_{\text{mixed}} \)). Note that the heat capacity is a function of temperature, whereas the mass is not and can be taken out of the integral. In this case data from [Smith et al., 1996] is used for the heat capacities of the gaseous components. The temperature after mixing is obtained by dividing a range in which \( T_{\text{mixed}} \) has to lie (initially between \( T_{\text{eg,in}} \) and \( T_{\text{steam,in}} \)) into ten pieces. Starting from the lower temperature boundary \( T_{\text{mixed}} \) is increased until the left-hand term of formula 4.4.8 is larger than zero. Then the two new boundary values are the last value that the left-hand term of formula 4.4.8 is smaller than zero and the value where the left-hand term of formula 4.4.8 was larger than zero. This way the temperature \( T_{\text{mixed}} \) is solved with a precision of \( \Delta T_{\text{mixed}}/T_{\text{mixed}} \) of \( 1 \times 10^{-8} \) K. The mixing-process is illustrated by the line between points 1 and 2 in Figure 4.10 for the data from Table 4.10. Note as well that the calculated temperature is valid for all mass flows having the same ratio \( \dot{m}_{\text{steam}}/\dot{m}_{\text{eg}} \) with all other parameters remaining the same.

Subsequently the condensation process is calculated. During condensation heat of evaporation is released. The resulting change in temperature can be calculated by an energy balance for all phases. Again it is assumed that no heat is transferred out of the system and that no shaft work is being done. The potential energy and the kinetic energy are assumed constant. This reduces the energy balance to an enthalpy balance:

\[
\Delta H_{\text{deg}} + \Delta H_v + \Delta H_{\text{cond}} = 0
\]

Formula 4.4.9

The state of the condensate is calculated by first evaporating condensate present at temperature \( T_{\text{mixed}} \), subsequently heating it as vapour to temperature \( T_{\text{a cond}} \) and then condensing it at temperature \( T_{\text{a cond}} \). This simplifies the calculation. The enthalpy balance can then be described by formula 4.4.10.

\[
\int_{T_{\text{mixed}}}^{T_{\text{a cond}}} \dot{m}_{\text{deg}} \cdot c_{p,\text{deg}} \cdot dT + \int_{T_{\text{mixed}}}^{T_{\text{a cond}}} \dot{m}_v \cdot c_{p,v} \cdot dT + \dot{m}_{\text{cond, in}} \cdot h_{\text{cond}}(T_{\text{mixed}}) - \dot{m}_{\text{cond, out}} \cdot h_{\text{cond}}(T_{\text{a cond}}) = 0
\]

Formula 4.4.10

With subscript deg referring to dry exhaust gas (i.e. exhaust gas without water vapour), subscripts cond,in and cond,out referring to the amount of condensate entering and exiting respectively and \( h \) the specific enthalpy (J/kg). \( \dot{m}_v \) is defined in formula 4.4.11.

\[
\dot{m}_v = \dot{m}_{v,\text{eg in}} + \dot{m}_{\text{steam}} + \dot{m}_{\text{cond, in}} = \dot{m}_{v,\text{out}} + \dot{m}_{\text{cond, out}}
\]

Formula 4.4.11

With subscript v,eg in the amount of vapour in the entering exhaust gas, steam referring to the amount of steam injected and v,out referring to the amount of vapour after condensation.

\( \dot{m}_{\text{cond, out}} \) is an intricate function of time and will be treated in more detail in §4.4.3. In the present section the amount of condensing water is gradually increased, until the amount of water vapour equals the equilibrium vapour pressure. The temperature corresponding to every amount of condensed water is calculated by solving formula 4.4.10 in a similar way as formula 4.4.8, with a precision of \( 1 \times 10^{-5} \) K. \( h_{\text{cond}} \) is calculated by interpolating tabulated
values from [Smith et al., 1996]. The condensation process is illustrated in Figure 4.10, between point 2 and 3. The amount of water vapour that condenses is the difference in water vapour content in exhaust gas between point 2 and 3 in Figure 4.10. Note that this is only a fraction of the injected steam, visible in Figure 4.10 as the difference in water vapour content in exhaust gas between point 2 and 1.

Figure 4.10 also clearly shows that the increase in temperature due to the heat release during condensation cannot be ignored, and is in fact the main reason that the actual amount of water that condenses is only a fraction of the injected steam. Note that this figure can also be used for estimations of how much steam will condense with another initial temperature or different amount of steam injected.

From the amount of condensate the resulting particle radius can be calculated by formula 4.4.12 under a number of assumptions.

- Primary homogeneous nucleation can be neglected. Given the average relative supersaturation of 200%, for the SJAC-case, this is a valid assumption, see for example [Kashchiev, 2000].
- Condensation on the wall can be ignored. This is true for the 15 kW-case, where the surface of the wall is less than 5% of the total particle surface. For larger scale SJAC this is not important at all, due to the decrease of surface area to volume ratio.
- The initial particle radius and the effects on the growth velocity associated with the initial particle radius are ignored. This assumption will be investigated in §4.4.3.

\[
\rho_l \cdot \frac{4}{3} \pi \cdot \frac{c_{part}}{\rho_{eg}} \cdot \frac{\dot{m}_{eg}}{\dot{m}_{cond}}
\]

With \( r_p \) the radius of the particle, \( \rho_l \) the density of the liquid (water) and exhaust gas respectively and \( c_{part} \) the particle concentration. Note that since \( c_{part} \) is defined as a concentration per normal cubic meter, the exhaust gas density is defined at normal conditions as well.

\[
Formula 4.4.12
\]
Figure 4.10 Changes in water vapour content and temperature because of injection of 10% steam in saturated exhaust gas of 30°C. Line between points 1 and 2 is the mixing line. The line between points 2 and 3 is the condensation line. The line between points 2 and 3 the saturation curve (i.e. the percentage water vapour air can contain at a certain temperature)

In order to get a feeling of typical particle concentrations, the particle concentrations measured in a number of studies are summarised in Table 4.11. It should be noted that the range of concentrations is pretty wide. The values as measured by [Van Rens et al., 2007] and those presented in Chapter 3 correspond well with other literature.

<table>
<thead>
<tr>
<th>Study</th>
<th>Particle concentration* [number of particles/mn$_3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Andersson and Wedekind, 2001]</td>
<td>$6 \times 10^{14}$ - $1.1 \times 10^{15}$</td>
</tr>
<tr>
<td>[Burtscher, 2000]</td>
<td>$2 \times 10^{11}$ - $8 \times 10^{13}$</td>
</tr>
<tr>
<td>[Hall et al., 2000]</td>
<td>$&gt;2 \times 10^{14}$</td>
</tr>
<tr>
<td>[Van Rens et al., 2007]</td>
<td>$2 \times 10^{13}$ - $6 \times 10^{13}$</td>
</tr>
<tr>
<td>Chapter 3</td>
<td>$3 \times 10^{11}$ - $2 \times 10^{14}$</td>
</tr>
</tbody>
</table>

*The data from [Andersson and Wedekind, 2001] and [Hall et al., 2000] is converted from number of particles per kWh to number of particles per m$_n^3$ using the data from the ONAN 12.0 MDJF generator (i.e. a flow of 100 kg/h (72 m$_n^3$/h) for a 14 kW engine)

Figure 4.11 shows the influence of the particle concentration on the radius of grown particles.
The cyclone is simulated by the model of Barth. This model is pretty generic, but holds for cyclones that are smooth and well-designed [Hoffman and Stein, 2002].

\[
\eta_{SJAC}(r_p) = \frac{1}{1 + \left(\frac{r_{50}}{r_p}\right)^{6.4}}
\]

With \( \eta_{SJAC}(r_{\text{part}}) \) the efficiency of separation of the SJAC for every radius \( r_p \). \( r_{50} \) is the radius at which 50% of the particles are separated from the gas stream, also referred to as cut-off radius. Figure 4.12 shows the efficiency of a cyclone for every radius for a cut-off radius of 500 nanometres according to the model of Barth.
Figure 4.13 shows the expected number removal efficiency of the SJAC-cyclone combination as a function of the concentration of particles, based on the assumptions in this section.

Figure 4.13 shows that based on these global considerations alone, the concentration is a very important parameter. In fact it looks like the SJAC does not work properly for concentrations larger than $3 \times 10^{13} \text{#/m}^3$. These results are, however, not conclusive. Only when the influence of the initial particle distribution is considered, definitive conclusions can be drawn. The influence of initial particle distribution is the focus of §4.4.3.

§4.4.3 Influence of initial particle distribution

When the influence of the initial particle distribution is considered, it is crucial to know how the growth velocity of a single particle is related to the particle radius. This is described in for example [Seinfeld and Pandis, 1998] for condensation in atmospheric conditions. This section follows the derivation in [Seinfeld and Pandis, 1998], but now for condensation on particulate matter in gas which is deliberately supersaturated. Note that all assumptions of §4.4.2 are still valid in this section besides the assumption of neglecting the initial particle radius.

For the derivation of the growth formula it is assumed that a particle is much larger than the mean free path (i.e. the average distance a molecule travels before colliding with another molecule). The resulting formulae are corrected for use in the region of the mean free path.

The rate of condensation is determined by the rate of water vapour transport to the particle surface. The mechanism governing this transport is diffusion. Diffusion of component $i$ in medium $j$ is described by Fick’s law as:

$$\vec{j}_i = -D_{ij} \nabla c_i$$  

Formula 4.4.14

With $\vec{j}_i$ the molar flux of species $i$, $D_{ij}$ the binary diffusion coefficient of component $i$ in medium $j$ (exhaust gas) and $\nabla c_i$ the concentration gradient of species $i$. 

---

Figure 4.13 Theoretical efficiency SJAC on global considerations for different particle concentrations
Now let’s elaborate this further for a spherical particle. Diesel particulate matter is not spherical as discussed in section §2.2.2 When water is condensed at the particle surface, however, it will smooth out the surface to become a sphere. For a spherical particle the concentration of water vapour will only vary in the direction perpendicular on the surface, i.e. in spherical coordinates in r-direction, with \( r=0 \) at the centre of the particle. This means that:

\[
\nabla c_i = \frac{\partial c_i}{\partial r}
\]

Formula 4.4.15

Between every \( r \) and \( r+\Delta r \) the net storage of moles of species \( i \) should equal the difference between the influx and outflux of species \( i \), or in formula form:

\[
\frac{\partial (c_i \cdot V)\bigg|_{r}^{r+\Delta r}}{\partial t} = \left( j_i A \right)_{r} - \left( j_i A \right)_{r+\Delta r}
\]

Formula 4.4.16

Rewriting equation 4.4.16 leads to 4.4.17:

\[
\frac{\partial c_i}{\partial t} \cdot \left( \frac{4}{3} \pi r^3 + 3r^2 \Delta r + 3r \Delta r^2 + \Delta r^3 \right) - \frac{4}{3} \pi \cdot r^3 = 4 \pi \cdot r^2 \frac{\partial^2 c_i}{\partial r^2} - 4 \pi (r + \Delta r)^2 \frac{\partial^2 c_i}{\partial r^2}
\]

For infinitesimal small \( \Delta r \) formula 4.4.17 can be significantly simplified:

\[
\frac{\partial c_i}{\partial r} \left( 4 \pi \cdot r^2 + 4 \pi \cdot r^2 \right) - 4 \pi \cdot r^2 \frac{\partial c_i}{\partial r} = 0
\]

Formula 4.4.18

If we assume steady-state, i.e. \( \frac{\partial c_i}{\partial t} = 0 \), it follows that \( \frac{\partial^2 c_i}{\partial r^2} = 0 \). With the boundary conditions that the water vapour concentration at the surface is the equilibrium concentration at the surface (i.e. \( c(r_0) = c_s \)), and that the concentration infinitely far away from the particle is \( c, \infty \), the concentration profile can be solved, resulting in formula 4.4.20.

\[
c_i(r) = c_{i,\infty} + \frac{r_p}{r} (c_{i,s} - c_{i,\infty})
\]

Formula 4.4.20

The mass flow of a species to a single particle is the molar flux to the particle, which is minus the flux away from the particle, times the molar mass and the surface of the particle.

\[
m_i \mid_{x_s} = -\frac{j_i}{x_s} \cdot M_i A_s = D_{ij} M_i A_s \nabla c_i \mid_{x_s}
\]

Formula 4.4.21

With \( m_i \mid_{x_s} \) the mass flow of component \( i \) at a location \( x \) at the surface, \( j_i \) the molar flux at location \( x \) on the surface (defined away from the particle, hence the minus sign), \( A_s \) the area of the surface, \( M_i \) the molecular weight of the component \( i \), and \( \nabla c_i \mid_{x_s} \) the derivative of the concentration in (multi-dimensional) space at location \( x_s \).

For calculation purposes it is more convenient to write the concentration as a partial pressure, because the equilibrium vapour pressure for a certain temperature is tabulated. Using the ideal gas law, the partial pressure is calculated from the concentration using formula 4.4.22.
\[ c_i = \frac{n_i}{\text{Vol}} = \frac{p_i}{RT} \]  

Formula 4.4.22

With \( n_i \) the amount of moles of component \( i \), \( \text{Vol} \) the volume of all components, \( p_i \) the partial pressure of component \( i \) and \( R \) the universal gas constant with units \( \text{J/(kg.mole)} \).

Assuming spherical particles, and combining formulae, 4.4.20 to 4.4.22, leads to a formula for the transport of water vapour to a particle in exhaust gas, which assuming that all transported vapour condenses (otherwise, a build up of water vapour would occur, which is in contrast to the assumption that \( dc_i/dt=0 \))

\[
\frac{dm_{i,pp}}{dt} = \dot{m}_v = \frac{4\pi \cdot r_p \cdot D_{v,p} \cdot M_{H_2O}}{R} \left( \frac{p_{v,eq}}{T_{\infty}} - \frac{p_{v,s}}{T_s} \right)
\]

Formula 4.4.23

With \( dm_{i,pp}/dt \) the mass of condensate per particle. Note that since some vapour is converted to condensate the (overall) concentration of vapour decreases, and the assumption leading to the concentration profile (i.e. \( dc_i/dt=0 \)) is strictly speaking not valid anymore. A quasi steady-state is assumed, in which the concentration profile is recalculated for every small overall change of concentration.

For large surfaces the equilibrium vapour pressure at the surface is equal to the equilibrium vapour pressure at the local temperature, assuming slow condensation of pure water on a surface that does not interact with water.

For small particles the actual vapour pressure at the surface is slightly higher, because the surface tension has to be overcome. This phenomenon is called the Kelvin-effect, and is described in formula 4.4.24.

\[
p_{v,s} = p_{v,eq}(T_s) \cdot e^{\frac{2\sigma_{H_2O}M_{H_2O}}{RT_s r_p p_t}}
\]

Formula 4.4.24

With \( p_{v,eq} \) the temperature dependant saturated vapour pressure in Pa, \( \rho \) the density and \( \sigma \) the surface tension in N/m.

Note that formulae 4.4.23 and 4.4.24 imply that the growth velocity of smaller particles is smaller than the growth velocity of larger particles. This means that particles that have a large initial radius will always remain larger than particles with a small initial radius.

The particle radius at time \( t \) can be calculated by a volume balance, leading to formula 4.4.25.

\[
r_p(t) = r_{p,0} + \frac{3}{4 \cdot \pi \cdot \rho_1} \int_0^t \frac{dm_{i,pp}}{dt} \, dt
\]

Formula 4.4.25

With subscript 0 referring to the value of the variable at \( t=0 \).

If water vapour diffuses to a particle that has a radius, which is in the same order of magnitude as the mean free path, the flux of water vapour cannot be seen as a continuum anymore. Several correction factors are in use. They are compared with measurements by [Seinfeld and Pandis, 1998]. In this study the semi-empirical Fuchs-Sutugin correction factor is used, as it shows a good agreement with measurements.
Formula 4.4.26

$$FS = \frac{0.75\alpha\left(1 + \frac{\lambda_v}{r_p}\right)}{\left(\frac{\lambda_v}{r_p}\right)^2 + \frac{\lambda_v}{r_p} + 0.283\alpha\frac{\lambda_v}{r_p} + 0.75\alpha}$$

With FS the Fuchs-Sutugin correction factor and \(\alpha\) the so-called accommodation coefficient, which describes the likelihood of sticking. When \(\alpha=0\) no particles stick, while when \(\alpha=1\) all particles stick. It is assumed that for condensation \(\alpha=1\). Formula 4.4.26 is then equal to the correction factor used in [Hinds, 1999]. Note that [Seinfeld and Pandis, 1998] use another correction factor for their examples of growth of cloud droplets. If \(r_p\) approaches to infinity, FS approaches 1, i.e. it converges to the value of the continuum regime for large particles. FS approaches to zero if \(r_p\) approaches zero. The mean free path of the vapour molecules, \(\lambda_v\), in formula 4.4.26, is defined by:

\[
\lambda_v = \frac{3D_v}{\bar{u}_v}
\]

Formula 4.4.27

With \(D_v\) the diffusion coefficient of water vapour in exhaust gas, and \(\bar{u}_v\) the mean thermal speed of the water vapour molecules. Note that the mean free path is a weak function of temperature.

For the size range of diesel particulate matter formula 4.4.23 is modified, substituting \(p_{\nu,s}\) with formula 4.4.24 and substituting \(D_{\nu,p}\) by \(D_v\) FS, with FS as described in formula 4.4.26, which results in formula 4.4.28.

\[
\frac{dm_{\nu,pp}}{dt} = \frac{4\pi r_p D_v M_{H_2O}}{R} \cdot 0.75\alpha\left(1 + \frac{\lambda_v}{r_p}\right) \left(\frac{\lambda_v}{r_p}\right)^2 + \frac{\lambda_v}{r_p} + 0.283\alpha\frac{\lambda_v}{r_p} + 0.75\alpha
\]

In order to solve this formula for every ‘t’ it is crucial to get a good description of the temperature change. Figure 4.10 clearly showed that the change in average temperature cannot be ignored. In order to calculate the average temperature the total amount of condensing water needs to be determined.

\[
\frac{dm_{\text{cond}}}{dt} = \sum_{r_p} \left( N(r_p) \frac{dm_{\nu,pp}(r_p)}{dt} \right)
\]

Formula 4.4.29

With \(N(r_p)\) the number of particles with a certain radius.

When the condensation rate is calculated, first the condensation rate at initial conditions is calculated. When \(\frac{dm_{\nu,pp}}{dt}\) is known, the total amount of condensing water can be calculated by formula 4.4.29 and from that amount the change in average temperature can be calculated by solving formula 4.4.10. It is generally assumed that the volume in which the
temperature is (much) smaller than the temperature infinitely far away from the particle is small in comparison to the total volume, and hence the temperature infinitely far away from the particle can be assumed equal to the average temperature.

In order to calculate the influence of the initial radius it is necessary to find the temperature on the droplet surface. This is not straightforward as will be discussed in the next section.

§4.4.4 Influence assumptions in temperature gradient

In this section the influence of the assumptions in temperature gradient between the particle surface and the gas infinitely far away from the particle on the resulting particle radius and removal efficiency will be investigated.

Three assumptions for the temperature gradient between the particle surface and the gas infinitely far away from the particle will be investigated. Those are:

- no temperature gradient (formula 4.4.30)
- a small temperature gradient based on conduction (formula 4.4.37)
- a temperature gradient based on conduction (formula 4.4.36)

All other variables are kept constant.

The first two assumptions will probably introduce an error, but they will simplify the calculation considerably. The main effect of simplification of the calculation is that the calculation time is shortened.

Let’s first assume that heat conduction is so fast relatively to mass condensation that the temperature $T_s$ equals $T_\infty$ (meaning no temperature gradient) and formula 4.4.28 reduces to formula 4.4.30.

\[
\frac{dm_{i,pp}}{dt} = \frac{4\pi \cdot r_p \cdot D_v \cdot M_{H_2O}}{RT_\infty} \cdot FS \cdot \left( P_{v,\infty} - P_{v,eq}(T_\infty) \cdot e^{\frac{2\sigma_{H_2O} M_{H_2O}}{RT_\infty T_v \cdot \rho_l}} \right)
\]

Formulæ 4.4.30

Whether or not this assumption will hold for the SJAC-case will be shown by comparing this assumption by other assumptions of the temperature gradient in the remainder of this section.

For the calculation of a temperature gradient, it is assumed that the heat accumulated by the particle and water on the particle is negligible in comparison to the heat transported. This is a fair assumption, given the small particle mass and small temperature difference. It is assumed that heat is transported by conduction through the gas. For the relatively small temperature differences this is a fair assumption. The heat balance at the surface of a particle reduces to formula 4.4.31.

\[
\tilde{q} A_s = -k \nabla T|_{s,v} A_s = \frac{dH_{\text{cond}}}{dt} \equiv h_{\text{cond}} \frac{dm_{i,pp}}{dt}
\]

Formula 4.4.31

with $k$ the thermal conductivity and $H_{\text{cond}}$ the enthalpy that is released by condensation at the surface of a certain particle and $h_{\text{cond}}$ the mass specific enthalpy. Note that the specific enthalpy is a function of temperature and hence a function of time, but since $h_{\text{cond}}$ only varies by 1% in the region of practical application of the SJAC $h_{\text{cond}}$ can be assumed constant.
For spherical particles formula 4.4.31 reduces to:

\[-4\pi \cdot r^2_p k \frac{\partial T}{\partial r} = h_{\text{cond}} \cdot \frac{\text{d}m_{l,\text{pp}}}{\text{d}t}\]  

Formula 4.4.32

By making an energy balance, in a similar fashion as the mass balance for the concentration profile, it can be concluded that for steady-state, i.e. \( \frac{\partial T}{\partial t} = 0 \), it follows that \( \frac{\partial^2 T}{\partial r^2} = 0 \). The temperature distribution can subsequently be solved with \( T=T_s \) at the surface of the particle and \( T=T_{\infty} \) infinitely far away from the particle.

\[ T(r) = T_s + r_p \frac{T_s - T_{\infty}}{r}\]  

Formula 4.4.33

Using the partial derivative of formulae 4.4.33 in formula 4.4.32, the temperature at the particle surface can be described by formula 4.4.34.

\[ T_s = \frac{\text{d}m_{l,\text{pp}}}{\text{d}t} \cdot h_{\text{cond}}(T_s) = \frac{4\pi \cdot k \cdot r_p}{4\pi \cdot k \cdot r_p} + T_{\infty} = T_{\infty}(\delta + 1)\]  

Formula 4.4.34

With \( \delta \) a dimensionless variable that is an indication of the size of the temperature gradient. Note that formula 4.4.34 is an implicit formula, i.e. \( \text{d}m_{l,\text{pp}}/\text{d}t \) is a function of \( T_s \), see formula 4.4.28.

The heat conductivity is different for particles with a size close to the mean free path. The heat conductivity is described by formula 4.4.35.

\[ k = \frac{k_{\text{eg}}(T_s)}{1 + \alpha_T r_p \rho_{\text{eg}} \cdot c_{p,\text{eg}} \cdot \bar{u}_{\text{eg}}(T_s)}\]  

Formula 4.4.35

With \( \alpha_T \) the thermal accommodation coefficient and \( \bar{u}_{\text{eg}} \) the mean thermal speed of the exhaust gas molecules. \( k_{\text{eg}} \) is the heat conductivity in the exhaust gas if the exhaust gas is a continuum. Note that ignoring the size dependency of the heat conductivity leads to an error in heat conductivity of 50% and more for particles smaller than 100 nanometres in radius.

Combining formulae 4.4.28 and 4.4.34 leads to an implicit expression for the growth velocity, since \( \delta \) is a function of \( \text{d}m_{l,\text{pp}}/\text{d}t \).

\[ \frac{\text{d}m_{l,\text{pp}}}{\text{d}t} = \frac{4\cdot \pi \cdot r_p D_v \cdot F S \cdot M_{\text{H}_2\text{O}}}{RT_{\infty}} \left( p_v(T_{\infty}) \cdot \frac{1}{1+\delta} \cdot p_{v,\text{eq}}(T_{\infty} \cdot (1+\delta)) \cdot \left( \frac{2M_{\text{H}_2\text{O}} \sigma}{RT_p r_p} \right)^{1+\delta} \right)\]  

Formula 4.4.36

Note that this formula is valid for every temperature gradient based on conduction.

Let’s assume a small temperature gradient, or in other words that \( \delta \ll 1 \). Then formula 4.4.36 can be written as the explicit formula 4.4.37 with the help of the Clausius-Clapeyron equation and some mathematical simplifications [Seinfeld and Pandis, 1998]. They defined their formula for the time derivative of the particle diameter. Here the time derivative of the mass of condensate per particle is used.
\[
\frac{dm_{t,pp}}{dt} = \frac{\rho_{v}(T_{\infty})}{p_{v,eq}(T_{\infty})} \cdot \frac{\sigma}{2M_{H_{2}O}} \cdot e^{RT_{\infty}p_{v,eq}} \cdot \frac{p_{v}(T_{\infty})}{p_{v,eq}(T_{\infty})} \cdot e^{RT_{\infty}p_{v,eq}}
\]

Formula 4.4.37

If formula 4.4.37 is used to calculate \(\frac{dm_{t,pp}}{dt}\) and this is subsequently used in formula 4.4.34 it follows that for the SJAC-case \(\delta\) can have a value exceeding 0.1 and strictly speaking the assumption, that \(\delta\) is much smaller than 1, does not hold. In the rest of this section it will be investigated if the assumption of a small temperature gradient is sufficient.

Figure 4.14 shows the influence of the different assumptions with regard to the temperature gradient on growth velocity by showing the decrease of water vapour content in dry exhaust gas as a function of time, based on a measured particle distribution scaled to a total particle concentration of \(2.5 \times 10^{13} \, \text{1/m}_m^3\), see Figure 4.15 for the shape of the initial distribution.

Figure 4.14 Change in vapour mass present in the exhaust gas over time. From top till bottom: the green line is condensation based on a temperature gradient based on conduction, the red line is condensation based on a small temperature gradient based on conduction and the blue line is assuming no temperature gradient.

Figure 4.14 shows that if no temperature gradient is assumed, the condensation velocity and hence the particle growth is overestimated. This is due to the fact that the temperature gradient acts as a brake on the particle growth. When a small temperature gradient is assumed, the growth velocity is slightly overestimated, but after 2 milliseconds the condensed mass is almost equal to the condensed mass without assuming a size for the temperature gradient. Note that since the growth velocity is importantly determined by the temperature gradient, it is essential that formula 4.4.35 is used for the heat conductivity.

It has to be noted that particle growth is not entirely finished after two milliseconds. In fact particle growth never entirely finishes, because at a certain point in time the vapour pressure at the surface of the smallest droplets is in equilibrium with the surroundings, whilst the vapour pressure at the surface of the larger droplets is slightly lower than the
vapour pressure of the surroundings. As a result, the large droplets will continue to grow, and hence reduce the vapour pressure of the surroundings until the vapour is in equilibrium with an infinitely flat surface of liquid water. This means that the vapour pressure at the surface of the small droplets is higher than the surroundings, and a driving force for shrinking these droplets is present. Because the large particles will only grow slowly due to the small concentration difference, the shrink velocity is much smaller than the initial growth velocity. For the considerations in this chapter a growth time of 2 milliseconds is used, before the particles are being removed, as particles only grow slowly after 2 milliseconds.

Figure 4.15 shows the initial particle size distribution and the resulting particle size distributions due to the different temperature assumptions after 2 milliseconds of growth and a total particle concentration of $2.5 \times 10^{13}$ $1/m^3$. The used initial distribution is a measured initial distribution.

The particle size distribution that results from the calculation without temperature gradient has a slightly higher mode and is slightly wider than the particle size distribution resulting from both a small temperature gradient and a temperature gradient based on heat conduction. The particle distribution resulting from assuming a small temperature gradient can barely be distinguished from a temperature gradient based on conduction.

Subsequently the influence of the assumptions of the temperature gradient on the removal efficiency of the SJAC is investigated, see Figure 4.16.
Figure 4.16. Influence of different assumptions for the temperature gradient on the calculated removal efficiency of the SJAC with a cyclone with a cut-off radius of 500 nm for different initial radii. The blue line is the removal efficiency assuming no temperature gradient. The red line is the removal efficiency assuming a small temperature gradient based on conduction and the green line is based on assuming a temperature gradient based on conduction.

Figure 4.16 shows, that assuming no temperature gradient leads to an overestimation of the removal efficiency for all particles. The overestimation does not exceed 10%. The assumption of a small temperature gradient overestimates the removal efficiency of particles smaller than 100 nanometres slightly, but the difference is never large. The influence of the different assumptions on the number removal efficiency of the SJAC over the entire particle distribution is shown in Table 4.12.

Table 4.12. Calculated number removal efficiency of the SJAC based on a measured distribution with a total particle concentration of $2.5 \times 10^{13}$ $1/m^3$ based on different assumptions

<table>
<thead>
<tr>
<th>Assumption</th>
<th>Removal efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>No particle distribution</td>
<td>34.1</td>
</tr>
<tr>
<td>Particle distribution, but no temperature gradient</td>
<td>34.2</td>
</tr>
<tr>
<td>Particle distribution and a small temperature gradient</td>
<td>32.2</td>
</tr>
<tr>
<td>Particle distribution and a temperature gradient based on conduction</td>
<td>31.7</td>
</tr>
</tbody>
</table>

Both Figure 4.16 and Table 4.12 show that assuming a small temperature gradient is a good approximation for a temperature gradient based on conduction. Table 4.12 also shows that assuming no temperature gradient or assuming no particle distribution are a good approximation for the removal efficiency according to a temperature gradient based on conduction after 2 milliseconds, although they slightly overestimate the actual particle removal. Assuming no temperature gradient is inadequate for calculating the time dependency of the condensed mass of water vapour.

The calculation could be further improved by the use of non-equilibrium thermodynamics.

§4.4.5 Comparison of simulation with measurement results

From §4.4.4 it can be concluded that assuming a particle distribution is not necessary to calculate the removal efficiency. Still for the calculation the particle distribution is used, without assuming a temperature gradient. For different conditions removal efficiency curves are calculated for different particle concentrations, which are compared to measured
results, see Figure 4.17. For the curve with a steam injection of 8.3 kg/h and a temperature after cooling of 30°C the average particle distribution of the two measured distributions is used.

If the measured number removal efficiencies of the SJAC are compared to the theoretically expected removal efficiency it shows that the calculation, assuming no temperature gradient and using the measured particle distribution is a good approximation of the actual removal efficiency. This means that the calculation can also be used as a tool for investigating options to enhance the removal efficiency of the SJAC.

§4.5 Alternative strategies to enhance particle diameter

In order to enhance the particle removal by the SJAC three different strategies can be discerned. The first strategy is to reduce the particle concentration, which increases the removal efficiency, as illustrated in Figure 4.17. This could be achieved by agglomeration, which is treated in §4.5.1. The second strategy is to increase the mass of water vapour that condenses. This could be achieved in a number of ways. One is by mixing the exhaust gas with (saturated) air, which is treated in §4.5.2. Another possibility is to stage the steam injection and cool between the steam injection steps. This is explained in more detail in §4.5.3. The third strategy is to enhance the removal efficiency of the cyclone. This is investigated in §4.5.4.

§4.5.1 Agglomeration

Agglomeration can be enhanced by increasing the residence time of the particles. The process of agglomeration is determined by Brownian motion. The rate at which particles larger than the mean free path of radius \( r_j \) collide with a stationary particle with radius \( r_i \), larger than the mean free path, is given by formula 4.5.1.
with $b_{j \rightarrow i}$ the number of collisions of all particles with radius $j$ with one particle with radius $i$, $D_j$ the diffusion coefficient of the particles with radius $j$. $A_{ij}$ is the “collision surface”, i.e. the surface associated with the distance the particles have relative to each other when the particles collide. This distance is $r_{ij}$, which is simply the radius of particle $i$ plus the radius of particle $j$. $dc/dx$ is the particle concentration gradient at the collision surface. Formula 4.5.1 can simply be extended to all particles with radius $r_j$ by multiplying it with the concentration of particle $i$.

The rate of collisions per unit volume between two particles of different radii can be described by formula 4.5.2.

$$J_{ij} = J_{i \rightarrow j} + J_{j \rightarrow i} = 4\pi \cdot \left(r_{p,i} + r_{p,j}\right) \cdot \left(D_i + D_j\right) \cdot c_{part,i} \cdot c_{part,j}$$  \hspace{1cm} \text{Formula 4.5.2}

With $J_{ij}$ the collision rate of particles of radius $r_i$ with particles of radius $r_j$ (not equal to $r_i$) in $1/(\text{m}^3\text{s})$. $J_{i \rightarrow j}$ is the rate that particles of radius $r_i$ collide with stationary particles with radius $r_j$ and $J_{j \rightarrow i}$ the rate that particles of radius $r_j$ collide with stationary particles with radius $r_i$.

Formula 4.5.2 is often rewritten as formula 4.5.3 for $r_i$ not equal to $r_j$.

$$J_{ij} = K_{ij} \cdot c_{part,i} \cdot c_{part,j}$$  \hspace{1cm} \text{Formula 4.5.3}

With $K_{ij}$ the coagulation coefficient of particles with radius $r_i$ with particles of radius $r_j$ in $\text{m}^3/\text{s}$. For any radius $r_i$ and $r_j$ much larger than the mean free path, $K_{ij}$ can be expressed as formula 4.5.4.

$$K_{ij} = 4 \cdot \pi \cdot \left(r_{p,i} + r_{p,j}\right) \cdot \left(D_i + D_j\right)$$  \hspace{1cm} \text{Formula 4.5.4}

In the case of agglomeration of two particles with the same radius, larger than the mean free path, the agglomeration can be described by formula 4.5.1. It is important to realise that all particle transport is covered by the flux of particles with radius $i$ to all particles of radius $i$, as is described in formula 4.5.5.

$$J_{ii} = J_{i \rightarrow i} = 4\pi \cdot \left(2 \cdot r_{p,i}\right) \cdot D_i \cdot c_{part,i}^2 = \frac{1}{2} K_{ii} \cdot c_{part,i}^2$$  \hspace{1cm} \text{Formula 4.5.5}

With $K_{ii}$ described as formula 4.5.4.

For particle sizes typical for diesel particulate matter several corrections are needed. General practice is to change the description of formula 4.5.4. The most used form for coagulation in the size regime of diesel particulate matter is the Fuchs form as shown below and for example in [Lehtinen, 1997]. Formula 4.5.4 can still be recognised in the numerator.

$$K_{ij} = \frac{4\pi \cdot \left(D_{agg,i} + D_{agg,j}\right) \cdot \left(r_{p,i} + r_{p,j}\right)}{r_{p,i} + r_{p,j} + \sqrt{\xi_i^2 + \xi_j^2}} \cdot \frac{4 \cdot \left(D_{agg,i} + D_{agg,j}\right)}{r_{p,i} + r_{p,j} + \sqrt{\xi_i^2 + \xi_j^2}}$$  \hspace{1cm} \text{Formula 4.5.6}
With \( D_{agg,i} \) a changed form of the diffusion coefficient as is described in formula 4.5.7. \( u_i \) is the mean thermal speed of the particles in m/s, and \( \xi_i \) in m as expressed in formula 4.5.8.

\[
D_{agg,i} = \frac{k_i T}{6\pi \cdot \mu \cdot r_{p,i}} \left( \frac{5 + 4 \cdot \frac{\lambda_{eg}}{r_{p,i}} + 6 \cdot \left( \frac{\lambda_{eg}}{r_{p,i}} \right)^2 + 18 \cdot \left( \frac{\lambda_{eg}}{r_{p,i}} \right)^3}{5 - \frac{\lambda_{eg}}{r_{p,i}} + (8 + \pi) \cdot \left( \frac{\lambda_{eg}}{r_{p,i}} \right)^2} \right) \quad \text{Formula 4.5.7}
\]

The term before the brackets in formula 4.5.7 is the normal expression for the diffusion coefficient larger than the mean free path.

\[
\xi_i = \frac{\pi \cdot u_i}{48 \cdot r_{p,i} \cdot D_{agg,i}} \left( 2 \cdot r_{p,i} + \frac{8 \cdot D_{agg,i}}{\pi \cdot u_i} \right)^3 \quad \text{Formula 4.5.8}
\]

If it is assumed that with every collision the particles stick together, the change in particle distribution can be calculated.

\[
\frac{dc_{part,i}}{dt} = - \int_0^\infty K_{j} c_{part,j} e_{part,j} dr_{p,j} + \frac{1}{2} \int_0^{r_{p,i}} K_{r_{p,k}} e_{r_{p,k}} c_{part,k} c_{part,i} dr_{p,k} \quad \text{Formula 4.5.9}
\]

The first term in this formula is the decrease in particle concentration due to agglomeration of the particle with radius \( r_i \) with other particles. Note that a collision between two particles of the same radius leads to a decrease of two particles, and therefore the first term, also holds for particles with radius \( r_j \) equal to radius \( r_i \). The last term is the increase in particle concentration of particles with radius \( r_i \) due to the agglomeration of smaller particles to particles with a radius of \( r_i \). By taking \( r_{p,i} \) as upper boundary every collision is counted twice (including the particle radius where \( r_{p,k} \) equals \( r_{p,i} \)), so the integral needs to be multiplied by a half.

It is possible to enhance the residence time and hence agglomeration before or after cooling of the exhaust gas. Let’s assume first that the number of particles in a kilogram of exhaust gas is constant throughout the temperature range of the exhaust gas, i.e. no spontaneous nucleation of condensables in the exhaust gas, and let’s assume that no condensation takes place on the particles before steam injection. In that case the concentration of particles for high temperature is much lower than the particle concentration at low temperature. On the other hand an increase in temperature increases diffusivity, due to faster movement of particles at higher temperatures. Table 4.13 shows the effect of agglomeration on the particle distribution, assuming that all particles that collide stick together. In order to calculate the decrease in particle concentration after 1 second, the change in particle concentration with the Fuchs form for the coagulation coefficient is multiplied by 1 second. This will lead to an error due to the fact, that in that second the particle concentration decreases continuously and hence the collision rate decreases continuously. If the decrease in particle concentration is small, the error is still rather small. The change in particle concentration is the sum of collisions divided by the total particle concentration. Note that all the assumptions and the mathematical simplification lead to an overestimation of the actual decrease in particle concentration.
Table 4.13 Decrease in particle concentration due to agglomeration

<table>
<thead>
<tr>
<th>Calculation</th>
<th>(c) ([1/m^3])</th>
<th>(T) ([K])</th>
<th>Decrease in particle concentration after 1 second [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculation 1</td>
<td>(2.5 \times 10^{13})</td>
<td>303</td>
<td>1.2%</td>
</tr>
<tr>
<td>Calculation 2</td>
<td>(2.5 \times 10^{13})</td>
<td>603</td>
<td>1.3%</td>
</tr>
<tr>
<td>Calculation 3</td>
<td>(10 \times 10^{13})</td>
<td>303</td>
<td>4.9%</td>
</tr>
<tr>
<td>Calculation 4</td>
<td>(10 \times 10^{13})</td>
<td>603</td>
<td>5.0%</td>
</tr>
</tbody>
</table>

From Table 4.13 it can be concluded that it is not very useful to use agglomeration as a mechanism to reduce the particle concentration, because a long residence time is necessary to decrease the number distribution significantly. Note that, if for all temperatures the assumption is valid that all particles stick together, it is more beneficial to agglomerate at low temperature, because the volume needed to facilitate the same residence time is much lower.

§4.5.2 Exhaust gas mixing with cold saturated gas

Exhaust gas can be mixed with cold saturated gas to enhance the mass of water vapour that condenses. The gas can be cold air, or cooled and recycled exhaust gas. The latter is only interesting if the particle concentration is reduced first, i.e. a recycle of the exhaust gas after the cyclone, which is discussed in section §4.5.4. In this section the attention is focussed on injection of cold saturated air. Two moments of mixing are possible; before steam injection and after the condensation that follows steam injection. If air is injected before steam injection the exhaust gas will be diluted. It results in a smaller concentration of particles as well as a smaller concentration water vapour after steam injection. The injection of air affects the condensed mass by decreasing the temperature rise per mass steam injected during the mixing-process of steam with exhaust gas and by decreasing the temperature rise per mass condensed steam during the condensation-process, due to the increased mass that needs to be heated. This is illustrated in Figure 4.18 for a dilution air flow that is equal to the exhaust gas flow.

![Figure 4.18 Illustration of effect of dilution before steam injection (1-2a-3a) in comparison to the undiluted case](image-url)
Note that the actual amount of condensed water vapour has increased with dilution, as the amount of exhaust gas has doubled in the case of dilution.

If cold saturated gas is added after steam injection and condensation, the effect is that the temperature of the exhaust gas is lowered and the water vapour content is decreased. Whether this leads to supersaturation or not, depends on the water content of the injected gas. Figure 4.19 shows the influence of injecting saturated air of 30°C up to an amount that is equal to the exhaust gas flow (from point 3 to 4). Since the resulting mixture is supersaturated condensation takes place (from 4 to 5). From this figure the total amount of condensed water vapour can be calculated by adding up the decrease in water vapour between points 2 and 3 and the decrease in water vapour content between points 4 and 5 (note that the amount of dry exhaust gas is doubled between points 4 and 5).

![Figure 4.19 Illustration of effect of dilution after steam injection with saturated air of 30°C with a mass flow equal to the exhaust gas mass flow](image)

In Figure 4.20 the effect of dilution is shown on the removal efficiency as a function of particle concentration. In both dilution scenarios the dilution flow is equal to the exhaust gas flow. From Figure 4.20 it can be concluded that the effect of diluting the exhaust gas is not significant enough to consider it for actual use. Note that diluting the exhaust gas even more has a limited effect, and it is not considered practical.

§4.5.3 Staged steam injection with intercooling

Figure 4.18 shows that the ratio between condensed steam and injected steam is more favourable for smaller steam injections (compare y-coordinates y_{23}/y_{21} with y_{2a3a}/y_{2a1}). The absolute mass that condenses is however less, when less steam is injected. If the exhaust gas is cooled between the subsequent steam injections, the advantages of a large absolute mass of injected steam and the favourable ratio for smaller steam injection are combined. The ideal case would be an unlimited amount of these injection steps with intermediate cooling. In practice two or three injections of steam with intercooling seem realistic.

The effect of two injections of steam with intermediate cooling is illustrated in Figure 4.18. The condition of the exhaust gas during the first injection of steam will follow the line from
1 to 2a. Subsequently condensation takes place along line 2a to 3a. For the calculation of intermediate cooling it is assumed, that all water vapour that condenses in the cooler condenses on the cooler surface. The condition of the exhaust gas then travels along the line from point 3a to 1. With the second injection of steam, the exhaust gas goes to the condition of point 2a again, and after condensation ends at point 3a. This means that the percentage that is found after the first steam injection can simply be multiplied by two to obtain the maximum amount of condensed mass. Note that the effect of twin-injection with intercooling is exactly the same as dilution of exhaust gas before steam injection. The effect of twin-injection with intercooling on removal efficiency of the SJAC is illustrated in Figure 4.20.

Instead of cooling with a cooler it is also possible to cool intermediately by diluting the exhaust gas after the first steam injection. Of course it is also possible to combine the dilution of air and staged steam injection with intercooling in different ways than mentioned above, like first diluting and then staging steam injection. This is as attractive, from SJAC efficiency point of view, as first injecting half of the steam, then diluting the mixture with cold saturated air and subsequently cooling the exhaust gas to 30°C, before injecting the second half of the steam. The influence of this option is illustrated in Figure 4.20 as well.

From Figure 4.20 it can be concluded that the removal efficiency increases significantly, but still the removal efficiency does not exceed 50% for a particle concentration higher than $3 \times 10^{13} \text{1/m}^3$. 

![Figure 4.20 Influence of twin-injection with intercooling, SJAC with air dilution afterwards and twin-injection with air dilution between injections followed by cooling on the removal efficiency of SJAC](image_url)
§4.5.4 Enhancing cyclone efficiency

In order to enhance the removal efficiency of the grown particles the exhaust gas could be cleaned by a very efficient cyclone with a cut-off radius of 800 nanometres. An engine of 500 kW, a small engine for inland shipping generates approximately 4000 kg/h exhaust gas. It is impossible to design a single cyclone with this cut-off diameter with an acceptable pressure drop over the cyclone. With a large number of cyclones in parallel the desired removal efficiency might be reached with an acceptable pressure drop, but it will be a very expensive device. Nevertheless, the influence of such a cyclone is illustrated in Figure 4.21. From this figure it can be concluded that such a cyclone would increase the particle removal efficiency, of the SJAC, but the removal efficiency would not exceed 50% for particle concentrations higher than $4 \times 10^{13} \text{ 1/m$^3$}$.

Another option is to use two cyclones in series. This means that two times the pressure drop over the cyclone is experienced. The influence of two cyclones in series is shown in Figure 4.21. The result is that particles that are already removed with a reasonable efficiency are removed more effectively.

A different approach is to return (a part of) the cleaned exhaust gas to the cyclone. This way (a part of) the exhaust gas is cleaned multiple times. In order to make this work the cyclone has to be designed for a larger gas flow. The exhaust gas that will be recycled has to be pressurised. The advantage is that only one cyclone is necessary. The influence of this recycle is shown in Figure 4.21 for a recycle stream as big as the exhaust gas stream before mixing with the recycle stream. For particle concentrations larger than $4 \times 10^{13} \text{ 1/m$^3$}$ the additional removal efficiency is less than 10%. Note that recycling of exhaust gas is a feasible way to improve the efficiency of the cyclone in part load situations. Normally the gas velocity at part load situations is much lower than the design velocity, and as a result the removal efficiency at part loads is much lower than the design efficiency.

It is also possible to cool the cleaned exhaust gas intended for the recycle. In that case the process has the additional benefits of dilution with a cold gas, as described in section §4.5.2. Note that since the cleaned exhaust gas still contains particles, the results are slightly different. Mixing can occur before or after steam injection and in case of staged steam injection also in-between the steam injection stages. Two cases have been calculated. Mixing after steam injection, and mixing between two steam injection stages. The results are shown in Figure 4.22. From this figure it must be concluded that even if a lot of effort is put into increasing the removal efficiency of the first generation SJAC the particle concentration is just too large to remove more than 50% of the particle concentration.
Figure 4.21 Influence of changes in removal efficiency cyclone on efficiency SJAC

Figure 4.22 Influence of a cooled recycle on overall removal efficiency of the SJAC
§4.6 Synthesis

Measurements show that the SJAC-principle works. Up to 24% of particle mass, according to absolute filter measurements, and up to 33% of the number of particles can be removed with the SJAC, using a cyclone with a cut-off diameter of 1 micrometer. If the data from SMPS measurements are converted to mass data, the SJAC seems quite efficient, with 43% removal efficiency. However a lot of uncertainties surround this conversion. Absolute filter measurements are recommended if the particle mass is of interest, as interpretation of the measurements is relatively straightforward.

In a particle reduction system that contains a cooler, it is imperative to measure not only the system efficiency, but also the efficiency of the particle removal device alone, because measurements in this section show that particle accumulation in the cooler can seriously affect the conclusions of an experiment. In addition to this, accumulation of particulate matter in the cooler may eventually lead to cooler malfunction and it is therefore useful to know how much particulate matter accumulates in the cooler.

The particulate matter removal efficiency of SJAC as built is insufficient to expect widespread application. A calculation is made to investigate the potential of the present SJAC set-up. It is found that the calculation shows good agreement with the measured values. It is found that SJAC is especially sensitive to particle concentration. The calculation shows that in the present set-up more than 50% removal efficiency is only possible for concentrations lower than \(2.5 \times 10^{13} \text{ 1/m}_n^3\).

Subsequently the calculation is used to study different configurations of SJAC. One option is to decrease the particle distribution before SJAC by agglomeration due to Brownian motion. It is found that a residence time of a second is insufficient to decrease the number concentration significantly. It is found, that if it is assumed that all particles that collide stick to each other, it is best to agglomerate at low temperatures from the viewpoint of required volume for agglomeration. Another option is to enhance the amount of steam that condenses. This is either done by diluting the exhaust gas before or after steam injection or done by injecting steam in multiple stages, with cooling in-between. It is also possible to enhance the removal efficiency of the cyclone by putting two cyclones in series or recycling a part of the cleaned exhaust gas. In the end all the options could be combined.

Even if all options for increasing the removal efficiency of SJAC are combined, the removal efficiency of SJAC does not exceed 50% for particle concentrations higher than \(5 \times 10^{13} \text{ 1/m}_n^3\) according to the calculation, while particle concentration from diesel engines might exceed \(10 \times 10^{13} \text{ 1/m}_n^3\). Therefore SJAC is not deemed very attractive for application in shipping.
Chapter 5. SJAC-ESP
§5.1 Introduction
Chapter 4 concluded with the remark that the SJAC-concept as elaborated in that chapter was not deemed very suitable for shipping. Therefore research continued with the same aim, i.e. developing a technique that is capable of removing particulate matter regardless of the fuel composition. A new concept was developed to remove particulate matter, as is described in section §5.2. In section §5.3 measurement results are presented of experiments performed with the new concept. Those measurements have been performed with different engines, different load cycles and different fuels. Section §5.4 describes the theory of particle removal based on the concept, and a model is developed to predict the removal efficiency. Section §5.5 concludes with the achieved results and the developments still to be done.

§5.2 SJAC-ESP concept

§5.2.1 General concept
It was discussed in section §2.6.5 that an ESP is capable of removing particulate matter with great efficiency (theoretically over 99%). However, due to the construction of the ESP, application on ships was not foreseen, because the common type of ESP is not robust enough. The idea is to develop a robust, compact and cheap ESP that can be applied in maritime conditions.

The working principle of any ESP is to charge particles with ions, and capture those charged particles by an electric field, as is explained in much more detail in section §5.4. The captured particles need to be removed periodically or continuously. ESPs are found in two distinctly different variants. In a one-stage ESP the charging and collection of the particles takes place in a single stage with one electric field, whereas in a two-stage ESP charging of the particles and collection of the particles take place in two stages with two electric fields, as illustrated in Figure 5.19.

A one-stage ESP has the advantage of continuously charging particles, thereby increasing particle charge over the entire length of the ESP and prohibiting particles to slip through, when they lose their charge. A one-stage ESP, the type of ESP that is offered by Wärtsilä for cleaning diesel exhaust gas for land-based applications, does not have a construction that is considered sufficiently robust for application at sea. That is because in a one-stage ESP the electrodes are hanging from a few insulators, which are heavily stressed during ship movement.

A two-stage ESP has the advantage that charged particles need to travel a short distance, before they are captured. However, charging time is short and particles that loose their charge are not captured. A 2-stage ESP has a robust construction, but is difficult to clean on-line, because the collector plates are spaced closely together to get a compact device.

The idea is to create a self-cleaning ESP by coating the particulate matter with a water layer, in order to allow captured particulate matter to stream of the collecting electrodes. This way a two-stage ESP can be continuously used to remove particulate matter. The way to coat the particles with water is by creating a supersaturation of water vapour by the
injection of steam. This should be done upstream of the ESP. This process is similar to the SJAC-process described in Chapter 4, and hence the name of the technology SJAC-ESP. However, it is no longer the goal to make particles as large as possible, meaning that the steam injection rate can be reduced in comparison to Chapter 4. Typical rates mentioned for operation of wet-ESP is 100 times the mass of fluid in comparison to the mass of PM. For the 15 kW engine used in the previous experiments, assuming a particulate matter emission of 0.2 g/kWh, approximately 3 kg/h steam should be injected assuming that 10% of the steam condenses. Therefore less steam is required for the SJAC-ESP in comparison to the SJAC. The necessary steam for the SJAC-ESP can be made from the exhaust gas heat, see section §6.2. The SJAC-ESP in the exhaust gas stream of a diesel engine is shown in a block diagram in Figure 5.1. Note that the SJAC-ESP may also reduce SOx as is investigated in section §5.3.3.

![Figure 5.1 Schematic set-up of the SJAC-ESP](image)

**§5.2.2 Implementation**

The first set-up was similar to the set-up of the SJAC. Instead of a coalescer now a 2-stage ESP was present, see Figure 5.2. The used ESP was a Euromate HFE 25. The capacity of this ESP was too large for the exhaust gas flow from the diesel engine. Therefore part of the ESP was blocked by insulating plates. Depending on the experimental conditions, 1/8 or 1/4 of the capacity of the ESP was used. The unused capacity was blocked with insulating plates. The charging section and the collection section of the ESP are shown in Figure 5.3 and Figure 5.4.

![Figure 5.2 Photo of SJAC-ESP set-up during first measurements](image)
### Table 5.1 Devices in Figure 5.2

<table>
<thead>
<tr>
<th>Number</th>
<th>Device</th>
<th>Number</th>
<th>Device</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Steam generator</td>
<td>4</td>
<td>ESP</td>
</tr>
<tr>
<td>2</td>
<td>Steam injection flange</td>
<td>5</td>
<td>Sampling point</td>
</tr>
<tr>
<td>3</td>
<td>Static mixer</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 5.3 Photo of the ionisation section. The high-voltage electrodes are drawn, because they are too thin to be visible in the photo.

Figure 5.4 Photo of the collection section, with 75% of the capacity blocked

### §5.3 Measurement results and discussion

#### §5.3.1 Investigation of the measurement window

The initial measurements have been performed behind an ONAN 12.0 MDJF diesel generator, which was also used in the experiments, described in Chapter 4, with ¼ of the capacity of the ESP. The used fuel contained maximally 50 ppm sulphur. Filter measurements at 110°C were performed to verify the performance of the SJAC-ESP, because the poor performance of the original SJAC concept was most pronounced during those measurements, and because interpretation of the results is straightforward.
First the influence of steam-injection rate on the removal efficiency of the ESP was investigated in order to determine the operating window of the SJAC-ESP. Results are summarised in Table 5.2. The removed particulate matter is solely due to the removal by the ESP. These values do not include removal in the coolers.

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Number of measurements</th>
<th>Average percentage removed mass PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>No steam, ( V_c=5,\text{kV}, v=0.37,\text{m/s} )</td>
<td>3</td>
<td>87%</td>
</tr>
<tr>
<td>2% steam, ( V_c=5,\text{kV}, v=0.37,\text{m/s} )</td>
<td>1</td>
<td>79%</td>
</tr>
<tr>
<td>3% steam, ( V_c=5,\text{kV}, v=0.37,\text{m/s} )</td>
<td>2</td>
<td>70%</td>
</tr>
</tbody>
</table>

Clearly, the SJAC-ESP performs significantly better than the SJAC. The measurement without steam is for reference only, because particulate matter build-up will in the long run lead to malfunction of the ESP. During the measurements with 3% steam the voltage in the collection section was instable, due to fouling of the insulators. If measurements are corrected for the instability a removal efficiency of 82% could be achieved.

A few adjustments were made to the collection section to improve the voltage stability. The insulators were substituted by newly designed insulators and the direction of the electric field was changed. At the same time the electric field was reduced, because it was found that it interacted with the electric field in the charging section. This should reduce particulate matter removal efficiency. The potential in the collection section and the capacity of the ESP (and hence the velocity through the ESP) have been used as variables. This yielded the results shown in Table 5.3. The standard deviation is indicated in percentage removed mass PM.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Number of measurements</th>
<th>Average percentage removed mass PM</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>3% steam, ( V_c=-2,\text{kV}, v=0.37,\text{m/s} )</td>
<td>3</td>
<td>83%</td>
<td>3%</td>
</tr>
<tr>
<td>3% steam, ( V_c=-1,\text{kV}, v=0.37,\text{m/s} )</td>
<td>3</td>
<td>68%</td>
<td>8%</td>
</tr>
<tr>
<td>3% steam, ( V_c=-2,\text{kV}, v=0.74,\text{m/s} )</td>
<td>3</td>
<td>79%</td>
<td>3%</td>
</tr>
</tbody>
</table>

The removal rates with a voltage in the collection section of -2 kV look especially promising. The condition with -1 kV was deliberately chosen to observe the behaviour with less favourable parameters. The lower voltage showed a significantly lower removal efficiency than the conditions at -2 kV (95% reliability interval). Initially it was expected that the effect of doubling the gas velocity through the ESP had exactly the same effect as halving the voltage in the collection section. However, Table 5.3 clearly shows that this is not the case. Because the removal rate barely dropped with doubling velocity of the gas (no significant difference), it is interesting to do additional measurements with higher gas velocities through the ESP. Unfortunately this was not possible with the present set-up, because on one hand the capacity of the ESP could not be reduced further and on the other hand the gas velocity from the engine could not be increased. It is recommended for future research to extend the measurements to higher velocity through the ESP. In subsequent testing with the SJAC-ESP, the last measurement condition from Table 5.3 was used.
The results look promising from the viewpoint of efficiency. However, issues with durability remained. After four hours of operation, operator intervention was needed, because the insulators in the charging section were fouled and needed to be cleaned. Starting up after shut-down of the installation was troublesome, because condensation occurred amongst others on the electrical insulators, which meant that the ESP short-circuited. In order to solve these problems the insulators in the ionisation section were redesigned, and all insulators are now continuously dried by warm air. Whether or not these parts will solve the durability issues, is part of the investigation during the 500-hour endurance test.

§5.3.2 Endurance test

§5.3.2.1 Preparation for endurance test
Apart from the redesigned parts, mentioned in section §5.3.1, a number of other preparations were necessary before the endurance test could take place. In order to perform a 500-hour endurance test, the installation should be able to run with minimum operator interventions. In fact the installation was able to run unmanned, apart from refilling the fuel tank and changing the waste water storage tank.

The changes to the installation are listed below:

- The fuel tank was replaced by a larger one. The fuel tank could not be located close to the engine, however, and an additional fuel pump was necessary to provide the engine with fuel.
- The used fuel contained 0.18 mass percent sulphur compared to maximally 50 ppm in earlier tests.
- The system was automated and got a new data acquisition system.
- A safety control system was installed, in order to shut down the entire installation in case of a malfunction of one of the components in the system.
- The coolers were substituted by a shell-and-tube style cooler to avoid clogging of the cooler, which was experienced in the coolers used in previous experiments. Clogging of the coolers leads to a high pressure drop over the coolers, which can ultimately lead to engine overheating or engine malfunction.
- In order to prevent the condensate that is formed on the wall of the new coolers from negatively influencing the SJAC-ESP, these condensate droplets are separated from the gas by a cyclone with a cut-off diameter of approximately 10 micrometers. This cyclone is located before steam injection. The cyclone is not meant to remove particulate matter from the exhaust gas. In fact, it will barely remove any particulate matter, given the cut-off diameter.

§5.3.2.2 Operational behaviour
The endurance test was performed over a continuous period of 500 hours, of which the installation was effectively operational for 142 hours. Eight runs lasted longer than 10 hours each. They amounted to 129 hours of operation. Table 5.4 shows the duration of those runs and the reasons for stops.
Table 5.4 Reasons for shut-down during the eight longest continuous runs during the endurance test

<table>
<thead>
<tr>
<th>Start experiment</th>
<th>Run number</th>
<th>Duration [hour:min]</th>
<th>Reason for shut-down</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 29th 2007</td>
<td>1</td>
<td>23:25</td>
<td>Exhaust gas temperature halfway cooler too high</td>
</tr>
<tr>
<td>May 30th 2007</td>
<td>2</td>
<td>14:29</td>
<td>Backpressure on engine too high</td>
</tr>
<tr>
<td>May 31st 2007</td>
<td>3</td>
<td>10:20</td>
<td>Backpressure on engine too high</td>
</tr>
<tr>
<td>June 1st 2007</td>
<td>4</td>
<td>18:51</td>
<td>Exhaust gas temperature halfway cooler too high</td>
</tr>
<tr>
<td>June 3rd 2007</td>
<td>5</td>
<td>18:40</td>
<td>Shut-down by operator</td>
</tr>
<tr>
<td>June 4th 2007</td>
<td>6</td>
<td>14:20</td>
<td>Short-circuit of insulator charging section</td>
</tr>
<tr>
<td>June 8th 2007</td>
<td>7</td>
<td>14:18</td>
<td>Exhaust gas temperature halfway cooler too high</td>
</tr>
<tr>
<td>June 11th 2007</td>
<td>8</td>
<td>14:36</td>
<td>Exhaust gas temperature halfway cooler too high</td>
</tr>
</tbody>
</table>

In six out of eight cases shut-down was caused by cooler fouling. Cooler fouling led either to a reduced heat transfer, which resulted in too high temperatures of the exhaust gas, or to an increase in pressure drop over the cooler, which led to a too high pressure drop over the entire system. Re-evaluation of the design showed that this was due to a miscommunication with the equipment supplier, which lead to a heat exchanger with insufficient capacity.

The system was once shut down by the operator, because additional condensation occurred in the exhaust pipe after the ESP. This resulted in condensate with some particulate matter dripping on the ground. If the system would not have been shut down by the operator, the system would have shut down automatically within the next few hours, because the pressure drop over the system was reaching its maximum. The short-circuit over the insulator of the charging section occurred after approximately 100 hours of operation, but showed that this particular insulator design was not ideal. This possibility was anticipated and insulators of a different design were available. Changing an existing charging section took some time, however.

It proved hard to start the system up after a shut-down. This was not related to the time needed to clean the cooler for example. The reasons are discussed below and summarised in Figure 5.5 together with the time that the installation was not operational due to the fact that the installation could not be restarted. To give a complete overview, the time that the installation was in operation is also included.

Figure 5.5 Reasons for problems restart and influence on the time in operation during 500-hours endurance test; numbers have the unit hours
In case of an emergency stop all electricity to the installation was stopped by the automation. This is a safe strategy, but meant that the insulators were not dried by warm air anymore, because in this case the automation also shut the heating of the air down. This meant that the solution for the problematic start-stop behaviour did not work during the endurance test. It was observed, however, that it was beneficial to supply the insulators with warm air, before starting up the diesel engine and ESP. The non-recurrent problem was a start-up problem, when this strategy did not seem to work in a long weekend. When it was retried two days later start-up was successful again. During the measurements in the slipstream of a 350 kW engine the start-up issue was addressed (see section §5.3.3).

In the beginning of the endurance test some alarm settings were set too conservative, meaning that the installation shut down, when there was no danger for the installation. This had to do with a cooling liquid that remained colder than expected. Gas leakage from the system proved to be a tough problem to tackle. The ESP was not built as a device that necessarily had to be gas tight. Quite some work was necessary to make and keep it gas tight. If the device had been designed to be gas tight, gas leakage would not have been a big issue.

The “rest”-entry contained amongst others time between stop and start when the installation stopped when the operator was not present, for example during the night.

Inspection of the installation after the endurance test showed that the drain in the cyclone got clogged. The cyclone was filled for a very substantial part with water. This probably influenced the pressure drop over the setup too. It could have caused re-entrainment of water from the cyclone into the gas stream as well.

§5.3.2.3 Particulate matter removal and particulate matter balance
Particulate matter samples were taken before the exhaust gas cleaning section (sample point 1), after cooling (sample point 2), and after the total system (sample point 3), see also Figure 5.6.

Table 5.5 shows the measurement results after 0, 50 and 100 hours of operation. The dust content in raw exhaust gas (sample point 1) increases significantly over time. Also the initial emission of 111 mg/m\(^3\) is high compared to the value of 50 mg/m\(^3\) as measured previously from the same engine. This might be due to the different fuel, because the PM-emission of 0.43 g/kWh is still within the expected range. Engine emissions increased to almost 500 mg/m\(^3\) or 5.9 g/kWh. Note, that that value is seven times higher than the 1999
emission limit for particulate matter. Therefore, it seems unlikely that the increase in raw exhaust gas emissions is due to run-in phenomena. Whether the increase is real and if so, what causes the increase, cannot be derived from the measured parameters. A possible explanation is accumulation of particulate matter in the sample tubes, when sampling is inactive. The accumulated particulate matter is subsequently sampled when sampling becomes active again.

Table 5.5 Particulate matter mass content during endurance test

<table>
<thead>
<tr>
<th>Sample point</th>
<th>Time SJAC in operation [hour]</th>
<th>PM [mg/m^3]</th>
<th>PM [g/kWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>111</td>
<td>0.43</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>344</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>496</td>
<td>5.9</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>65</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>45</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>140</td>
<td>1.8</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>19</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>43</td>
<td>0.21</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>490</td>
<td>6.1</td>
</tr>
</tbody>
</table>

Another striking result is the large mass of particulate matter on the third sample point after 100 hours. It is larger than the emission measured at the second sample point and almost as large as the emission at sample point one. It is also very different from particulate matter emissions measured earlier at the same sample point. The concentration of particulate matter in the exhaust gas at the third sample point can only be higher than at the second sample point, if there is some form of re-entrainment of the captured particles. Clearly visible on the filter is a big “lump” of particles. This seems to indicate that build-up of particulate matter in the sample tube is the cause of the high particulate matter mass measured. The measurement after 100 hours at sample point 3 is therefore treated as unrepresentative.

Table 5.6 Particulate matter mass removal efficiency during endurance test

<table>
<thead>
<tr>
<th>Hours in operation</th>
<th>Totally removed</th>
<th>Removed in system excl. coolers and cyclone</th>
<th>Removed in coolers and cyclone</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 hour</td>
<td>83%</td>
<td>70%</td>
<td>41%</td>
</tr>
<tr>
<td>50 hour</td>
<td>87%</td>
<td>4%</td>
<td>87%</td>
</tr>
<tr>
<td>100 hour</td>
<td>-</td>
<td>-</td>
<td>72%</td>
</tr>
</tbody>
</table>

Table 5.6 shows the removal rate of particulate matter in different parts of the installation. The values in this table should be treated with the greatest care, due to the uncertainties in the measured values of the emission. The total removal rate is higher than 80%. However after 50 hours there is a significant drop in removal rate of the system excluding coolers and cyclone, whilst the overall efficiency is still at a good level. This is not expected from the voltage measurements of the ESP. During the water measurement from the cyclone, it was found that after 100 hours of operation, no water was coming from the drain of the cyclone. This is supported by the observation in section 5.3.2.2, where water was found in the cyclone. This may have influenced the removal rate in the coolers and cyclone. Another interesting result was the change in voltage in the collection section. It was tuned to -2 kV. The actual voltage migrated slowly (a timescale of hours) between -1 and -2 kV. If the voltage dropped till -1kV, it slowly increased to -2kV again, without operator intervention. The voltage in the collection section never reached 0 kV.
A particulate matter balance was made, in order to see if the removed particulate matter leaves the system, or if it results in a build-up of particulate matter. The removal of particulate matter from the gas phase is presented in Table 5.7 together with the amount of particulate matter found in the water streams that leave the cooler and cyclone and the droplet removal device. In the ideal case the amount of particulate matter in the water should equal the amount of particulate matter that was removed from the gas phase. Table 5.7 shows that not to be the case. However from this data, one can not conclude that an actual accumulation of particulate matter occurred, given the uncertainties in the measurement of the particulate matter composition in the exhaust gas. The possible accumulation in the ESP did not yet give operational problems.

### Table 5.7 Particulate matter balance during endurance test

<table>
<thead>
<tr>
<th>Time in operation [hour]</th>
<th>Cooler and cyclone [g/kWh]</th>
<th>ESP [g/kWh]</th>
<th>Total [g/kWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.18</td>
<td>0.15</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>0.012</td>
<td>0.001</td>
<td>0.013</td>
</tr>
<tr>
<td>50</td>
<td>3.58</td>
<td>0.01</td>
<td>3.59</td>
</tr>
<tr>
<td></td>
<td>0.12</td>
<td>0.01-0.04</td>
<td>0.13-0.16</td>
</tr>
</tbody>
</table>

In order to properly assess the long-term performance of the ESP it is strongly recommended to do a new and longer endurance test in the order of 500 to 1000 hours of operation. The cooler capacity should be enlarged in order to control the pressure drop.

### §5.3.3 Measurements in a slipstream of a 350 kW diesel engine

#### §5.3.3.1 Introduction

Previous tests have all been performed on a small diesel generator. In order to test the SJAC-technology in more realistic conditions, the SJAC-technology has been tested in a slipstream of a 350 kW engine. The specifications of the test engine are listed in Table 5.8.

### Table 5.8 Specifications of test engine

<table>
<thead>
<tr>
<th>Engine parameters</th>
<th>MAN 4L 20/27</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine Name</td>
<td>MAN 4L 20/27</td>
</tr>
<tr>
<td>Engine type</td>
<td>4-stroke in-line turbocharged engine</td>
</tr>
<tr>
<td>Number of cylinders</td>
<td>4</td>
</tr>
<tr>
<td>Bore/stroke [mm/mm]</td>
<td>200/270</td>
</tr>
<tr>
<td>Total displacement [l]</td>
<td>34</td>
</tr>
<tr>
<td>Maximum engine power at maximum speed</td>
<td>350 kW @ 1000 rpm</td>
</tr>
<tr>
<td>Maximum engine power during experiments</td>
<td>210 kW @ 1000 rpm</td>
</tr>
</tbody>
</table>

The engine power was limited to 200 or 210 kW, due to the temperature increase of the exhaust gas turbine inlet temperature, which resulted from the pressure drop over the SJAC-ESP, which was maximally 7 kPa. The engine was tested over two load-profiles: a propeller curve, to simulate that the engine is powering a fixed propeller, and a constant engine speed curve, to simulate that the engine is powering something which requires a constant engine speed, like a pitch-controlled propeller or a generator. The load curves are described in ISO 8178-4 [ISO, 2007] and are summarised in Table 5.9 and Table 5.10. Every cycle was measured from high load to low load. The emissions over one cycle are measured in one day.
Table 5.9 Propeller profile according to ISO-8178-4 cycle E3

<table>
<thead>
<tr>
<th>Engine power [%]</th>
<th>100</th>
<th>75</th>
<th>50</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine speed [%]</td>
<td>100</td>
<td>91</td>
<td>80</td>
<td>63</td>
</tr>
<tr>
<td>Relative operational time [%]</td>
<td>20</td>
<td>50</td>
<td>15</td>
<td>15</td>
</tr>
</tbody>
</table>

Table 5.10 Constant engine speed profile according to ISO-8178-4 cycle E2

<table>
<thead>
<tr>
<th>Engine power [%]</th>
<th>100</th>
<th>75</th>
<th>50</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine speed [%]</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Relative operational time [%]</td>
<td>20</td>
<td>50</td>
<td>15</td>
<td>15</td>
</tr>
</tbody>
</table>

Three different fuels have been used, as listed in Table 5.11. MGO 0.1% and MGO 0.16% are future and present inland shipping fuels respectively. RMA-30 is an intermediate fuel oil, used in sea shipping. It was the heaviest fuel on which the engine could run.

Table 5.11 Fuel specification

<table>
<thead>
<tr>
<th>Fuel name</th>
<th>MGO 0.1%</th>
<th>MGO 0.16%</th>
<th>RMA-30</th>
</tr>
</thead>
<tbody>
<tr>
<td>C %-%wt</td>
<td>86.2</td>
<td>86.2</td>
<td>85.7</td>
</tr>
<tr>
<td>H %-%wt</td>
<td>13.7</td>
<td>13.6</td>
<td>12.8</td>
</tr>
<tr>
<td>N %-%wt</td>
<td>&lt;detection limit</td>
<td>&lt;detection limit</td>
<td>&lt;detection limit</td>
</tr>
<tr>
<td>O %-%wt</td>
<td>&lt;detection limit</td>
<td>&lt;detection limit</td>
<td>&lt;detection limit</td>
</tr>
<tr>
<td>S %-%wt</td>
<td>0.1</td>
<td>0.16</td>
<td>1.5</td>
</tr>
</tbody>
</table>

The engine forced the gas through the slipstream by throttling the main exhaust gas stream with a valve. In commercial applications the engine will also have to force the gas through SJAC-ESP. In our case the ESP came equipped with a fan. Because of its design, it had to run continuously during the experiments, in order not to create a big pressure drop over the fan. Additional valves were installed to be able to bypass the SJAC-ESP and to shut down the entire slipstream. A schematic overview of the connection between the engine and the exhaust gas aftertreatment system, together with the location of the sample points is given in Figure 5.7. Particulate matter was measured by filter measurements and SMPS-measurements (see sections 2.4.2 and 2.4.3). SOx-emissions were measured by bubbling sampled exhaust gas through a layer of hydrogen peroxide, which converts all SOx to SO$_4^{2-}$ which is determined off-line. The emissions of NOx, CO, CO$_2$ and O$_2$ were logged. CO$_2$ and O$_2$ measurements have both been used to calculate the exhaust gas flow.

![Figure 5.7 Schematic overview of exhaust gas piping and sample points in the 350 kW-case](image-url)
§5.3.3.2 Operation

The SJAC-ESP was switched on and off 32 times during the tests. In total, approximately 32 hours of operation of the SJAC-ESP have been accumulated during in the slipstream of the 350 kW engine. The experiments were a success from an operational point of view. Start-stop behaviour was unproblematic. Peculiarities were not discovered during inspection. Other outcomes of the test are discussed below.

Analysis of the measurement results indicated, that the slipstream flow meter has not been working properly. The flow through SJAC-ESP could also be derived from the temperature after steam injection and the amount of steam injected. The results showed that the flow through SJAC-ESP does not vary proportional to the exhaust gas flow from the engine, but is more or less constant. This means that particulate matter in the slipstream was not sampled isokinetically. For particles smaller than 1 micrometer the Stokes number is maximally 0.002 for the given geometry, and no correction is necessary (see [Hinds, 1999]). The flow through SJAC-ESP varies for each load point, but ranges between 68 kg/h and 98 kg/h. The lowest mass flows through SJAC-ESP were obtained at 25% load. The maximum value is close to the maximum design flow of 100 kg/h.

Because it is expected that the removal efficiency increases with decreasing velocity, the found particulate matter removal efficiencies at part load are underestimations for the actual removal efficiencies. The amount of steam injected was tuned to expected exhaust gas flow and not to the actual gas flow. This means that too little steam was injected, which is expected to influence the particulate matter removal efficiency negatively as well.

§5.3.3.3 Particulate matter removal

Particulate matter of undiluted exhaust gas was measured at sample points 1, 5 and 8 as shown in Figure 5.7. Analysis of the measured data showed that all measurements at sample point 5 were unrepresentative. Closer inspection of the filter revealed a small lump of particulate matter in the middle of the filter. This probably had to do with accumulation of particulate matter in the sampling tube. As a result no measurement is available to assess the influence of the cooler and cyclone on the total removal efficiency. Presented removal efficiencies in this section refer to the removal efficiency including cooler fouling, unless stated otherwise. Measurements over the propeller curve with MGO 0.16% were redone with a different sample system to assess the influence of cooler fouling on the measurement results (see Figure 5.13 and Table 5.12).

Figure 5.8 to Figure 5.11 show the measured mass of particulate matter expressed in mg/m₃ and g/kWh.
Figure 5.8 Emission of particulate matter over propeller curve upstream and downstream of SJAC in mg/m³.

Figure 5.9 Emission of particulate matter over constant engine speed curve upstream and downstream of SJAC in mg/m³.

Figure 5.10 Emission of particulate matter over propeller curve upstream and downstream of SJAC in g/kWh.
The variation in the measurement results is quite high, and the number of measurements is maximally two. It leads to a maximum estimated standard deviation of 20 mg/m$^3$, or 0.13 g/kWh. Therefore, not too many conclusions can be drawn from this data with regard to the differences in emissions of the two MGO fuels. Statistically speaking the load profiles with MGO fuels are not different from each other. Clearly the amount of particulate matter is reduced by the SJAC-ESP. The emission of particulate matter at low load and low engine speed with RMA-30 is considerably higher than the emissions with inland shipping fuel, while at high load the emissions do not differ significantly. This may be related to less efficient combustion of the RMA fuel at low loads. The specific fuel consumption with RMA-30 was approximately 10 g/kWh (4%) higher than with MGO. For both MGO fuels the emission decreases with decreasing engine load.

Figure 5.12 shows the total efficiency according to the mass measurement. Average mass removal efficiency over the cycle ranges from 57 to 78%. The removal efficiency of SJAC for particulate matter cannot be calculated over the propeller cycle with 0.16% sulphur in fuel, because both measurements at 75% load after the SJAC were faulty. The standard deviation in the average removal efficiency is 6%.
After analysing the measurement results in the slipstream, it became clear that the measurements downstream of cooler and cyclone, but upstream of the SJAC were all faulty. A sampling system was designed where the sample tubes were purged with pressurised air, just before measurement. The collection section was cleaned before the measurements were repeated. Measurements with MGO 0.16% have been repeated over the propeller curve.

![Graph showing PM removal efficiency](image)

**Figure 5.12** Total PM removal efficiency SJAC-ESP with 350 kW engine as function of engine load according to filter measurements

![Graph showing PM concentration](image)

**Figure 5.13** Particulate matter removal in coolers and cyclone and SJAC during additional measurements 350 kW case with MGO 0.16%
Table 5.12 Particulate matter removal in coolers and cyclone and SJAC during additional measurements 350 kW case with MGO 0.16%

<table>
<thead>
<tr>
<th>Engine Load→</th>
<th>100%</th>
<th>75%</th>
<th>50%</th>
<th>25%</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total removed [%]</td>
<td>92</td>
<td>87</td>
<td>85</td>
<td>70</td>
<td>88</td>
</tr>
<tr>
<td>Removed in cooler and cyclone [%]</td>
<td>34</td>
<td>29</td>
<td>3</td>
<td>0</td>
<td>28</td>
</tr>
<tr>
<td>Removed by SJAC-ESP [%]</td>
<td>87</td>
<td>81</td>
<td>84</td>
<td>70</td>
<td>83</td>
</tr>
</tbody>
</table>

Note that the removal rate found during these measurements is higher than earlier measurements behind the 350 kW engine with this fuel. From these measurements, it can be concluded that the coolers and cyclone had a minor influence on the total removal efficiency of the SJAC system. If the previously measured removal efficiencies in the slipstream are corrected for the removal in the cooler and cyclone, the average removal efficiency of SJAC without the coolers and cyclone ranges between 41% and 70%.

The measurements with SMPS did not give representative results at sample point 6 (see Figure 5.7), because the pressure at sample point 6 was too low to pressurise sufficient gas through the SMPS. The pressure at sample point 9 was high enough, because the fan in the ESP increased the pressure slightly. This means that no measurement is available to assess the influence of the cooler and cyclone on the total removal efficiency. Flows from other sample points were sufficient for representative measurements.

Measurement results on the raw exhaust gas are discussed in Chapter 3.

The shapes of the profiles of cleaned exhaust gas are in general similar to those of untreated exhaust gas, as shown in Figure 5.14 for a few loads, but a significant amount of particulate matter is removed. This means that also the smallest fraction of the particulate matter is removed well.

![Figure 5.14](image-url)  
*Figure 5.14 Comparison of the particle concentration density for untreated exhaust gas with exhaust gas cleaned by SJAC-ESP for two engine loads for the 350 kW case with MGO 0.16%*

The particle removal efficiency is calculated on number basis, see Figure 5.15. In general the number removal is even slightly higher than the mass removal according to the mass measurements. The results from MGO 0.1% over the propeller curve is not shown, because
the particle number at small diameters is underestimated for the raw exhaust gas. In this case at least fifty percent of a substantial particle mode falls just outside the measurement window.

![Graph](image1)

**Figure 5.15** Removal efficiency number of particles 350 kW case at various engine loads

Figure 5.16 shows the mass removal efficiency after a conversion of the particle size distributions based on [Park et al., 2003] for high load. Note that SMPS mass removal results are indicative only. For completeness the formula for low load from [Park et al., 2003] has also been used to analyse the effect of the conversion formula on the mass removal efficiency. It has a minor effect on the removal efficiency, increasing the removed mass by 1% at most, and is not used in the remainder of the thesis. In this case the measurement with MGO 0.1% over the propeller curve is included, because the small particle mode just outside the measurement window, only has a minor influence on the particle mass.

![Graph](image2)

**Figure 5.16** Removal efficiency particle mass calculated from number measurements for the 350 kW case
§5.3.3.4 Influence of SJAC-ESP on SOx-concentration

At several sample points the SOx-concentration was measured. Figure 5.17 shows as an example the SOx-concentration in exhaust gas for fuel with 0.16% sulphur over the propeller curve at several sample points (see Figure 5.7). The results at sample point 3 were in good agreement with the expected SOx-concentrations based on fuel composition, fuel consumption and carbon dioxide level in the exhaust gas, except for the measurement with RMA-30. Measurements of the SOx-concentration with RMA-30 suggested a higher sulphur content in the fuel, than found during the fuel analysis.

![SOx-concentration on dry base in exhaust gas for fuel with 0.16% sulphur over propeller curve](image)

Figure 5.17 SOx-concentration on dry base in exhaust gas for fuel with 0.16% sulphur over propeller curve

The SOx-concentration data in exhaust gas show, that barely any SOx is removed in the cooler and cyclone, nor after steam injection. The SOx-concentrations at sample points 3, 4 and 7 are the same within the measurement error. Therefore it is not possible to make an SOx-balance over the cooler and cyclone. Analysis of the water from the cooler confirms that only a very small fraction (smaller than 3 \times 10^{-5} \text{ mol/kg}) of SOx is removed in the cooler. However, the SOx that is found in the water from the cooler, can lead to a pH as low as 2. Corrosion resistivity will be a major issue when designing the cooler and cyclone.

Figure 5.18 shows the influence of the three different fuels (and hence different SOx-concentrations) on SOx-removal efficiency.
Figure 5.18 Percentage SOx-removed in electrostatic precipitator

For the two tested inland shipping fuels approximately 60% of SOx was removed in the ESP over the propeller curve and approximately 50% over the constant engine speed curve. With heavy fuel oil the percentage removed SOx is notably lower than with inland shipping fuels. The absolute value is approximately a factor 10 higher, though. The limited effect with high sulphur levels may have to do with the equilibrium of sulphate in the condensed water.

No water came out of the droplet removal device. It can be explained by the buffer volume in the droplet removal device and the short operating time before shut-down due to the experimental set-up. Therefore it was not possible to make an SOx-balance over the ESP.

The removed amounts of SOx are nice to have from environmental point of view, but they are too low to be an additional selling point for the SJAC. Please note that the reported values are valid for the present configuration. Changes to the exhaust gas cooling could influence the removed amount of SOx significantly.

§5.4 Simulation of SJAC-ESP

§5.4.1 Introduction

In Figure 5.1 the SJAC-ESP is shown in a block-diagram. In cold exhaust gas, steam is injected to create a supersaturation, which in its turn leads to condensation on the particles. These particles with a water coating are subsequently captured in an electrostatic precipitator. The process of condensation on particles by the injection of steam in cold saturated exhaust gas is the same as in the SJAC-concept and is described in section §4.4. In the following sections it is described what happens after the particles acquired a water coating.
For this calculation the parameters and dimensions from Table 5.13 are used. These parameters were used during the experiments with the small diesel generator, as described in section §5.3.1. The used particle distribution is a log-normal distribution with a particle mode at 35 nanometres and a standard deviation of 0.5 and a particle concentration of $2.5 \times 10^{13}$. For the assumption of the temperature gradient a small temperature gradient is assumed (see section §4.4.4).

<table>
<thead>
<tr>
<th>Engine and steam parameters</th>
<th>ESP parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine power [kW]</td>
<td>14 Length<em>width</em>height</td>
</tr>
<tr>
<td></td>
<td>1 charging section [m]</td>
</tr>
<tr>
<td>Exhaust gas flow [kg/h]</td>
<td>100 Voltage charging section [kV]</td>
</tr>
<tr>
<td>CH-ratio of fuel [mass/mass]</td>
<td>5.5 Radius charging wires [m]</td>
</tr>
<tr>
<td>Air excess ratio [-]</td>
<td>1.5 No. of parallel charging sections</td>
</tr>
<tr>
<td>Temperature of exhaust gas [°C]</td>
<td>30 Length<em>width</em>height</td>
</tr>
<tr>
<td></td>
<td>1 collection zone [m]</td>
</tr>
<tr>
<td>Injected steam [kg/h]</td>
<td>3 Voltage collection section [kV]</td>
</tr>
<tr>
<td>Temperature of injected steam [°C]</td>
<td>110 No. of parallel collection sections</td>
</tr>
</tbody>
</table>

§5.4.2 Qualitative description of mechanisms in ESP

As mentioned earlier, the ESP consists of two parts. One part with the main function to charge particles, and one part to collect the charged particles. Although it is possible to describe the processes for any geometry, the explanation becomes easier to visualise when a specific geometry is used. In this case the geometry of the 2-stage ESP from the SJAC-ESP is used, see Figure 5.19.

The centre of the charging section is a thin wire with a high potential (in this case positive), between earthed plates. This means that an electric field is present in the charging section. Close to the surface of the thin wire, this electric field is so strong that gas molecules breakdown into positive and negative ions and electrons. The negative ions and electrons are attracted by the electric field towards the thin wire at high potential. The positive ions are pushed out of the region close to the surface of the thin wire by the electric field. A fraction of the generated ions of opposite polarity will collide with each other, leading to neutral molecules; this is called recombination. The recombination of positive and negative ions or electrons is visible as a glow, called corona. Note that with a negative potential at the wire,
the process involved is the same, but this time, positive ions are attracted to the wire-electrode, and negative ions and electrons are pushed out of the region close to the electrode.

The ions pushed out of the region close to the wire-electrode, will travel towards the earthed plates. However, during this process they will encounter particulate matter. If the ion and particle collide with each other, the ion will loose its charge and the particle obtains a charge. The charged particles are then attracted towards the plate electrodes, but since they are much bigger than ions, the drag force on the particles is bigger and the particles are only slowly attracted towards the plate electrodes. Most particles exit the charging section with a charge, and are then collected in a separate section, where the distance to travel towards the collection electrode is significantly reduced, in order to capture particles much more quickly in order to get a more compact device. Note that, because the collection section does not have sharp edges, the break-down electric field is not exceeded, or put differently, no ions are formed in the collection section, and hence particles are only collected in this section.

§5.4.3 Quantitative description particle charging section

The description of the particle charging section starts with the description of the electric field, caused by the potential difference in a wire-plate geometry. This is the left hand part of Figure 5.19. What is known of the geometry is that electric field lines depart and arrive perpendicular to the surface of the wire and plate. This enables us to get an idea of the actual field. Actually the electric field is the same as the field between a wire and an imaginary wire with equal but opposite charge at double the distance of the plates at zero potential. Note that the addition of a plate in the latter configuration halfway the two wires does not influence the electrical field, as long as its infinitely wide, or infinitely thin, i.e. that the electric field is not influenced by the edge of the added plate. In order to calculate the electric field of the wire-plate geometry it is assumed that the electric field is similar to the electric field of two wires, which are assumed to be infinitely long.

The line charge on an infinitely long wire can be calculated according to formula 5.4.1 [Tipler and Mosca, 2004].

\[
q_l = \frac{(V_1 - V_2)}{2K_E \cdot \ln(r_2 / r_1)}
\]

Formula 5.4.1

With \( q_l \) the line charge in C/m, \( K_E \) the Coulomb constant, which equals \( 9.0 \times 10^9 \) Nm²/C², also expressed as \( \frac{1}{4\pi\varepsilon_0} \) in literature with \( \varepsilon_0 \) the permittivity of the vacuum in C²/Nm², \( V_1 \) the potential at a distance \( r_1 \) and \( V_2 \) the potential at a distance \( r_2 \).

With the help of the line charge the electric field around a single wire can be calculated. It is given by formula 5.4.2 [Tipler and Mosca, 2004].

\[
\vec{E} = \vec{E}_r \cdot \hat{r} = 2K_E \frac{q_l}{r} \frac{(V_1 - V_2)}{r \cdot \ln(r_2 / r_1)} \hat{r}
\]

Formula 5.4.2

With \( \vec{E} \) the electric field vector in V/m, \( E_r \) the size of the vector \( \vec{E} \), \( \hat{r} \) a unit-vector with the direction of \( \vec{p} \), and \( r \) the size of vector \( \vec{r} \).
If a x-y coordinate system is chosen in the centre of the wire, as defined in Figure 5.19, formula 5.4.2 can also be rewritten in a field in x-direction and y-direction as illustrated in formula 5.4.3.

$$\vec{E} = E_x \cdot \hat{x} + E_y \cdot \hat{y}$$

**Formula 5.4.3**

With \( \hat{x} \) a unit-vector with the direction of the field \( \vec{E}_x \), and \( \hat{y} \) a unit vector with the direction of \( \vec{E}_y \) and \( E_x \) and \( E_y \) the size of the field in respectively x and y direction.

This way the electric field around an infinitely long wire can be written as formula 5.4.4.

$$\vec{E} = E_x \cdot \hat{x} + E_y \cdot \hat{y} = \frac{x}{x^2 + y^2} \frac{(V_1 - V_2)}{\ln(r_2 / r_1)} \cdot \hat{x} + \frac{y}{x^2 + y^2} \frac{(V_1 - V_2)}{\ln(r_2 / r_1)} \cdot \hat{y}$$

**Formula 5.4.4**

Note that x and y are scalars representing the distance from the centre of the coordinate system in x and y direction respectively, the direction is incorporated in the directional vectors.

As mentioned above, the wire-plate geometry is calculated by two infinitely long wires with equal but opposite polarity. Let’s first describe the sum of the two electric fields in terms of a coordinate-system \( x_a-y_a \) in the centre of the actual wire and a coordinate system \( x_b-y_b \) in the imaginary wire, with the x and y coordinate systems pointing in the same direction. The electric field is then:

$$\vec{E} = \left( \frac{x_a}{x_a^2 + y_a^2} + \frac{x_b}{x_b^2 + y_b^2} \right) \cdot \left( \frac{V_1 - V_2}{\ln(r_2 / r_1)} \right) \cdot \hat{x} + \left( \frac{y_a}{x_a^2 + y_a^2} - \frac{y_b}{x_b^2 + y_b^2} \right) \cdot \left( \frac{V_1 - V_2}{\ln(r_2 / r_1)} \right) \cdot \hat{y}$$

**Formula 5.4.5**

\( x_b \) can be described in terms of \( x_a \), and \( y_b \) in terms of \( y_a \). Because of the definition of the two coordinate systems, \( y_b \) is simply \( y_a \). \( x_b \) is the distance between the wire electrodes minus \( x_a \). This way the electric field is described by formula 5.4.6.

$$\vec{E} = \left( \frac{x_a}{x_a^2 + y_a^2} + \frac{x_b}{x_b^2 + y_b^2} \right) \cdot \left( \frac{V_1 - V_2}{\ln(r_2 / r_1)} \right) \cdot \hat{x} + \left( \frac{y_a}{x_a^2 + y_a^2} - \frac{y_b}{x_b^2 + y_b^2} \right) \cdot \left( \frac{V_1 - V_2}{\ln(r_2 / r_1)} \right) \cdot \hat{y}$$

**Formula 5.4.6**

With \( dbe \) the distance between the electrodes.

For the description of \( V_1 \), \( V_2 \) and \( r_1 \) and \( r_2 \), it is most logic to choose \( r=0 \) at the centre of the wire. Then \( r_1 \) is at the surface of the wire, at a distance \( r_{wire} \), at a potential \( V_1 \) of 10 kV (see Table 5.13), and \( r_2 \) at the distance between centre of the wire and plate, at a potential \( V_2 \) of 0 V, or in other words:

$$\vec{E} = \left( \frac{x_a}{x_a^2 + y_a^2} + \frac{dbe - x_a}{(dbe - x_a)^2 + y_a^2} \right) \cdot \hat{x} + \left( \frac{y_a}{x_a^2 + y_a^2} - \frac{y_a}{(dbe - x_a)^2 + y_a^2} \right) \cdot \hat{y} \cdot \left( \frac{V_1}{\ln(dbe/(2 \cdot r_{wire}))} \right)$$

**Formula 5.4.8**

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The resulting electric field strength due to the potential difference in the wire-plate geometry, i.e. \( \sqrt{E_x^2 + E_y^2} \) for the configuration used in the SJAC-ESP experiments is shown in Figure 5.22. For this calculation the x- and y-direction are divided in 100 pieces, leading to 10,000 small blocks. The electric field in the middle of such a block is calculated. Note that if the particles have obtained a charge, they will also create a small electric field around the particle. In the real situation the electric field is limited to a certain threshold above which the gas breaks down into ions.

The required electric field for the gas to break down for a wire in a cylinder is given for particle-free air at standard conditions (20°C) by an empirical formula in formula 5.4.9 [Hinds, 1999].

\[
E_{onset} = 3 \cdot 10^6 \left( 1 + \frac{3 \cdot 10^{-2}}{r_{wire}} \right)
\]

With \( E_{onset} \) the corona onset electric field. This formula is approximately valid for a wire-plate geometry very close to the wire, because in this case the electric field does not deviate very much from the electric field for a wire-cylinder geometry.

In this case the required potential is given by formula 5.4.10

\[
V_{onset,20^\circ C} = E_{onset} \cdot r_{wire} \cdot \ln \left( \frac{d_{be}}{2 \cdot r_{wire}} \right)
\]

With \( V_{onset,20^\circ C} \) the corona onset potential at standard conditions. For the specific geometry and conditions a potential of approximately 3.2 kVolts is enough to create a corona discharge at the surface of the wire.

The corona onset potential is temperature dependent, by way of the density, and depends on the humidity of air. With increasing temperature the break-down voltage decreases and for positive direct current an increase in air humidity increases the break-down voltage [Ryan, 1994]. A correction factor for the break-down field is given by formula 5.4.11 after [Ryan, 1994].

\[
V_{onset} = V_{onset,20^\circ C} \cdot \rho_{rel} \left( 1 + 0.014 \cdot \left( \frac{hum}{\rho_{rel}} - 11 \right) \right)
\]

With \( V_{onset} \) the onset potential for changing pressure, temperature and humidity. \( \rho_{rel} \) the density relative to the standard conditions and ‘hum’ the humidity in g/m³. Formula 5.4.11 holds for \( 1 \leq hum/\rho_{rel} < 15 \). For values larger than 15 an error in the order of 15% may occur. Note that saturated gas at 30°C already exceeds this upper boundary. Still, this formula can be used as an indicator, despite the considerable error. The correction factor is shown in Figure 5.20.
For the working conditions of the SJAC-ESP, saturated gas at 41.3°C, the corona-onset voltage is 5.15 kV. Which is still below the operating conditions. For more reading on typical operating conditions, see Table 5.13 and Chapter 7.

Charged particles will also influence the electric field between the electrodes of opposite polarity. This effect has not been taken into account. The influences of humidity, gas composition, particulate matter and water droplets on the electric field and ion motion in the charging and collection section are not considered in the discussion below, unless mentioned specifically.

As mentioned, positive ions are expelled out of the region where the gas breaks down. Ion movement in a stationary, particle free gas is governed by the force of the electric field and by the motion due to diffusion. The charge flux is expressed by [Fjeld et al., 1983] as formula 5.4.12.

\[
\vec{j}_q(r) = -D_{ion} \nabla c_q(r) + Z_{ion} \vec{E}(r)c_q(r)
\]

Formula 5.4.12

With \(\vec{j}_q\) the charge flux in C/(m²s), \(\vec{r}\) the position vector in m, \(D_{ion}\) the ion diffusivity in m²/s, \(c_q\) the charge concentration in C/m³, \(Z_{ion}\) the electrical ion mobility in m²/(Vs), which is related to the mechanical mobility by \(Z_{ion} = q_{ion} B_{ion}\) with \(q_{ion}\) the ion charge in C and \(B_{ion}\) the mechanical mobility in m/(Ns) and \(\vec{E}(r)\) the local electric field at position \(\vec{r}\) in V/m. The diffusivity is described by the Einstein relation [Einstein, 1905], and is here rewritten to the form in formula 5.4.13.

\[
D_{ion} = k_B T B_{ion} = \frac{k_B T Z_{ion}}{q_{ion}}
\]

Formula 5.4.13
With $k_b$ Boltzmann constant in J/K, and $T$ absolute temperature in K

Formula 5.4.12 can be rewritten to formula 5.4.14, using the Einstein relation.

$$\vec{j}_q (\vec{r}) = -D_{ion} \left[ \nabla c_q (\vec{r}) - \frac{q_{ion}}{k_b T} \vec{E}(\vec{r}) c_q (\vec{r}) \right]$$  \hspace{1cm} \text{Formula 5.4.14}$$

Note that formula 5.4.12 and 5.4.14 are very important formulae, because they also hold for the transport of charged particles. If the rate of the ions expelled from the corona region were known, formula 5.4.14 could be used to calculate the charge flux and the ion concentration. In this simulation, however, a uniform concentration of ions is assumed throughout the charging section, except close to a particle, where it is determined by the electric field due to the particle charge. The assumed value for the overall concentration of ions is $5 \times 10^{14}$ m$^{-3}$. In this calculation the charging rate due to diffusion and the electric field are calculated for each effect separately and then added together to obtain the total charging rate, see formula 5.4.24.

The formula for the average charging rate due to field charging, in the absence of diffusion, is given in [Lawless, 1996]. It is given in formula 5.4.15, rewritten in the notation of this thesis.

$$\frac{d n e_{fc}}{d t} = \left( \frac{3\varepsilon_r}{\varepsilon_r + 2} \right) \left( \frac{E_{is} r_p^2}{K_E e c} \right) \left( \frac{1}{\zeta} \right) - 2 \left( \frac{1}{\zeta} \right) n e + \left( \frac{(e_r + 2)}{3\varepsilon_r} \right) \left( \frac{K_E e c}{E_{is} r_p^2} \right) \left( \frac{1}{\zeta} \right) n e^2$$  \hspace{1cm} \text{Formula 5.4.15}$$

With $d n e_{fc}/d t$ the charging rate in 1/s due to field charging, $\varepsilon_r$ the permittivity of the material of the particle relative to the permittivity of the vacuum (or in other words the dielectric constant of the particle), $E_{is}$ the field strength due to the voltage on the wire-electrode in V/m, $e c$ the elemental charge for charging with positive ions $1.6 \times 10^{-19}$ C, $n e$ the number of elemental charges, a natural number for charging with positive ions, and $\zeta$ a variable for convenience of notation, expressed in formula 5.4.16 with unit seconds. Note that the field charging rate depends on the particle charge, as would be expected from the theoretical discussion.

$$\zeta = \frac{1}{\pi K_E e c z_{ion} e c}$$  \hspace{1cm} \text{Formula 5.4.16}$$

Note that $\zeta$ is a function of the ion concentration.

If formula 5.4.15 would be solved, assuming $n e(0)=0$, $n e$ at infinite time, i.e. at $d n e_{fc}/d t=0$, which is $n e_{sat} = \left( \frac{3\varepsilon_r}{\varepsilon_r + 2} \right) \left( \frac{E_{is} r_p^2}{K_E e c} \right)$ and $E_i$ independent of time, a more common form is obtained for field charging, as shown in for example [Hinds, 1999].

$$n e_{fc} (t) = \left( \frac{3\varepsilon_r}{\varepsilon_r + 2} \right) \left( \frac{E_{is} r_p^2}{K_E e c} \right) \left( \frac{t}{\zeta + t} \right) = n e_{sat} \left( \frac{t}{\zeta + t} \right)$$  \hspace{1cm} \text{Formula 5.4.17}$$

It is very important to keep in mind that formula 5.4.15 is only valid in the absence of any other charging mechanism, because if $n e_{sat}$ would be exceeded, formula 5.4.15 would expect an increase in charging rate due to field charging, which will increase until infinity.
The average charge due to diffusion charging in the absence of an electric field is commonly expressed as empirical formula 5.4.18 [Hinds, 1999]:

\[
ne_{\text{diff}}(t) = \left( \frac{r_p k_b T}{K_E e c^2} \right) \ln \left( 1 + \frac{r_p \overline{u}_{\text{ion}}}{D_{\text{ion}}/\zeta} \right) 
\]

Formula 5.4.18

This formula is valid for the free molecular regime (i.e. for particles much smaller than the mean free path), but misses fundamental basis for using it in the transition and continuum regime [Fjeld and McFarland, 1989].

Charging due to the diffusion of ions in the absence of an electric field is given by [Chang, 1981] for use in the transition regime for round particles, see formula 5.4.19.

\[
dt \frac{dne_{\text{diff}}}{dt} = \frac{4 \cdot ne}{\zeta + \zeta \cdot \left( 1 + \kappa \cdot \frac{e c^2 K_E}{r_p k_b T} \right) \cdot \frac{e c^2 K_E}{\zeta} \cdot e \cdot r_p k_b T} 
\]

Formula 5.4.19

With \( \kappa \) a dimensionless variable to compensate for the fact that the particle has a radius close to the main free path. It is defined in formula 5.4.20.

\[
\kappa = \frac{2 - \alpha_i \overline{u}_{\text{ion}} \hat{\lambda}_{\text{ion}}}{3 \alpha_i u_d r_p} 
\]

Formula 5.4.20

With \( \alpha_i \) the sticking probability for ion surface collisions, and \( u_d \) the drift velocity of an ion due to an external electric field, i.e. \( u_d = Z_{\text{ion}} E \), and \( \hat{\lambda}_{\text{ion}} \) the mean free path of the ions.

Using formula 5.4.21 from [Hinds, 1999], and using formula 5.4.13, formula 5.4.20 can be rewritten to formula 5.4.22.

\[
D_{\text{ion}} = \pi \frac{\overline{u}_{\text{ion}} \hat{\lambda}_{\text{ion}}}{8} 
\]

Formula 5.4.21

\[
\kappa = \frac{2 - \alpha_i}{3 \alpha_i u_d r_p} \frac{8 k_b T}{\pi e c \cdot E} 
\]

Formula 5.4.22

For particles that are large in comparison to the mean free path, \( \kappa \) converges to zero. Note that the initial charging rate, i.e. the case of no elemental charge on the particles, should be obtained using l'Hôpital’s rule. The initial growth velocity due to diffusion charging is then given by formula 5.4.23.

\[
\frac{dne_{\text{diff}}}{dt}(0) = \frac{4}{(1 + \kappa) \cdot \zeta \cdot \left( \frac{e c^2 K_E}{r_p k_b T} \right)} 
\]

Formula 5.4.23

In this simulation it is assumed that the total charging rate at a certain time \( t \) is given as the sum of the charging rate due to diffusion in the absence of an electric field plus the charging rate due to the electric field in the absence of diffusion, as long as the number of elemental charges does not exceed \( ne_{\text{sat}} \). If \( ne_{\text{sat}} \) is exceeded the charging rate is only determined by \( dn_{\text{diff}}/dt \).

\[
\frac{dne}{dt}(x,y,r_p,t) = \frac{dne_{\text{diff}}}{dt}(x,y,r_p,t) + \frac{dne_{\text{fc}}}{dt}(x,y,r_p,t) 
\]

Formula 5.4.24
Note that the charging rate is a function of the electric field strength, which is a function of location, and since the number of elemental charges is influenced by the charging rate due to field charging, also \( \frac{dne_{\text{dt}}}{dt} \) is a function of location.

The number of elemental charges is subsequently calculated as indicated in formula 5.4.25.

\[
ne(t + dt) = ne(t) + \frac{dne}{dt}(t) \cdot dt
\]

Formula 5.4.25

If it is assumed that particles are travelling at a uniform speed in y-direction throughout the entire charging section, the parameter time and y-coordinate are linked to each other by the velocity in y-direction \( u_y \). The steps in time correspond to the steps in y-direction as used in the calculation of the electric field in the charging section. In the calculation of the charge on the particles after the charging section it is assumed that particles in the charging section do not move in x-direction. This simplifies the calculation significantly, but may lead to an overestimation of the charge on the particles that are strongly influenced by field charging. On the other hand, particles close to the earthed plates, which will get the least charge, can be collected in the charging section due to movement in x-direction, and this is ignored with the present assumption as well.

The outcome of the calculation is for every \( x \), \( y \) and \( r_p \) an average number of elemental charges, which is most likely not an integer. At present the calculation continues with calculating with these average number of elemental charges, and only at the end of the charging section a charge distribution is assumed. This introduces an error in the calculation of the charging rate, because the average charging rate of a particle with an average charge of for example 1.5 is slower than the average of the charging rate of 50% particles with 1 elemental charge and 50% particles with 2 elemental charges. This way the actual particle charge is slightly underestimated.

As mentioned above a distribution of the elemental charges was assumed after the charging section, per \( x \) and \( r_p \), because a non-integer number of elemental charges is physically impossible. It is assumed that the charge distribution is similar to the Boltzmann equilibrium charge distribution with an average charge as calculated. The distribution is then a discrete Gaussian distribution given by formula 5.4.26.

\[
f_{ne} = \sum_{ne=ne_{\text{av}}} e^{-\frac{(ne-ne_{\text{av}})^2}{2sd^2}}
\]

Formula 5.4.26

With \( f_{ne} \) the probability density function, \( ne \) the actual number of elemental charges, \( ne_{av} \) the calculated average charge and \( sd \) the standard deviation, defined as formula 5.4.27.

\[
sd = \sqrt{\frac{r_p k_b T}{K_E \cdot ec^2}}
\]

Formula 5.4.27

It is important to realise that for very small particles this formula is an approximation, because if the average charge of the distribution is calculated it is not equal to the average charge as given. Note that according to this distribution it is possible to have negatively charged particles, i.e. \( ne \) is negative. It is unlikely that this will really happen for unipolar charging.
The maximum charge on a droplet is limited. If the repulsion of electric charges in the droplet exceeds the force that keeps the droplet together, the droplet will shatter. The maximum amount of charge is determined by the Rayleigh limit (formula 5.4.28).

\[ n_e \text{max,}_R = \frac{16\pi\sigma \cdot r_p^3}{K_F e^2} \]

Formula 5.4.28

With \( \sigma \) the surface tension of the droplet. The calculated number of elemental charges is checked against the Rayleigh limit. If the Rayleigh limit is exceeded in the calculation in this thesis the particle charge is adjusted to the first natural number of elemental charges below the Rayleigh limit. Note that a different limit is applicable for solid particles.

§5.4.4 Particle collection section

§5.4.4.1 Relative velocity of a charged particle

After charging the particle, the particle will be collected. The transport of charged particles can be described in a similar way as formula 5.4.11 for ion transport, i.e. transport is governed by both diffusion and the external electric field. It is assumed that diffusion is ignored. The first step in determining the particle collection efficiency is to determine the velocity of a particle due to an electric field. Let’s assume that constant velocity is achieved in an infinitesimal small time and the only forces acting on the charged particle are an electrical force and a drag force. In that case the sum of the forces is zero, or in other words:

\[ \sum F = 0 \]

with the vector notation to stress the importance of the direction of the electric field. The electric force can be expressed as:

\[ F_e = qE = ne \cdot ec \cdot \vec{E} \]

Formula 5.4.30

The drag force on a particle is expressed by Stokes’ law with the Cunningham correction factor, for particles having a Reynolds numbers less than 1.

\[ F_D = -\frac{6\pi\mu_g \vec{u}_{rel} r_p}{C_c} \]

Formula 5.4.31

with \( \vec{u}_{rel} \) the velocity of the particle relative to the gas velocity, \( \mu_g \) the dynamic viscosity of the gas medium and \( C_c \) the Cunningham correction factor, to correct for the fact that particles are of a size similar to the mean free path, as expressed in formula 5.4.32 [Hinds, 1999].

\[ C_c = 1 + \frac{\lambda_g}{r_p} \left( 1.17 + 0.5025 \cdot e^{-0.78 r_p} \right) \]

Formula 5.4.32

with \( \lambda_g \) the mean free path, the average distance a gas molecule travels before encountering another gas molecule, which is 66.5 nm for air in normal conditions. Lambda varies inversely with gas density. Formula 5.4.32 is an empirical formula with a claimed precision of 2.1% for solid particles.
Substituting formulae 5.4.30 and 5.4.31 in formula 5.4.29 results in formula 5.4.33 for the velocity of a particle relative to the gas velocity.

\[ \ddot{u}_{rel} = \frac{ne \cdot ec \cdot \vec{E} \cdot C_c}{6\pi\mu_g r_p^6} \]  

Formula 5.4.33

From the velocity of a charged particle relative to the gas velocity the removal efficiency can be determined under a number of assumptions. In the following subsections the influence of several assumptions on particle removal efficiency will be discussed.

§5.4.4.2 Deutsch-Anderson equation

The most frequently used expression for collection of charged particles is the Deutsch-Anderson equation. It is often used to compare different electrostatic precipitators. Before the assumptions that lead to the Deutsch-Anderson equation are discussed a coordinate system is defined, illustrated in Figure 5.21.

The assumptions for the Deutsch-Anderson equation are the following:

- Gas and particles move in the y-direction with the same constant velocity \( u_y \).
- The particles are uniformly distributed in the x- and z-direction at every y location, i.e. constant mixing is assumed in x-direction.
- The electric field in the collection section is constant and uniform.
- Particles attain an electric drift velocity \( u_x \) in the x-direction infinitely fast.
- Once particles reach the collection electrode, they are removed from the system and do not influence particle removal.
- Particle size distribution in ESP does not change due to coagulation, condensation or evaporation.

The particle concentration in the exhaust gas changes when particles reach the collection electrode. For a particle of radius \( r_p \) and \( ne \) elemental charges, the change in particle concentration can be described as a function of the particle concentration in an infinitesimal small volume close to the surface of the collection electrode, as expressed in formula 5.4.34.

\[ \frac{dc}{dt} = -c_{ae} (t) \left| \frac{\dot{u}_x}{w_c} \right| \]  

Formula 5.4.34
With \( c_{ae} \) the particle concentration at the collection electrode, which is in the case of constant mixing in \( x \)-direction equal to the concentration at location \( y \), and \( w_c \) the distance between electrodes with opposite polarity. \( dt \) can also be expressed as a function of the location in the collection zone, according to formula 5.4.35 and formula 5.4.34 becomes formula 5.4.36.

\[
dy = \bar{u}_y dt
\]

\[
\frac{dc}{dy} = -\frac{u_x}{w_c \cdot u_y} c_{ae}(y)
\]

Since the particle concentration is uniformly distributed over \( x \) for every \( y \), i.e. \( c_{ae}(y) = c(y) \), formula 5.4.36 is a first order differential equation and its solution is shown in formula 5.4.37, with \( c_{in} \) the particle concentration at \( y = 0 \).

\[
c(y) = c_{in} \cdot e^{-\left(\frac{|\bar{u}_y|}{w_c u_y}\right)}
\]

From this formula the removal efficiency can be calculated for a particle with radius \( r_p \) and a number of elemental charges \( n_e \).

\[
\eta_{D-A}(r_p, n_e) = 1 - e^{-\frac{\bar{u}_y L_c}{u_y w_c}}
\]

With \( \eta_{D-A} \) the removal efficiency according to the Deutsch-Anderson equation and \( L_c \) the length of the collection section. If the velocity in \( y \)-direction is substituted by the total flow through the ESP ‘\( \Phi \)’ in \( \text{m}^3/\text{s} \), formula 5.4.38 can be rewritten to the more common form of formula 5.4.39.

\[
\eta_{D-A}(r_p, n_e) = 1 - e^{-\frac{\bar{u}_y A_c}{\Phi}}
\]

With \( A_c \) the total surface of the collection electrodes. To obtain the total removal efficiency, the formula needs to be integrated for every \( r_p \) and summed for every \( n_e \), because \( n_e \) is not continuous.

\[
\eta_{tot} = \frac{\sum \int c(ne, r_p) \cdot \eta(ne, r_p) \, dr_p}{\sum \int c(ne, r_p) \, dr_p}
\]

Note that for the actual calculation of the total removal efficiency the particle radius is not a continuous function and the total removal efficiency is approximated by the sum of \( \Delta r_p \) over the particle size range. Note that the plots of the particle concentration in the ESP, as presented in section §5.4.4.5 are an approximation, because the calculation is split up in small slices in \( y \)-direction, and the plotted concentration is obtained from formula 5.4.37.

§5.4.4.3 Uniform flow distribution

In the derivation of the Deutsch-Anderson equation it was assumed that the particle distribution is uniform over the \( x \)-direction. This assumption is now released. The following assumptions are used for the calculation of the uniform flow distribution without Brownian motion.

- Gas and particles move in the \( y \)-direction with uniform velocity \( u_y \)
• Particles are uniformly distributed in the z-direction, i.e. collection is a 2-D problem
• The electric field in the collection section is constant and uniform
• The particles attain an electric drift velocity $u_x$ in the x-direction infinitely fast
• Once particles reach the collection electrode, they are captured and do not influence particle removal
• Particle distribution in ESP does not change due to coagulation, condensation or evaporation
• No forces present to equalise the distribution in x-direction

It is possible to solve this problem analytically. Up till formula 5.4.36 the derivation is the same as in section §5.4.4.2. However now $c_{ae}(y)$ is equal to $c_{in}$ until all particles are removed, and when all particles are removed $c_{ae}(y)=0$. The point where all particles are removed is simply the time to travel to one side of the collection zone to the other, multiplied by the velocity in y direction, as expressed in formula 5.4.41.

$$c_{ae}(y) = c_{in} \quad \forall y < \frac{w_c \cdot |u_y|}{u_x(n_e, r_p)}$$  

$$c_{ae}(y) = 0 \quad \forall y \geq \frac{w_c \cdot |u_y|}{u_x(n_e, r_p)}$$  

Which leads to formula 5.4.42 for the removal efficiency according to a uniform flow profile for a particle with radius $r_p$.

$$\eta(r_p, n_e) = \frac{\frac{u_x(n_e, r_p)}{|u_y| \cdot w_c} \cdot L_c}{\forall L_c < \frac{w_c \cdot |u_y|}{u_x(n_e, r_p)}}$$  

$$\eta(r_p, n_e) = 1 \quad \forall L_c \geq \frac{w_c \cdot |u_y|}{u_x(n_e, r_p)}$$  

It is expected that the resulting concentration profile for particles with a single radius and charge is a triangular area with high concentration divided by a straight line from the area with no particles. However the plots of the particle concentration in the ESP are an approximation, because the calculation is split up in small blocks in x- and y-direction, see Figure 5.21. The used approach for the calculation of the particle concentration in the ESP is indicated in Appendix A.

§5.4.4.4 Laminar velocity distribution
For most practical considerations of the application of the SJAC-ESP the gas flow between the plates in the collection zone is laminar. Therefore the influence of the laminar flow profile is calculated. It will be assumed that this velocity profile is immediately achieved, when the gas enters the collection zone. Other assumptions are listed below:
• Gas between the collector plates has a laminar velocity profile, reached immediately between the plates
- Gas flow before the collector plates is uniform in x-direction, as is the particle distribution
- Particle velocity in y-direction is equal to the gas velocity, and is reached infinitely fast
- Particles are uniformly distributed in the z-direction, i.e. collection is a 2-D problem
- The electric field in the collection section is constant and uniform
- The particles attain an electric drift velocity $u_x$ in the x-direction infinitely fast
- Once particles reach the collection electrode, they are captured and do not influence particle removal
- Particle distribution in ESP does not change due to coagulation, condensation or evaporation
- No forces present to equalise the distribution in x-direction

The velocity profile is expressed as follows:

$$
\bar{u}_y(x) = \bar{u}_{y,max} \cdot \frac{(0.5 \cdot w_c)^2 - x^2}{(0.5 \cdot w_c)^2}
$$

with $\bar{u}_{y,max}$ the maximum velocity, which equals $1.5 \cdot u_{y,gem}$.

The solution of this distribution is not obtained analytically but numerically by calculating the particle concentration everywhere in the collection section and from the concentration, or rather rate of particles leaving the collection section, the removal efficiency is calculated. See for more detail appendix A.

### §5.4.4.5 Simulation results

In order to be able to simulate the process, the electric field and the ion concentration in the charging section needs to be known. The calculated electric field is shown in Figure 5.22.

The ion concentration could be derived from measurement of the current in the charging section. However, because the current was not measured, the ion concentration is estimated. This is done by finding the ion concentration, which seems realistically from power consumption and removal efficiency point of view. It is estimated at $5 \times 10^{14}$ ions/m$^3$, which is at the high end of the range predicted by [Hinds, 1999]. This corresponds with an estimated current of 25 $\mu$A and a power consumption of 0.25 W per charging section. Table 5.14 lists the number removal efficiency according to the calculation of the Deutsch-Anderson equation and the laminar flow profile. It clearly shows that the ion concentration in the charging section is an important parameter, whose value should be chosen carefully.

For the chosen value of $5 \times 10^{14}$ ions/m$^3$ approximately 18% of the incoming charges end up on a particle. In the calculation it is assumed that the ion concentration is constant, but the value of 18% clearly shows that the charging process influences the ion concentration. This makes it even harder to properly describe the ion concentration in the charging section. Additionally constants have been used for air at standard conditions, instead of exhaust gas at elevated temperatures and humidity.
Table 5.14 Influence of ion concentration charging section on calculated removal efficiency in ESP

<table>
<thead>
<tr>
<th>Ion concentration charging section [1/m^3]</th>
<th>Removal efficiency with uniform flow [%]</th>
<th>Removal efficiency according to Deutsch-Anderson [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.75 \times 10^{14}</td>
<td>62.3</td>
<td>47.0</td>
</tr>
<tr>
<td>2 \times 10^{14}</td>
<td>80.2</td>
<td>59.5</td>
</tr>
<tr>
<td>3 \times 10^{14}</td>
<td>85.0</td>
<td>63.0</td>
</tr>
<tr>
<td>5 \times 10^{14}</td>
<td>89.4</td>
<td>66.4</td>
</tr>
<tr>
<td>7.5 \times 10^{14}</td>
<td>91.5</td>
<td>68.1</td>
</tr>
<tr>
<td>10 \times 10^{14}</td>
<td>93.3</td>
<td>69.9</td>
</tr>
<tr>
<td>15 \times 10^{14}</td>
<td>95.1</td>
<td>71.0</td>
</tr>
<tr>
<td>30 \times 10^{14}</td>
<td>97.6</td>
<td>72.9</td>
</tr>
<tr>
<td>75 \times 10^{14}</td>
<td>100.0</td>
<td>76.9</td>
</tr>
<tr>
<td>100 \times 10^{14}</td>
<td>100.0</td>
<td>81.5</td>
</tr>
<tr>
<td>150 \times 10^{14}</td>
<td>100.0</td>
<td>90.4</td>
</tr>
</tbody>
</table>

Figure 5.23 and Figure 5.24 give the calculated efficiency based on a ion concentration of $5 \times 10^{14}$ 1/m$^3$ as a function of distance in the ionisation section and as a function of the initial particle radius, i.e. the particle radius before condensation. The difference between the exact solution of the laminar flow case and the approximation is also shown. It shows that the difference between the two is less than 5 percent. The difference is caused by the division of the collection section in small blocks. It should be noted that the exact solution can be calculated faster than the approximation, and hence the exact solution is preferred.

Figure 5.24 illustrates that the initial particle removal with a parabolic velocity profile is higher than with the Deutsch-Anderson equation or uniform flow profile. That is because it is assumed that the velocity profile over the entire ESP is discontinuous. It is uniform in the charging section, and is upset into several parabolic velocity profiles upon entering the collection section. This leads to a discontinuous particle concentration at the entrance of the collection section, see also Figure 5.26, which in its turn leads to a relatively high initial particle removal in the collection section. A proper description of the flow profile including the development of the flow profile will lead to a more realistic removal efficiency.

The obtained concentration profiles for different particle sizes are shown in Figure 5.25 to Figure 5.27. The difference between the different concentration profiles is quite distinct. In Figure 5.25 several straight lines are visible for the removal of particles with one initial radius. The different lines stem from different particle charges, due to the position of the particle in the charging section. The particle removal of particles with an initial radius of 10 and 100 nanometres is approximately equal, because the particles are similar in size after they obtain their water coating. In Figure 5.27 the scale is different, because of the locally very high concentration due to the upset of the velocity profile upon entering the charging section. Therefore, it seems more efficient than the other assumptions based on colours, but it is not, as illustrated in Figure 5.24. Figure 5.27 shows no difference in concentration in y-direction, as expected, because of the perfect mixing in that direction.

The different situations that were tested in section §5.3.1 and presented in Table 5.2 and Table 5.3 are now calculated. The results are shown in Table 5.15. The calculated trends differ quite significantly from the measurements.
If the velocity through the ESP is halved, or in other words, the width of the charging and collection section are enhanced, the expectation from measurement is that the removal efficiency is not influenced a lot. The calculation shows different results, however. The removal efficiency should increase significantly. This can already be predicted by looking at Figure 5.25 to Figure 5.27. If the ratio between velocity in x-direction and velocity in y-direction is doubled, due to a decrease of the velocity in y-direction of a factor two, the removal efficiency will significantly increase. In addition to this the particles will obtain a higher charge due to a longer charging time, which only enhances this effect. Halving the voltage in the collection section halves the attracting force in the collection section, and hence halves the velocity in x-direction. Therefore the removal efficiency reduces in comparison to the voltage of -2kV with a velocity of 0.37 m/s. The removal efficiency without steam is only approximated, because the smallest particles only obtain a small charge, average less than 4 elemental charges for particle radii up to 40 nanometres, in contrast to condensed water, where the minimum number of elemental charges 300 is. With these low number of elemental charges the distribution as proposed in formula 5.4.26 is an approximation of the actual distribution, which might lead to a calculated removal efficiency that is discontinuous. The last influence was the particle concentration. In the present calculation the particle concentration only influences the amount of condensed water on the particles, and with that particle radius. It has no other effect in the charging section, because it is assumed that the particle concentration is independent of the fraction of ions used in the charging process. Please note that the fraction used ions increases to 47% for a concentration of $25 \times 10^{13} \text{1/m}^3$, which is approximately the upper limit of particle concentration. Although the collection efficiency does not drop considerably particle concentration may have a significant effect, when the interaction between particle charge and ion concentration is properly described. A strong influence of the particle concentration is not found in the measurements.

| Table 5.15 The calculated influence of different operating conditions in the ESP |
|-------------------------------|------------------|------------------|
|                              | Number removal efficiency | Number removal efficiency |
|                              | with uniform flow [%] | according to Deutsch-Anderson [%] |
| Base case calculation        | 89.4              | 66.4             |
| ($u_{ESP}=0.74 \text{m/s, } V_c=-2 \text{kV, 3% steam}$) |                       |                  |
| $u_{ESP}=0.37 \text{m/s, } V_c=-2 \text{kV, 3% steam}$ | 100.0             | 88.6             |
| $u_{ESP}=0.37 \text{m/s, } V_c=-1 \text{kV, 3% steam}$ | 93.3              | 69.6             |
| $u_{ESP}=0.37 \text{m/s, } V_c=5 \text{kV, no steam}$ | 91.6              | 89.8             |
| $u_{ESP}=0.74 \text{m/s, } V_c=-2 \text{kV, 3% steam, } c_{part}=25 \times 10^{13} \text{1/m}^3$ | 74.8              | 55.5             |

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Figure 5.22 Calculated electric field in charging section. The colour bar is expressed in V/m, and is manually maximised at $3 \times 10^6$ V/m. Note the dimensions of x- and y-axis.

Figure 5.23 Removal efficiency as function of initial particle radius. The blue line represents the exact solution with uniform flow profile, the red line the approximation of the uniform flow profile, the black line the parabolic flow profile and the purple line the Deutsch-Anderson equation.
Figure 5.24 Efficiency as a function of distance in the collection section. The red line the approximation of the uniform flow profile, the black line the parabolic flow profile and the purple line the Deutsch-Anderson equation.

Figure 5.25 Calculated particle concentration of different particle sizes in collection section with the assumption of a uniform flow profile.
Figure 5.26 Calculated particle concentration of different particle sizes in collection section with the assumption of a parabolic flow profile.

Figure 5.27 Calculated particle concentration of different particle sizes in collection section with the Deutsch-Anderson equation.
Clearly the simulation does not predict the trend for the velocity as is found for velocity in the measurements. A number of issues should be addressed to get a better understanding of the processes at hand. First and foremost the ion concentration should be described well in the charging section. This is not so easy, because it was found in the previous section that the charge leaving the ionisation section on the particles is a significant fraction of the entering charge. The current in both ionisation section and collection section should be measured in order to get more information on the charging and collection processes. The current in the collection section will give additional information on the charge on the collected particles. A second improvement would be to use a proper description of the velocity profile through the collection section. A third improvement would be to include the effect of the captured particulate matter on the particle removal efficiency; more specifically the possible decrease in electric field and the reduction of the cross-section between the plates. A fourth improvement would be to include diffusion of the particles, which is mainly important for the small particles, especially without steam injection. Diffusion has two effects. It will strive for a homogeneous concentration, on the other hand it will result in particle collisions with the walls in the collection section. Note that the Deutsch-Anderson equation incorporates the strongest case of diffusion, with regard to the mixing of particles, but excludes the removal due to diffusion.

It is important to realise that the calculated particle radius after condensation is important for the calculation, but is modelled and not verified by any other measurements than those discussed in Chapter 4

A second generation SJAC was developed. The idea behind the SJAC-ESP is that wet diesel particulate matter is captured by a filter. This wet diesel particulate matter subsequently flows off the filter, thereby automatically cleaning it. Diesel particulate matter is moisturised by condensation of steam on the particulate matter.

Investigation of the operating window, showed a removal efficiency up to 82% when steam was injected. It was found that the insulators were critical for proper functioning of the ESP. All insulators have been redesigned. The SJAC-ESP has accumulated 175 hours of operation including 142 hours during a 500 hours endurance test with a 15 kW engine, which delivered 100 kg/h exhaust gas. The cooler of the exhaust gas was prone to fouling, and increased the pressure drop over the installation considerably. A longer duration test is necessary to investigate if the electrodes of the ESP are sufficiently cleaned.

The tests in the slipstream of a 350 kW engine show that initial problems with start-stop behaviour have been solved. Three different fuels were used; a MGO with 0.1% sulphur, a MGO with 0.16% sulphur and a heavy fuel oil (RMA-30) with 1.5% sulphur. The average mass removal efficiency over a cycle ranges between 57 and 78%, according to filter measurements, including particulate matter removal in coolers, and between 41% and 70%, excluding particle removal in the cooler. The results of the SMPS show reproducible shapes. The number removal efficiency ranged between 70% and 83% over the cycle. Calculated mass removal efficiency averaged over a cycle from SMPS measurements show a removal efficiency ranging from 65 to 85%.
Some SOx is removed in the ESP, but with approximately 50% for MGOs and 30% for RMA-30 the removal is more a “nice to have” than additional selling point. It is critical to use acid-resistant materials when the exhaust gas temperature is lower than 190°C, and for the fluid waste streams. With the present cooler barely no SOx was removed in the coolers, the condensate leaving the coolers was very acidic however. Additional SOx-removal could be obtained by using a different cooling technique. This will be shortly addressed in Chapter 6 on exhaust gas system design.

A calculation was made to estimate the potential of the SJAC-ESP. Large uncertainty in the calculation is the ion concentration in the charging section. It was found that the removal efficiency is strongly dependant on this parameter. Presently the ion distribution is not properly described, and this should be the first improvement to the calculation. Current in ionisation section should be measured to get an indication of the ion concentration. Preferably also the current in the collection section is measured for an indication of charge on the collected particles. The simulation confirmed that the removal efficiency of the SJAC-ESP is barely size-dependent for particles smaller than 150 nm. Larger particles are collected slightly more efficient. The simulation found that the removal efficiency can be influenced strongly by the velocity through the ESP. This was not found in the measurements. The simulation is not yet good enough to be a good base for dimensioning the ESP.
Chapter 6. Exhaust system design
§6.1 Introduction
In this chapter the focus is transferred from the existing lab-scale SJAC-ESP towards a preliminary design for a full-scale exhaust gas system. The focal point is not the SJAC-ESP itself, but the systems surrounding the SJAC-ESP that are necessary for successful application, more in particular exhaust gas cooling and the treatment of waste water from the SJAC-ESP. It is not the goal to make a detailed design of the exhaust system. In this chapter several design options are indicated and the effects of the options are discussed. In chapter 7 designs for inland shipping and ferries are elaborated.

§6.2 Exhaust gas cooling
In section §5.2.1 the general concept of the SJAC-ESP was discussed. A certain realisation for cooling was chosen and tested, based on the already existing set-up and expected reliability. However, fundamentally different choices could have been made. In order to assess the options for the system a block-diagram is made which gives the necessary functions, see Figure 6.1. As references the heat in the exhaust gas is given based on data from a MAN 9L 40/54 engine [MAN, 2004], an engine used in ferry applications [Brussen et al., 2006], and the heat duty for the creation of steam is given, based on the ratio between mass flow steam and mass flow exhaust gas during the experiments with the SJAC-ESP (mass flow steam divided by mass flow exhaust gas is 0.03).

Figure 6.1 Block-diagram of necessary functions in SJAC-ESP system

An important observation is that after creating steam for steam injection in the exhaust gas still high-value heat is available. This heat could be used to generate additional steam to generate electricity with a steam turbine or by injecting it directly into the diesel engine (steam injected diesel (STID), see e.g. [Chomiak et al., 2004]). Given the fact that a steam turbine and STID need high-pressure (and thus warmer) steam, it makes more sense to make the high-pressure steam first. The low-pressure steam could be taken out of the turbine half-way, be generated by a separate cooler or made directly from the high-pressure steam. Taking the steam for steam injection halfway out of the turbine leads to most generated power and needs only one cooler and pump. This way approximately 10% of the energy over 190°C can be converted to electrical power, under certain assumptions, see Chapter 7.

Normally exhaust gas cooling with diesel engines running at heavy fuel oil stops at 180-190°C because at those temperatures sulphuric acid will start to condense, which will corrode the most common construction materials. Sticky hydrocarbons will also start to
condense below these temperatures. In the case of the SJAC-ESP, exhaust gas needs to be cooled to approximately 30°C. A large amount of low-value heat needs to be removed from the exhaust gas, in a very unfavourable temperature regime from fouling point of view. This could be done with a regular heat exchanger, as was done during the experiments with the SJAC-ESP, if dimensioned properly. However, the heat could also be removed by a direct contact cooler, i.e. the coolant is in direct contact with the warm fluid. The big advantage of a direct contact cooler is that it can also work as a scrubber, thereby removing a significant amount of sulphur oxides. Scrubbers are already marketed as a tool to reduce sulphur oxide emissions, see also section §2.6.4. It can be expected that at least 80% of the SOx is reduced this way. Scrubbers also remove particulate matter. Disadvantage of scrubbers is that they yield a large amount of waste water that needs to be cleaned. This will be discussed in section §6.3. The SJAC-ESP is compatible with sea water scrubbers presently being marketed. However, during the tests with the SJAC-ESP a lower exhaust gas temperature after cooling has been used. A higher exhaust gas temperature is possible, but more steam should be injected to yield the same amount of condensate, see the discussion in section §4.4. The implication of the exhaust gas temperature after cooling on the economics of the system is discussed in section §7.4.3.

The different options for cooling are summarised in Table 6.1. In Chapter 7, the dimensions for coolers will be calculated and the best concept from economy point of view will be identified.

Table 6.1 Different options for cooling in SJAC-ESP system

<table>
<thead>
<tr>
<th>Steam generation</th>
<th>Cooling to goal temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling by an indirect contact cooler</td>
<td>Cooling by an indirect contact cooler</td>
</tr>
<tr>
<td>Cooler to generate low-pressure steam for steam injection</td>
<td>Cooling by a direct contact cooler</td>
</tr>
<tr>
<td>Cooler to generate high-pressure steam</td>
<td>Cooling by a direct contact cooler</td>
</tr>
</tbody>
</table>

§6.3 Waste water

§6.3.1 Introduction

The SJAC-ESP system creates two waste water streams as illustrated in Figure 6.1. One from the cooler and one from the ESP. The waste water streams need to fulfil certain requirements before they can be discharged. For inland shipping no uniform rules are defined. As a guideline for the Netherlands, the Dutch “helpdesk water”, a governmental organisation for advice on water policy, water management and water safety, proposed the limits as presented in Table 6.2.

Also for sea shipping no uniform rules are defined yet. The systems that clean the waste water from SOx-scrubbers should fulfil the following requirements according to MEPC.130(53) [IMO, 2005]. “They should

(a) eliminate, or reduce to a level at which they are not harmful, hydrocarbons, carbon residue, ash, vanadium, other heavy metals, and other substances contained within EGCS-SOx unit’s (SOx-scrubbers, GvR) wash water that may have an adverse impact on ecosystems if discharged overboard

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(b) ensure that the approach adopted, to control wash water quality and residual waste is not achieved in a way that causes pollution in other areas or environmental media

(c) also taking into account guidelines to be developed by the Organization”

This is notably vague and open to debate, until the international maritime organization (IMO) develops the guidelines for the discharge limits of sea water scrubbing. In addition [IMO, 2005] states that the sludge from the waste water treatment may not be burned in an on-board waste-incinerator.

It seems likely that the effluents from the SJAC-ESP have to fulfil the same regulation, as the waste water of an SOx-scrubber contains the same pollutants as the waste water from the SJAC-ESP (although not in the same concentrations).

To give an indication what could be expected the requirements for bilge-water and sewage waste water are shown in Table 6.2.

<table>
<thead>
<tr>
<th>Table 6.2 Regulation or guidelines for waste water treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH Suspended solids [mg/kg] Oil in water [mg/kg]</td>
</tr>
<tr>
<td>Inland shipping [Helpdesk water, 2007]</td>
</tr>
<tr>
<td>Bilge-water sea shipping [IMO, 2003]</td>
</tr>
<tr>
<td>Sewage waste water on sea ships [IMO, 2006]</td>
</tr>
</tbody>
</table>

This section clearly shows that there is a need for a regulation for waste water limits, in order to prevent the discussion what the level is on which certain pollutants are not harmful anymore, and to prevent ship owners from suddenly having to retrofit, or even replace the existing water treatment facility.

§6.3.2 Components of waste water

The composition of the waste water streams was determined. The measurements were done when the coolers were still of the spiral-type that clogged easily, see Figure 4.7. The cooling was realised by two indirect coolers, that both delivered a waste water stream. The results are given in Table 6.3 to Table 6.5. The concentrations of pollutants in the water from the coolers are an average of two samples. Those samples correlated well with each other. The concentration of pollutants in water from the ESP is determined only once, due to the lower amount of waste water.

The concentration suspended dust was determined by weighing the mass of dust on a filter from a known volume of waste water. The waste water was filtered by a Whatman GMF 150 filter with 98% retention of particles with a diameter of 1 μm. The dust was dried over silicagel and additionally dried in an oven at 60°C. The pH of the waste water was determined after filtration of the suspended dust. The filtrate is also analysed on BTEX-(Benzene, toluene, ethylbenzene and o,m and p-Xylene), with a GC-MS with a purge and trap analysis according to ISO 15680.
The concentration of mineral oil was determined by mixing the effluent of the filtration with dichloromethane, in which the oils will dissolve. The water and dichloromethane were subsequently separated. The dried dust, of which the mass was already determined, was added to the dichloromethane and hydrocarbons were extracted ultrasonically. Subsequently the dichloromethane was filtered from the dust. Water that was left in the dichloromethane was removed by sodium sulphate. The dichloromethane was substituted by toluene, by adding toluene and evaporating dichloromethane. This sample was cleaned by a florisil-column to remove polar compounds, which may influence the measurements. The florisil-column is rinsed with additional toluene to remove non-polar compounds which were inadvertently captured. The toluene solution (with a known volume) was analysed for oils in a GC-FID based on ISO 9377-2. It was also analysed in a GC-MS analysis according to ISO 11338-2 for polycyclic aromatic hydrocarbons.

Table 6.3 shows the main pollutants. If Table 6.3 is compared to Table 6.2, it becomes clear that the waste water stream needs thorough cleaning before the waste water is clean enough to be discharged.

| Table 6.3 Main data on the composition of the untreated waste water stream of SJAC-ESP |
|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| Condensed water stream 1 from cooler | Condensed water stream 2 from cooler | Water from ESP |
| Concentration suspended dust in water [mg/kg] | 112 | 307 | 720 |
| Concentration mineral oil in water [mg/kg] | 21 | 72 | 76 |
| pH | 3.3 | 2.9 | 4.2 |

Table 6.4 shows the amount of BTEX in the waste water stream as determined by GC-MS. The concentration of BTEX is low with in total approximately 4 ppb (on mass basis) of BTEX.

| Table 6.4 Concentration BTEX in waste water stream of SJAC in [μg/kg] |
|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| Condensed water stream 1 from cooler | Condensed water stream 2 from cooler | Water from ESP |
| Benzene | 1.25 | 2.53 | 1.57 |
| Toluene | 0.28 | 0.60 | 0.40 |
| Ethylbenzene | 0.06 | 0.07 | 0.10 |
| o-Xylene | 0.10 | 0.21 | 0.13 |
| m/p-Xylene | 0.16 | 0.32 | 0.20 |
| Total BTEX | 1.85 | 3.73 | 2.40 |

The tars, shown in Table 6.5, are all present in small quantities except for phenanthrene, pyrene and fluoranthene. According to [Kado et al., 2005] these are the main hydrocarbons in particulate matter. Because only phenanthrene can be found in the gas phase in significant quantity according to amongst others [Kado et al., 2005], particulate matter is the most likely source of hydrocarbons found in water. The total concentration PAH is 0.2 ppm at most, of which phenanthrene accounts for approximately 50%.
### Table 6.5 Concentration polycyclic aromatic hydrocarbon (PAH) in waste water stream of SJAC-ESP in [μg/kg]

<table>
<thead>
<tr>
<th></th>
<th>Condensed water stream 1 from cooler</th>
<th>Condensed water stream 2 from cooler</th>
<th>Water from ESP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acenaphthene</td>
<td>0.24</td>
<td>0.58</td>
<td>0.97</td>
</tr>
<tr>
<td>Acenaphthalene</td>
<td>0.47</td>
<td>2.32</td>
<td>0.71</td>
</tr>
<tr>
<td>Anthracene</td>
<td>0.27</td>
<td>1.24</td>
<td>0.39</td>
</tr>
<tr>
<td>Benzo(a)anthracene</td>
<td>0.53</td>
<td>0.90</td>
<td>1.39</td>
</tr>
<tr>
<td>Benzo(a)pyrene</td>
<td>0.03</td>
<td>0.04</td>
<td>0.05</td>
</tr>
<tr>
<td>Benzo(b)fluoranthene</td>
<td>0.74</td>
<td>0.80</td>
<td>1.53</td>
</tr>
<tr>
<td>Benzo(ghi)perylene</td>
<td>0.16</td>
<td>0.13</td>
<td>0.33</td>
</tr>
<tr>
<td>Benzo(k)fluoranthene</td>
<td>0.21</td>
<td>0.22</td>
<td>0.33</td>
</tr>
<tr>
<td>Chrysene</td>
<td>1.47</td>
<td>2.26</td>
<td>3.78</td>
</tr>
<tr>
<td>Dibenz(ah)anthracene</td>
<td>&lt;detection limit</td>
<td>&lt;detection limit</td>
<td>&lt;detection limit</td>
</tr>
<tr>
<td>Fluoranthene</td>
<td>11.3</td>
<td>22.2</td>
<td>31.6</td>
</tr>
<tr>
<td>Fluorene</td>
<td>2.85</td>
<td>9.29</td>
<td>12.5</td>
</tr>
<tr>
<td>Indeno(123-cd)pyrene</td>
<td>0.15</td>
<td>0.11</td>
<td>0.23</td>
</tr>
<tr>
<td>Naphtalene</td>
<td>5.5</td>
<td>6.1</td>
<td>6.3</td>
</tr>
<tr>
<td>Phenanthrene</td>
<td>29.2</td>
<td>87.0</td>
<td>102</td>
</tr>
<tr>
<td>Pyrene</td>
<td>15.2</td>
<td>27.3</td>
<td>43.2</td>
</tr>
<tr>
<td>Total analysed PAH</td>
<td>68.3</td>
<td>161</td>
<td>205</td>
</tr>
</tbody>
</table>

In addition to these measurements, the sum of sulphate and hydrogen sulphate concentration in the waste water streams during the measurements at the Royal Netherlands Naval College, see section §5.3.3, were determined as a mass of sulphates. Before the determination of the concentration of sulphates, all the hydrogen sulphate was converted to sulphate by the addition of a base. The maximum concentration with MGO fuel was 388.7 mg/kg, and the minimum with MGO fuel was 75.3 mg/kg. For intermediate fuel oil, the minimum measured concentration was 170.5 mg/kg and the maximum measured concentration was 3925 mg/kg. These concentrations are so high that it cannot be assumed anymore that all measured sulphate was present in the form of sulphate. Some hydrogen sulphate should be present. The equilibrium between hydrogen sulphate (HSO$_4^-$) and sulphate (SO$_4^{2-}$) is given by formula 6.3.1

$$K_Z = \frac{[H^+][SO_4^{2-}]}{[HSO_4^-]} \quad \text{Formula 6.3.1}$$

With $K$ an equilibrium constant which is $1.0 \times 10^{-2}$ [Verkerk et al., 1998] and the values between the brackets expressed as a molar concentration in water.

A molar balance dictates that the measured sulphate concentration (expressed in molar form) is the sum of sulphate and hydrogen sulphate. Note that it is assumed that all sulphuric acid is converted to hydrogen sulphate and sulphate. Given the strong acid that sulphuric acid is, this assumption seems fair.

$$[m_{\text{sulphates}}] = [SO_4^{2-}] + [HSO_4^-] \quad \text{Formula 6.3.2}$$

In addition to this the total charge of the water should equal zero, as is expressed in formula 6.3.3.

$$[H^+] - [HSO_4^-] - 2\cdot[SO_4^{2-}] = 0 \quad \text{Formula 6.3.3}$$

With help of formulae 6.3.1 through 6.3.3 all unknowns can be solved. After some mathematics two solutions are obtained, shown in formula 6.3.4.
Analysis of the solution shows that only the solution with the minus root is physically possible, as with the positive root the calculated concentration hydrogen sulphate is higher than the measured concentration sulphates, which would mean that a negative concentration sulphates would be present. From formula 6.3.4 with the negative root the concentration $H^+$ can be determined, by substitution of formula 6.3.2 in formula 6.3.3, leading to formula 6.3.5.

$$[H^+] = 2[m_{\text{sulphates}}] - [HSO_4^-]$$  \hspace{1cm} \text{Formula 6.3.5}

Subsequently the pH can be calculated with formula 6.3.6.

$$pH = -10 \log ([H^+])$$  \hspace{1cm} \text{Formula 6.3.6}

With help of these formulae, the pH of the waste water during measurements at the Royal Netherlands Naval College can be calculated. The calculated pH in the water from the cooler ranged between 2.1 and 2.9 for marine gas oils with 0.1 and 0.16% sulphur and between 1.3 and 2.5 for a heavy fuel oil containing 1.5% sulphur. The water is most acidic at low loads, probably due to the longer contact time between water and sulphur oxides. The weighted average, based on the weighted average concentration $[H^+]$, is a pH of 1.9 for a fuel with 1.5% sulphur.

In order to make a design for the water treatment it is necessary to translate these measurements to values that are to be expected on large scale. This is not particularly exact science. The main values are shown in Table 6.6. The assumptions and calculations that led to Table 6.6 are summarised below the table. Note that the water stream from direct contact cooling already fulfils the expected requirements for oil and dust. Only the pH will probably exceed regulation.

<table>
<thead>
<tr>
<th>Table 6.6: Predicted values for the main pollutants on industrial scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water stream from indirect contact cooling</td>
</tr>
<tr>
<td>Concentration suspended dust in water [mg/kg]</td>
</tr>
<tr>
<td>Concentration mineral oil in water [mg/kg]</td>
</tr>
<tr>
<td>pH</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

As a basis for this calculation a gas composition needs to be calculated. Data from the manual from a MAN 9L 40/54 engine are used [MAN, 2004]. Although the gas compositions from different engines are rather similar, this specific engine was chosen, because it is representative for ferries, according to [Brussen et al., 2006]. Ferries are foreseen as a market for first implementation, as will be discussed in Chapter 7.

The concentration suspended dust in water is calculated from assuming a percentage of the particulate matter removed. It is assumed that the engine emits 0.5 g/kWh particulate matter, of which 34% is removed in the cooler, which was equal to the particulate matter removal at full load as found in the experiments discussed in section §5.3.3.3. It is subsequently assumed that 70% of the remaining particulate matter is removed in the ESP.
This is converted to a concentration by calculating the water stream at every place. It is assumed that the temperature after cooling is 30°C and that the steam injection rate is 3% of the exhaust gas flow. Steam temperature is assumed to be 110°C. For indirect contact cooling it is calculated how much water would condense given the gas composition (0.09 kg/kWh). For direct contact cooling the amount of injected water is added. This amount is calculated by assuming that the water that is released in the sea can only be 5°C warmer than the temperature of the sea. This way the amount of injected water is 67 kg/kWh. It is assumed that the percentage of condensate removed in the ESP is proportional to the percentage of removed particulate matter mass. The amount of water from the ESP is then approximately 0.018 kg/kWh.

It is assumed that the measured hydrocarbon concentration in the effluent from the ESP was representative for the water from ESP, further it is assumed that the highest measured concentration hydrocarbons in the effluent from the coolers is representative for the concentration mineral oil in the condensate from indirect contact cooling. It is assumed that the absolute value of removed mineral oil by indirect contact cooling is also removed by direct contact cooling. As a result the concentration of hydrocarbons is much lower.

It is assumed that the engine is using a fuel with 3% sulphur. Two assumptions have been used to calculate the pH of water from cooling. It is assumed that the minimum pH is 2, because the pH is limited by the reaction time. It is noted that the measured pH at low loads was even lower with a fuel with 1.5% sulphur, but the average of 1.9 is close to the assumed pH of 2. Additionally the worst case scenario from water treatment point of view is assumed, i.e. all SOx present in the exhaust gas is removed in the cooler, as long as the water from the cooler is not more acidic than 2. It is assumed that the water from the ESP has a pH of 2.

§6.3.3 Particulate matter removal from waste water

The particulate matter concentration in water is from chemical engineering point of view dilute to very dilute with a particulate matter to water ratio of 1.3% for water from the ESP, 0.19% for water from the cooler and 2.5 ppm for the direct contact cooler. Several options to clean particles are available. The most important types of separation processes for cleaning the waste water from particulate matter are settling, either by gravity or centrifugal force, filtration and evaporation of water. Information on the three separation processes can be found in any good chemical engineering design book, e.g. [Sinnott, 1999] and [Perry and Green, 1984]. However to judge the viability of the settling-like separation processes the settling characteristics of the particles need to be determined first.

The settling characteristics of the particles depend on their radius. This is, however, not really straightforward, and care should be taken with the diameter, i.e. mobility or aerodynamic diameter (see section §2.2.3), that is used to describe the settling characteristics. In this study the mobility diameter was measured, and it is used as the basis for deriving the settling characteristics. In the following consideration it is assumed that the particles do not coagulate.
The mobility diameter directly correlates with the drag force, and the mechanical mobility \( B \), i.e. the velocity divided by the drag force of a particle. The mechanical mobility is given by formula 6.3.7.

\[
B \equiv \frac{u}{F_D} = \frac{C_c}{6\pi\mu \cdot r_B}
\]

With \( B \) the mechanical mobility, \( u \) the velocity, \( F_D \) the drag force, \( \mu \) the dynamic viscosity, \( r_B \) the mobility radius, and \( C_c \) the Cunningham correction factor. For water, in its liquid state, the mean free path is considerably smaller than the particle and \( C_c \) is approximately 1. With the help of the mobility the settling velocity can be described by the mobility times the settling force.

\[
\begin{align*}
\frac{u_{set}}{F_{set} \cdot B}
\end{align*}
\]

with subscript set for settling.

The settling force is the gravitational force minus the force due to buoyancy of the particle.

\[
\begin{align*}
\bar{F}_{set} &= \bar{F}_{grav} - \bar{F}_{Buoyancy} \quad \text{Formula 6.3.9}
\end{align*}
\]

with subscripts, grav for gravitational force and subscript Buoyancy for buoyancy. The gravitational force is described by the mass of the particle times the gravitational constant. The buoyancy force is based on the mass of the medium that is displaced by the volume of the particle. In water this is equal to the density of water times the displaced volume.

\[
\begin{align*}
\bar{F}_{set} &= m_p \cdot g - \rho_{H_2O} \cdot V_{disp} \cdot g
\end{align*}
\]

With \( m_p \) the mass of the particle and \( \rho_{H_2O} \) the density of water, and \( V_{disp} \) the displaced volume by the particle. The displaced volume by the particle is equal to the mass of the particle divided by the density of the particle including enclosed empty spaces. If we assume that those empty spaces are non-existent the density is the density of the particle material, as illustrated in formula 6.3.11. Note that the density of the particle material is not the same density as the mobility density derived by for example [Park et al., 2003].

\[
\begin{align*}
V_{disp} &= \frac{m_p}{\rho_{p,\text{encl}}} = \frac{m_p}{\rho_p}
\end{align*}
\]

Combining formulae 6.3.7 to 6.3.11 leads to formula 6.3.12 for the settling velocity of the particles.

\[
\begin{align*}
u_{set} &= \frac{\left(1 - \frac{\rho_{H_2O}}{\rho_p}\right) \cdot m_p \cdot g}{6\pi\mu \cdot r_B}
\end{align*}
\]

Using the mobility equivalent density this can be rewritten to formula 6.3.13

\[
\begin{align*}
u_{set} &= \frac{2\left(\rho_p - \rho_{H_2O}\right) \cdot \frac{\rho_B}{\rho_p} \cdot g \cdot r_B^2}{9\mu}
\end{align*}
\]

With \( \rho_B \) the mobility equivalent density. Note that even if the mobility equivalent density is equal to or lower than the density of water a particle will settle, as long as the bulk density of the particle material including enclosed spaces is larger than the density of water. If the bulk density of the particle material including enclosed spaces is lighter than water, the particle will float.
Using formula 2.2.13 after [Park et al., 2003] for the mobility equivalent density, leads to formula 6.3.14 for the settling velocity.

\[
 u_{set} = \left(1 - \frac{\rho_{H_2O}}{\rho_p}\right) \frac{2g}{9\pi\mu} \cdot 2.82 \cdot 10^{-2} \cdot r_B^{1.33}
\]

The settling velocity in water for a soot particle with a diameter of 100 nanometres is $2 \times 10^{-9}$ m/s, assuming the particle material is graphite, which has a bulk density of 2100 kg/m$^3$ [Verkerk et al., 1998]. From these data it becomes clear that settling under gravity is very slow, and a settling tank seems impractical for cleaning of the waste water from particulate matter. Note that if it was assumed that the particle contained enclosed spaces, the settling velocity would have been even lower. [Sinnott, 1999] shows that removal of those small particles by means of centrifugal device leads to a feasible device, as long as water flows are not too large.

§6.3.4 Water treatment systems

Given the fact that the actual discharge limits are not known it is not possible to select the best system for water treatment. Therefore, several different concepts are proposed to clean the waste water streams.

The first proposed waste water treatment system is a system in which a large fraction of the waste water is evaporated after the pH of the water is adjusted. At atmospheric pressure the heat necessary for evaporation should come from the exhaust gas or an additional heat source. If the water is evaporated at reduced pressures, the engine cooling water could be used as a heat source too. Sufficient energy is available in the engine cooling water to evaporate all waste water from the ESP and the formed condensate with indirect cooling. The engine cooling water does not contain enough energy to evaporate all the water from a direct contact cooler. With evaporation on atmospheric pressure the steam can directly be used. With evaporation at reduced pressures the evaporated water can be used as boiler feeding water. A drawback of evaporation is that solids and salts that crystallise can cause fouling on the heat exchanging surface. This system can only be used if the fouling issue is properly addressed. One option to address this issue is a scraped surface heat exchanger.

A system of hydrocyclones and a settling tank is used in sea water scrubbers of MES [MES, 2005b], see Figure 6.2. It is unclear how the pH of the scrubbing liquid is controlled. It could simply be done by varying the amount of purged water. The pH could also be controlled actively; in this case it would be preferred to adjust the pH before scrubbing. After the scrubber and degassing, the waste water is cleaned from solids by a series of primary hydrocyclones. The water stream without solids is cleaned by a series of secondary hydrocyclones from oil. The water from the secondary hydrocyclones is clean enough to be discharged. The solid-containing water fraction and the oil-containing fraction are further separated in a settling tank. Note that this is not very effective for fine dust, as commented in §6.3.3. The water from the settling tank is added to the waste water from the scrubber.
A third system could consist of pH-neutralisation, followed by a filter to remove the particulate matter. Subsequently the hydrocarbons are separated from the water by a hydrocyclone. Optionally the clean water is subsequently polished of hydrocarbons by an active coal filter, see Figure 6.3. Instead of hydrocyclones the water stream may also be concentrated by a very fine cross-flow filter, which rejects oils. Depending on the water concentration in the oily stream from the hydrocyclone, the oily stream is stored or further cleaned and concentrated by the bilge water system. This system is more suitable for the concentrated stream from indirect contact cooling.

For the direct contact cooler the water stream is very diluted. In fact it is predicted that the effluent water will fulfil the waste water limits already without treatment besides the pH (see §6.3.2 for more details). However, it is recommended to polish the water by filtration and an active coal filter, see Figure 6.4. Note that for the material of the direct contact cooler it might be more appropriate to adjust the pH before the direct contact cooler.

Alternatively the water from direct contact cooling could be recycled by cooling the water, as is done in the case of the MES scrubber. A purge is used to control the amount of water
in the loop and to control the concentration of pollutants. If necessary the water is filtered from large particles to prevent cooler fouling. If necessary, clean water can be added to the loop.

Figure 6.5 Water treatment of direct contact cooling with water recycling

The last option is to simply store the waste water and hand it in for treatment on shore, or alternatively neutralise it first, store it and then treat it on shore. The latter option is used in Chapter 7 when the costs of operation for inland ships and ferries are calculated.
Chapter 7. Market potential
§7.1 Introduction

In this chapter the market potential of the SJAC-ESP is investigated. First the two most interesting markets are identified. Subsequently for those two cases a study is made with regard to dimensions, additional power consumption and economics. In each case the SJAC-ESP is compared to competitive technology in order to assess the viability of the SJAC-ESP system for each market.

§7.2 Identification of markets

§7.2.1 Introduction

When identifying markets for emission technology in shipping, a distinction can be made between inland shipping and sea shipping, because the ships are very different. Besides this they use significantly different fuels, and the stakeholders in legislation and incentives have different roles. However, many of the other stakeholders are the same in both markets, and therefore they are treated together. Based on the stakeholder analysis two markets will be chosen for which an economic study will be done.

§7.2.2 Stakeholder analysis

All relevant stakeholders have been identified. They are placed in four categories. The first category is named legislation and incentives, as the stakeholders may require or provide a financial encouragement for the application of particulate matter reducing devices. The second category is the category implementation. This category lists the most important type of vessels the SJAC-ESP could be installed in. The specifics of these ships are elaborated below Figure 7.1. The third category is named industry, and contains all the relevant bodies involved in building and operating a ship. The last category are the non-governmental organisations, who have influence because they represent a large number of people, or other stakeholders mentioned in other categories. One important stakeholder is not named specifically, and that is the crew of the ship. The crew that is present, and the skills of the crew depend on the specifics of ship operation, and hence ship type. It is assumed that the SJAC-ESP does not require any specially trained crew-members, or additional crew.
The legislation and legislative bodies were already discussed in detail in section §2.5, they are only summarised here. However, besides legislation, financial incentives can be used to encourage ship owners to use cleaner technology.

- **CCNR**: The Central Commission for Navigation on the river Rhine, sets regulations for inland shipping on the river Rhine and its tributaries. Therefore it is an important body for long-distance inland shipping. The CCNR was the first body to issue legislation with regard to emission from inland shipping. The CCNR and European Union try to harmonise their legislation.

- **European Union**: The European Union has two roles. For inland shipping they make legislation for the entire European Union. The European Union tries to harmonise its inland shipping legislation with the CCNR legislation. The European Union does not pose legislation on sea shipping, although it could do that for ships in its waters and under its flag. At the moment the global approach with IMO is preferred.

- The IMO is the international body that can set binding emission limits, for all its member states, which makes it almost global legislation.

- Flag states may participate in CCNR, European Union and IMO, and have this way influence on legislation. Flag states could also use incentives to encourage the use of cleaner ships, by differentiating fairway fees, and, if arranged nationally, harbour fees. Flag states could also provide subsidies for the installation of clean technology.

- Port authorities could differentiate the harbour fees. They could also facilitate the use of shore-power etc.

### Implementation

- **Inland ferries**: for inland waters ferries have to compete with road transport and are therefore fast-ferries. They use high-speed four-stroke engines.

- **Inland cargo/container ships**: New ships use four-stroke engines. Old ships may have a (small) two-stroke engine. It is most likely that in due time these engines
will be replaced by a four-stroke engine. This is not straightforward, however, and
the propeller may need to be changed or a gearbox is required. From a historic
viewpoint the engines are relatively small, with engine powers of approximately
500 kW. New ships have engine power up to 2 MW.

- **Yachts**: People using yachts are luxury-minded. If a yacht is privately owned,
owners are willing to spend extra money for something they consider to be a
nuisance. This could be soot on deck or a visible plume. Yachts could be a niche-
market. Before installation the technology should be proven, though. Typically
yachts have a twin-engine configuration with high-speed diesel engines of
approximately 2 MW each. Note that the yachting sector is actively looking into
emission reduction. In fact ECN has been approached by the yachting sector and
asked questions with regard to the development phase of the SJAC-ESP.

- **Ferries**: Ferries transport a large number of people. The business is sensitive to
public opinion. Because ferries tend to travel the same route, they are also
sensitive to financial drivers, like differentiated fairway and port fees. Ferries are
often in a “harbour”, so the waste water of SJAC-ESP could be stored on board
and treated on land. It is a very interesting niche-market. Engines are often large
four-stroke engines. Note that a sea water scrubber was demonstrated on the Pride
of Kent (a ferry of P&O on the route Calais-Dover).

- **Dredgers**: Sustainable image is important. However, they are complex ships, and
they are not preferred for market introduction.

- **Tug boats**: Generally small boats with large engines. Space may be an issue, and
reliability is crucial. Tug boats are interesting, but not for first implementation.

- **Cruise ships**: These ships transport people, who are on holiday. Experience is a
key-word for the passengers. This means that this market segment is sensitive to
public opinion. Diesel engines are either large four-stroke engines, or two-stroke
ingines. It is an interesting market. Note that the Holland America line installed a
sea water scrubber on the MS Zaandam.

- **Navy vessels**: The navy may be exempted from emission limits, but they still want
to fulfil regulation, because of their reputation. Additional driver for them could be
visibility or a reduced thermal footprint. Other drivers involve health aspects of the
crew. The Netherlands Navy has already installed a particulate matter reduction
technique. A navy vessel could be interesting for a first demonstration, due to the
presence of a large trained technical staff.

- **Cargo ships/ Tankers**: They are most likely to follow the emission regulation.
Technology should be proven before application. Transportation is global.

- **Fishing boats**: They will just follow the emission regulation. They are sensitive to
differentiated fairway and port fees. Engines are generally rather small; up to 2
MW.

**Industry**

- **Design office**: The (re)design of ships is done in a design and engineering office.
They either are a part of a ship yard or operate independently. The design and
engineering offices have a large impact on detailed engineering, and hence are
important for application of the SJAC-ESP.

- **Ship yard**: The role of ship yards vary. They can build the entire ship, and install
or facilitate the installation of equipment by an auxiliary equipment suppliers. In
recent years ship yards function more and more as main contractors, who contract out more and more work.

- Auxiliary equipment supplier: They supply auxiliary equipment. Of more particular interest are the equipment suppliers who supply auxiliary equipment for the engine, either to the engine manufacturer or the ship yard. They might also install their equipment.

- Engine manufacturers: A distinction should be made between two-stroke and four-stroke engines. Modern 2-stroke engines are only used in sea shipping. Virtually all 2-stroke engines stem from MAN B&W and Wärtsilä, although they are built by licensees. Four-stroke engines are made by a larger variety of manufacturers. Large four-stroke engines of the medium speed type are produced by Wärtsilä, Caterpillar, MAN B&W and MTU. Smaller high-speed engines (max. 2 MW) are delivered by a large number of companies, amongst others Volvo (Penta), MTU, Cummins, Caterpillar, MAN and Scania. High-speed engines are often derived from trucking or rail transport. Almost all 2- and 4-stroke engines in the marine market are turbocharged.

- Classification societies: They ensure that ships are safely designed and fulfil all regulations. This includes fulfilment of emission regulations. It is important that a classification society states that a technology is safe and acknowledges the environmental performance.

- Oil Companies: They used to offer one type of inland shipping fuel, unless specifically requested differently, see ship owners. They seem to be diversifying their portfolio for inland shipping fuel slowly. Oil companies are just following legislation and demand. However, especially for sea shipping a change in the refining process may have huge implications on the availability and price of certain fuels, and vice versa a large change to the maximum fuel sulphur level in fuel may have a large influence on the availability and price of fuel. With the timely announcement of new fuel regulations IMO tries to tackle the availability issue, but fuel price is expected to increase significantly.

**Non Governmental Organisations (NGOs)**

- Ship owners: Ship owners are often organised in associations. For inland shipping in the Netherlands the main organisation is the CBRB (Centraal Bureau voor de Rijn en binnenvaart). A number of members in the Rotterdam area have taken the initiative to use low sulphur fuel (max. 50 ppm). [CBRB, 2007]. Intertanko is an example for sea shipping. It is the INTERnational association of independent TANKer Owners. The mission of Intertanko is to “provide leadership to the Tanker Industry in serving the world with the safe, environmentally sound and efficient seaborne transportation of oil, gas and chemical products.” This includes striving for “zero pollution” [Intertanko, 2007]. Another example is Intercargo. Intertanko wrote proposals for emission reduction which were discussed within IMO and led to the new proposals to drastically lower sulphur content in sea shipping, as discussed in chapter 2.

- IACS: International agency for classification societies.

- CONCAWE: CONservation of Clean Air and Water in Europe. The oil companies’ European association for environment, health and safety in refining and distribution. They participate in research projects.
• Euromot: The European Association of Internal Combustion Engine Manufacturers. It contains all major players for the shipping business (except for Mitsubishi Heavy Industries, who have a minor position in the sea shipping business).

• NGOs that defend the environment and champion a healthy, just and peaceful world, like FoE (Friends of the Earth) and Greenpeace. They could both be strong advocates for the technology as well as big opponents because of the water streams that are generated. FoE sent a proposal to IMO for new emission limits, which had to be discussed by the members of IMO, thereby influencing the debate.

§7.2.3 Most promising markets for PM-reducing equipment
The inland shipping market is very interesting for PM-reducing devices, because the maximum emission of PM is regulated. The direct competition with road transport means that inland shipping cannot afford to lose its emission advantage. Besides this, subsidies are given to build cleaner ships.

In sea shipping four interesting markets can be discerned for first market introduction. They are ferries, cruise ships, naval vessels and to a lesser extent yachts. For a first market introduction ferries are most interesting, because they generally sail on one route. This facilitates disposal of waste water on shore, and makes ferries susceptible to local regulations or incentives. Because ferries generally sail from one city to another over relatively short distances, reducing exhaust gas emissions of ferries will result in improved air quality of those cities. Besides this, it makes good publicity for the owner of the ferry.

§7.3 Inland shipping

§7.3.1 System dimensions
The system is dimensioned based on data measured on the test engine at the Netherlands Defence Academy, but assuming an engine output of 1000 kW. This engine was a MAN 4L 20/27. Engines from the same family are used in inland shipping in powerful tug boats [Stapersma, 2005]. The most important engine characteristics for sizing are summarised in Table 7.1.

<table>
<thead>
<tr>
<th>Engine parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine power</td>
<td>1000 kW</td>
</tr>
<tr>
<td>Fuel consumption</td>
<td>278 g/kWh</td>
</tr>
<tr>
<td>Exhaust gas flow</td>
<td>10.8 kg/kWh</td>
</tr>
<tr>
<td>Exhaust gas temperature</td>
<td>412°C</td>
</tr>
<tr>
<td>Overall air excess ratio</td>
<td>2.5</td>
</tr>
</tbody>
</table>

All four identified system options for cooling mentioned in Table 6.1 are studied. The options with low-pressure steam will be abbreviated as LP-steam, and options with high-pressure steam as HP-steam. The option with a heat exchanger is abbreviated as HEX. These abbreviations are useful for representation in tables and figures.

As guidelines for dimensioning the system the following is assumed:
• The mass ratio between injected steam and exhaust gas flow is 0.03.
Boiler feed water is 30°C and temperature of injected steam is 110°C for low-pressure steam, and 120°C when the steam is taken half way the turbine.

The exhaust gas temperature before steam injection is 30°C.

The inlet temperature of the coolant is 25°C.

The coolant exit temperature can be maximally 5°C higher than the inlet temperature.

The overall heat transfer coefficient of all heat exchangers is assumed to be 50 W/(m²K).

The condenser is assumed to be a plate-and-frame heat exchanger, all other indirect contact coolers are floating head shell-and-tube heat exchangers.

The velocity through the ESP is 0.74 m/s. The flow and temperature of air along the insulators of the ESP are proportional to the experimental situation, i.e. a gas temperature of 60°C and an air flow of 0.83 l/s for each ESP with the size of a Euromate SFE 50.

Heat capacity of the exhaust gas is calculated from the gas composition and temperature dependant heat capacity values from [Smith et al., 1996].

The exhaust gas temperature after cooling for steam generation cannot be lower than 190°C, because of the possibility of condensation of sulphuric acid and hydrocarbons.

When the temperature is lowered below 190°C in a heat exchanger, the construction material is C20-steel, a corrosive resistant, but expensive, material. Other used materials are RVS-316.

The pressure of the “high-pressure steam” is assumed to be 10 bar at a temperature of 240°C. The name high-pressure steam is used to contrast with low-pressure steam at atmospheric pressure. In this case low-pressure steam is taken out of the power turbine at a temperature of 120°C. The steam pressure after expansion is determined by 90% vapour after isentropic expansion. Due to the non-ideal expansion the actual vapour content is slightly higher. Isentropic efficiency of the steam turbine is 85%. The electrical efficiency of the generator attached to the steam turbine is 85% as well.

All pump duties are calculated assuming a head of 10 metres, an isentropic efficiency of 75% and an electric efficiency of 80%, unless noted differently.

The direct contact coolers are calculated with a Sulzer Mellapak 452Y structured packing, with a surface of 452 m²/m³. The program Sulpak has been used to determine the diameter of the column within the operating window. A minimum packing height is subsequently calculated assuming an overall heat transfer coefficient of 5.2 W/(m²K). The actual packing height is then obtained by filling out the minimum packing height in Sulpak, and is used in the tables describing the components. The height used in the economic calculation (see the next section) is the packing height plus 1 metre. Because no structured stainless steel packing was available in ICARUS, stainless steel cascade rings have been used instead for the economic calculation.

Reverse osmosis is scaled from SWRO-series of General electric for water containing up to 45 000 ppm NaCl [GE, 2008]

The cyclone dimensions are calculated based on scaling of a high-efficiency cyclone from [Sinnott, 1993]
Figure 7.2 Overview important variables in design for an inland ship
The high-pressure steam cycle is shown in Figure 7.3. A simple process flow diagram is shown in Figure 7.2.

![Figure 7.3 Dimensions for high-pressure cycle inland shipping](image)

Dimensions of the main components are summarised in Table 7.2, whereas the power consuming and producing devices are listed in Table 7.3. As a reference for dimensions of the heat exchangers heat duty and heat exchanger surface area are listed. For the direct contact cooler heat duty and approximate dimensions are given. Approximate dimensions are also given for the cyclone. Characteristic surfaces are given for the freshwater generator by reverse osmosis and the ESP; the membrane surface and collection surface respectively. Note that equipment for treatment of the waste water is not included. It is assumed, that the water can be stored or is clean enough to be discharged after neutralisation.

**Table 7.2: Main components and their size for a SJAC-ESP for a 1 MW engine**

<table>
<thead>
<tr>
<th>Component</th>
<th>LP-steam HEX</th>
<th>LP-steam direct contact cooler</th>
<th>HP-steam HEX</th>
<th>HP-steam direct contact cooler</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat exchanger LP-steam</td>
<td>15 m², 231 kW</td>
<td>15 m², 231 kW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat exchanger HP-steam</td>
<td></td>
<td></td>
<td>98 m², 738 kW</td>
<td>98 m², 738 kW</td>
</tr>
<tr>
<td>Heat exchanger for temperature before steam injection</td>
<td>307 m², 1142 kW</td>
<td></td>
<td>284 m², 635 kW</td>
<td></td>
</tr>
<tr>
<td>Direct contact cooler</td>
<td>d=2 m, h=2.13 m, 1142 kW</td>
<td></td>
<td></td>
<td>d=1.75 m, h=2.556 m, 635 kW</td>
</tr>
<tr>
<td>Cyclone</td>
<td>d=1.3 m, h=5.2 m, 369 m²</td>
<td>d=1.3 m, h=5.2 m, 369 m²</td>
<td>d=1.3 m, h=5.2 m, 369 m²</td>
<td></td>
</tr>
<tr>
<td>ESP</td>
<td>Aₑ=369 m²</td>
<td>Aₑ=369 m²</td>
<td>Aₑ=369 m²</td>
<td></td>
</tr>
<tr>
<td>Air compressor</td>
<td>39 m³/h, 2 kW</td>
<td>39 m³/h, 2 kW</td>
<td>39 m³/h, 2 kW</td>
<td></td>
</tr>
<tr>
<td>Steam turbine</td>
<td>10 bar steam, 86 kW</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Condenser</td>
<td>191 m², 476 kW</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water maker (reverse osmosis)</td>
<td>Aₑ=23 m²</td>
<td>Aₑ=23 m²</td>
<td>Aₑ=23 m²</td>
<td></td>
</tr>
</tbody>
</table>

**Table 7.3: Power consuming and producing devices for a SJAC-ESP for a 1 MW engine**

<table>
<thead>
<tr>
<th>Component</th>
<th>LP-steam HEX</th>
<th>LP-steam direct contact cooler</th>
<th>HP-steam HEX</th>
<th>HP-steam direct contact cooler</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condenser</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water maker (reverse osmosis)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Note that the cyclone is rather large, and given the fact that it acts as a guard it should be considered to omit the cyclone.

<table>
<thead>
<tr>
<th></th>
<th>LP-steam HEX</th>
<th>LP-steam direct contact cooler</th>
<th>HP-steam HEX</th>
<th>HP-steam direct contact cooler</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiler feed water pump</td>
<td>0.02</td>
<td>0.02</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Steam turbine</td>
<td></td>
<td>-86</td>
<td>-86</td>
<td></td>
</tr>
<tr>
<td>Cooling water pump</td>
<td>9.1</td>
<td>9.1</td>
<td>5.1</td>
<td>5.1</td>
</tr>
<tr>
<td>Pump for condenser</td>
<td></td>
<td>3.8</td>
<td>3.8</td>
<td></td>
</tr>
<tr>
<td>Pump for reverse osmosis</td>
<td>3.9</td>
<td>3.9</td>
<td>3.9</td>
<td>3.9</td>
</tr>
<tr>
<td>ESP</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Air compressor</td>
<td>1.6</td>
<td>1.6</td>
<td>1.6</td>
<td>1.6</td>
</tr>
<tr>
<td>Tracing</td>
<td>4.8</td>
<td>4.8</td>
<td>4.8</td>
<td>4.8</td>
</tr>
<tr>
<td>Total power consumption</td>
<td>20</td>
<td>20</td>
<td>-66</td>
<td>-66</td>
</tr>
</tbody>
</table>

From Table 7.3 it becomes clear that the fuel consumption increases with 2% for the SJAC-ESP with low pressure steam and decreases with over 6% when a power turbine is used to convert pressurised steam into electricity. Approximately 50% of the energy consumption is stemming from pumps for coolant, and 25% of the electricity consumption is determined by energy required for tracing. The low-value heat for tracing could alternatively be provided by the engine cooling water.

§7.3.2 Capital and operational expenditure

In order to investigate the financial implications of the SJAC-ESP first the price of the purchased process equipment (PPE) is determined. From the PPE the capital expenditure (CAPEX) is derived, i.e. the amount of money allocated to build the project. Subsequently operational expenditure (OPEX) and yearly costs are determined.

The approach for the calculation of the CAPEX is an approach used in cost estimations in chemical engineering; see for example [Peters and Timmerhaus, 1991]. The used approach is typically accurate within 30%. The cost factors are chosen based on the typical range of relative contributions of each cost factor. Some costs are only representative for new chemical plants or large extensions of a chemical plant, such as buildings and buildings services or yard improvement. In this cost estimation the costs for a m² or a m³ on a ship are not included, nor additional structures that are necessary to support the installation. The used factors are shown in Table 7.4. Factors that are zero are omitted in later tables that present a cost break-down.
### Table 7.4 Assumptions for estimation of the capital expenditure

<table>
<thead>
<tr>
<th>I: Direct costs</th>
<th>2.49*PPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purchased process equipment (PPE)</td>
<td>PPE</td>
</tr>
<tr>
<td>Installation costs</td>
<td>0.30*PPE</td>
</tr>
<tr>
<td>Instrumentation and control</td>
<td>0.13*PPE</td>
</tr>
<tr>
<td>Piping</td>
<td>0.66*PPE</td>
</tr>
<tr>
<td>Electrical</td>
<td>0.10*PPE</td>
</tr>
<tr>
<td>Buildings and building services</td>
<td>0</td>
</tr>
<tr>
<td>Yard improvements</td>
<td>0</td>
</tr>
<tr>
<td>Additional investment in service facilities</td>
<td>0.30*PPE</td>
</tr>
<tr>
<td>Land</td>
<td>0</td>
</tr>
<tr>
<td>II: Indirect costs</td>
<td>0.77*PPE</td>
</tr>
<tr>
<td>Engineering and supervision</td>
<td>0.25*PPE</td>
</tr>
<tr>
<td>Construction general expenses</td>
<td>0.08*Direct costs</td>
</tr>
<tr>
<td>Contractor’s fee</td>
<td>0.03*Direct costs</td>
</tr>
<tr>
<td>Contingency</td>
<td>0.08*(Direct costs+other indirect costs)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fixed capital investment (FCI)</th>
<th>3.26*PPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working capital</td>
<td>0.12*fixed capital investment</td>
</tr>
<tr>
<td>Investment costs</td>
<td>0.08*fixed capital investment</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Capital expenditure (CAPEX)</th>
<th>3.91*PPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCI + working capital and investment costs</td>
<td></td>
</tr>
</tbody>
</table>

The operating expenditure is calculated on the approach of [Peters and Timmerhaus, 1991] cost estimation for chemical engineering, too. However several costs are not applicable for the case of a ship. It is assumed that no additional operator is necessary for the SJAC-ESP. This means that no additional overhead is necessary to support the operator. Subsequently it is assumed that the owner of the aftertreatment device will not have laboratory charges. Overhead for the entire plant is also absent. It is assumed that no additional expenses are made for the general expenses, as mentioned in [Peters and Timmerhaus, 1991]. No costs for patents and royalties are assumed. The operational cost breakdown is shown in Table 7.5. All factors assumed zero, are omitted in later tables for the cost breakdown.
Table 7.5 Assumptions for calculation of operational expenditure

<table>
<thead>
<tr>
<th>Direct Production Cost</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Consumables</td>
<td>Different fuel price and neutralising agent</td>
</tr>
<tr>
<td>Utilities (electricity)</td>
<td>Additional fuel consumption due to electricity use</td>
</tr>
<tr>
<td>Waste water</td>
<td>Cost of waste water not fulfilling emission criteria after neutralising</td>
</tr>
<tr>
<td>Maintenance &amp; Repairs</td>
<td>5% of FCI</td>
</tr>
<tr>
<td>Operating Supplies</td>
<td>1% of FCI</td>
</tr>
<tr>
<td>Patents &amp; Royalties</td>
<td>0</td>
</tr>
<tr>
<td>Operating Labour</td>
<td>0</td>
</tr>
<tr>
<td>Supervision/Clerical</td>
<td>0</td>
</tr>
<tr>
<td>Laboratory Charges</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fixed Charges</th>
<th>(β∗0.03)FCI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Charge</td>
<td>β FCI</td>
</tr>
<tr>
<td>Local Taxes</td>
<td>2% of FCI</td>
</tr>
<tr>
<td>Insurance</td>
<td>1% of FCI</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Plant Overhead</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Expenses</td>
<td>0</td>
</tr>
<tr>
<td>Marketing, sales, distribution</td>
<td>0</td>
</tr>
<tr>
<td>Administrative</td>
<td>0</td>
</tr>
<tr>
<td>R&amp;D</td>
<td>0</td>
</tr>
</tbody>
</table>

| OPEX | Sum of direct production cost, fixed charges, plant overhead and general expenses |

The capital charge is the yearly payment to compensate the value of the invested money at the end of the economic lifetime. The value of the invested money at the end of the economic period, is the present value of the money plus the accumulated interest over the economic lifetime. It is expressed in formula 7.3.1

\[ \text{Val}_{\text{economic lifetime}} = (1 + i)^{\text{years}} \cdot \text{FCI} \]  

\[ \text{Formula 7.3.1} \]

\[ \text{Val}_{\text{economic lifetime}} \] is the value at the end of the economic lifetime, ‘i’ the interest defined as a ratio, years the duration of the economic lifetime, and FCI the fixed capital investment. The FCI is used, because in cost engineering it is assumed that the investment cost and working capital are not permanently allocated. The value after the end of the economic lifetime is paid yearly in constant portions over the period of the economic lifetime. The first portion will still accumulate the lifetime minus 1 years of interest, whereas the last period will not accumulate any interest. This is expressed in formula 7.3.2.

\[ \text{Val}_{\text{economic lifetime}} = \text{Yearly payment} \cdot \left[ (1 + i)^{\text{years} - 1} + \ldots + (1 + i)^{1} \right] \]  

\[ \text{Formula 7.3.2} \]

With yearly payment the yearly payment, or in other words the capital charge. If formula 7.3.2 is multiplied by \((1+i)\) on both sides of the formula, and the resulting \((1+i)\text{Val}_{\text{economic lifetime}}\) is rewritten to \(i\text{Val}_{\text{economic lifetime}}\) plus the right hand term of formula 7.3.2, formula 7.3.3 can be obtained.

\[ \text{Yearly payment} = \frac{i}{(1 + i)^{\text{years}} - 1} \cdot \text{Val}_{\text{economic lifetime}} \]  

\[ \text{Formula 7.3.3} \]

The capital charge was defined by the fixed capital cost multiplied by a factor \(\beta\). \(\beta\) is then calculated by formula 7.3.4.

\[ \beta = \frac{\text{Yearly payment}}{\text{FCI}} = \frac{i \cdot (1 + i)^{\text{years}}}{(1 + i)^{\text{years}} - 1} = \frac{i}{1 - (1 + i)^{-\text{years}}} \]  

\[ \text{Formula 7.3.4} \]
For the capital charge it is assumed that depreciation is linear over 10 years with an interest of 7 percent, which means that the factor $\beta$ is 0.142.

Table 7.6 shows the price estimations for several devices. Almost all prices are stemming from Aspen Icarus Process Evaluator, a price estimation programme for chemical engineers. Exceptions are the price for the ESP, which is based on a quotation (for a different number of ESPs) and the price of the reverse osmosis for boiler feed water which is based on listed prices in [DACE, 2006]. Construction material is RVS-316, except for the heat exchanger for the temperature before steam injection, which is made of more corrosive resistant C20-steel. Note that the price for tracing is not included. It is assumed to be included in the capital expenditure in the factor for piping.

Table 7.6: Price estimation for equipment of 1 MW SJAC-ESP in euro

<table>
<thead>
<tr>
<th></th>
<th>LP-steam HEX</th>
<th>LP-steam direct contact cooler</th>
<th>HP-steam HEX</th>
<th>HP-steam direct contact cooler</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat exchanger LP-steam</td>
<td>22 600</td>
<td>22 600</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat exchanger HP-steam</td>
<td></td>
<td></td>
<td>58 800</td>
<td>58 800</td>
</tr>
<tr>
<td>Heat exchanger for temperature before steam injection</td>
<td>218 900</td>
<td>206 700</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct contact cooler</td>
<td></td>
<td>124 700</td>
<td>113 300</td>
<td></td>
</tr>
<tr>
<td>Cyclone</td>
<td>50 400</td>
<td>50 400</td>
<td>50 400</td>
<td>50 400</td>
</tr>
<tr>
<td>Steam turbine</td>
<td></td>
<td></td>
<td>42 800</td>
<td>42 800</td>
</tr>
<tr>
<td>Condenser</td>
<td></td>
<td>19 513</td>
<td>19 513</td>
<td></td>
</tr>
<tr>
<td>Fresh water generator (reverse osmosis, incl. pump)</td>
<td>27 583</td>
<td>27 583</td>
<td>27 583</td>
<td>27 583</td>
</tr>
<tr>
<td>Boiler feed water pump</td>
<td>3 230</td>
<td>3 230</td>
<td>12 600</td>
<td>12 600</td>
</tr>
<tr>
<td>Cooling water pump</td>
<td>12 500</td>
<td>12 500</td>
<td>8 400</td>
<td>8 400</td>
</tr>
<tr>
<td>Pump for condenser</td>
<td></td>
<td></td>
<td>8 800</td>
<td>8 800</td>
</tr>
<tr>
<td>ESP</td>
<td>74 475</td>
<td>74 475</td>
<td>74 475</td>
<td>74 475</td>
</tr>
<tr>
<td>Air compressor</td>
<td>6 800</td>
<td>6 800</td>
<td>6 800</td>
<td>6 800</td>
</tr>
<tr>
<td><strong>Total price equipment</strong></td>
<td><strong>416 489</strong></td>
<td><strong>322 289</strong></td>
<td><strong>516 872</strong></td>
<td><strong>423 472</strong></td>
</tr>
</tbody>
</table>

From Table 7.6 it becomes clear that the main cost driver is the heat exchanger or direct contact cooler. Another important cost driver is the ESP. Together these two cover over 46% of the costs in the case of high-pressure steam generation and over 63% in the case of low-pressure steam generation.

From the price of the equipment the capital expenditure (CAPEX) and the fixed capital investment (FCI), i.e. the money that is permanently allocated to the project, can be estimated, see Table 7.7.
Table 7.7 Estimation of fixed capital investment and capital expenditure for 1 MW SJAC-ESP [*1000 euro]

<table>
<thead>
<tr>
<th></th>
<th>LP-steam HEX</th>
<th>LP-steam direct contact</th>
<th>HP-steam HEX</th>
<th>HP-steam direct contact</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. Direct Costs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Purchased Process Equipment</td>
<td>416</td>
<td>322</td>
<td>517</td>
<td>423</td>
</tr>
<tr>
<td>Installation of Purchased Equipment</td>
<td>125</td>
<td>97</td>
<td>155</td>
<td>127</td>
</tr>
<tr>
<td>Instrumentation and Controls</td>
<td>54</td>
<td>42</td>
<td>67</td>
<td>55</td>
</tr>
<tr>
<td>Piping</td>
<td>275</td>
<td>213</td>
<td>341</td>
<td>279</td>
</tr>
<tr>
<td>Electrical</td>
<td>42</td>
<td>32</td>
<td>52</td>
<td>42</td>
</tr>
<tr>
<td>Service facilities</td>
<td>125</td>
<td>97</td>
<td>155</td>
<td>127</td>
</tr>
<tr>
<td>II. Indirect Costs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Engineering and Supervision</td>
<td>104</td>
<td>81</td>
<td>129</td>
<td>106</td>
</tr>
<tr>
<td>Construction General Expenses</td>
<td>83</td>
<td>64</td>
<td>103</td>
<td>84</td>
</tr>
<tr>
<td>Contractor's fee</td>
<td>31</td>
<td>24</td>
<td>39</td>
<td>32</td>
</tr>
<tr>
<td>Contingency</td>
<td>100</td>
<td>78</td>
<td>125</td>
<td>102</td>
</tr>
<tr>
<td>III. Fixed Capital Investment (FCI)</td>
<td>1356</td>
<td>1049</td>
<td>1682</td>
<td>1378</td>
</tr>
<tr>
<td>IV. Working Capital</td>
<td>163</td>
<td>126</td>
<td>202</td>
<td>165</td>
</tr>
<tr>
<td>V. Start-up Costs</td>
<td>109</td>
<td>84</td>
<td>135</td>
<td>110</td>
</tr>
<tr>
<td>CAPEX</td>
<td>1627</td>
<td>1259</td>
<td>2019</td>
<td>1654</td>
</tr>
</tbody>
</table>

Even more interesting than the capital expenditure is the yearly costs of operation, called operational expenditure (OPEX), see Table 7.9. In order to calculate the OPEX an assumption of the load profile is necessary. Other assumptions are fuel and neutralising agent price, as well as the price for waste water. They are listed in Table 7.8.

Table 7.8 Costs of variables in OPEX calculation for inland shipping case

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent of time operational</td>
<td>33%</td>
</tr>
<tr>
<td>Average engine power</td>
<td>85%</td>
</tr>
<tr>
<td>Fuel price MGO</td>
<td>€609 per 1000 kg [Bunkerworld.com, 2008]</td>
</tr>
<tr>
<td>Efficiency electrical generator</td>
<td>85%</td>
</tr>
<tr>
<td>Price for waste water</td>
<td>€0.30 per litre waste water</td>
</tr>
<tr>
<td>Price neutralising agent (NaOH)</td>
<td>€266 per 1000 kg [ICIS, 2007]</td>
</tr>
</tbody>
</table>

The waste water is priced based on the costs to hand in 1000 litres of neutralised waste water, which is €0.30 per litre of waste water. For this economic calculation NaOH is used as a neutralising agent. Possibly the use of CaCO₃ is cheaper for neutralisation, but it has the drawback that it is heavier. As the waste water from a direct contact cooler seems to fulfil specifications for overboard discharge after neutralisation the costs of waste water for direct contact coolers is only based on waste water from the ESP, whereas in the case of the (indirect) heat exchanger the condensate also needs to be cleaned. From Table 7.9 it becomes clear that the main cost drivers are the costs for water treatment and the capital charge and other investment related costs.
Table 7.9 Estimation operational expenditure for SJAC-ESP for a 1 MW engine [*1000 euro/year]

<table>
<thead>
<tr>
<th></th>
<th>LP-steam HEX</th>
<th>LP-steam direct contact</th>
<th>HP-steam HEX</th>
<th>HP-steam direct contact</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Direct Production Cost</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Consumables</td>
<td>0.05</td>
<td>22</td>
<td>0.05</td>
<td>22</td>
</tr>
<tr>
<td>Utilities (electricity)</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Waste water</td>
<td>149</td>
<td>17</td>
<td>148</td>
<td>16</td>
</tr>
<tr>
<td>Maintenance &amp; Repairs</td>
<td>68</td>
<td>52</td>
<td>84</td>
<td>69</td>
</tr>
<tr>
<td>Operating Supplies</td>
<td>14</td>
<td>10</td>
<td>17</td>
<td>14</td>
</tr>
<tr>
<td><strong>Fixed Charges</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capital Charge (depreciation)</td>
<td>193</td>
<td>149</td>
<td>240</td>
<td>196</td>
</tr>
<tr>
<td>Local Taxes</td>
<td>27</td>
<td>21</td>
<td>34</td>
<td>28</td>
</tr>
<tr>
<td>Insurance</td>
<td>14</td>
<td>10</td>
<td>17</td>
<td>14</td>
</tr>
<tr>
<td><strong>OPEX</strong></td>
<td>474</td>
<td>293</td>
<td>549</td>
<td>368</td>
</tr>
</tbody>
</table>

The operational expenditure does not paint the entire picture, as in the case of high pressure steam, the system generates revenues of €42 000 per year, in the form of non-consumed fuel for electricity generation. However, this still means that the cheapest option for inland shipping is the configuration with low-pressure steam and a direct contact cooler. Note that the actual value of the OPEX is an estimation, and will strongly depend on whether or not it is allowed to discharge the water from the direct contact cooler and the actual costs of the waste water or the waste water treatment system.

The yearly costs for removing a kg of PM are summarised in Table 7.10 for the four different SJAC-ESP concepts, assuming an engine emission of 0.3 g PM/kWh, 34% PM removal in the coolers and 70% (of the remaining PM) in the ESP. Additional power consumption has been penalised by an additional particulate matter emission and net electricity generation has been rewarded with an avoided particulate matter emission. The emission for the required electrical power is calculated by assuming a generator efficiency of 85%. The emission of the generator is assumed to be equal to the main engine after particulate matter reduction.

Table 7.10: Costs to remove a kg PM with a SJAC-ESP on 1 MW-scale

<table>
<thead>
<tr>
<th></th>
<th>LP-steam HEX</th>
<th>LP-steam direct contact</th>
<th>HP-steam HEX</th>
<th>HP-steam direct contact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost to remove a kg PM</td>
<td>€806 per kg PM</td>
<td>€498 per kg PM</td>
<td>€841 per kg PM</td>
<td>€541 per kg PM</td>
</tr>
</tbody>
</table>

§7.3.3 Comparison with competitive technologies

For inland shipping the main competitor for the SJAC-ESP is a particulate matter filter. In order to be able to use a particulate matter filter the shipping sector should switch to fuel at the same standard as road transport. The costs for a particulate matter filter with low-sulphur fuel for inland shipping are estimated within the CREATING-project, based on extrapolation from data for road transport and different assumptions with regard to depreciation. In this case data is used from actual costs as made for installation on the inland ship Victoria, in the cleanest ship project [clearestship.eu, 2008]. This way the reliability of the cost estimation is improved.
The fixed capital investment, i.e. including equipment and engineering, for the particulate matter installation on board of Victoria was €278 per kW installed engine power [Blaauw, 2008]. The installation on the Victoria is a particulate matter filter that is regenerated by an auxiliary diesel burner. For the cost estimation it is assumed that the additional fuel consumption is 2%, as is expected in the cleanest ship project, and as expected by [Karila et al., 2004]. The price difference between fuel with 0.2% sulphur and 50 ppm sulphur is 25 to 30 euro per 1000 litres [Scheepvaartkrant, 2007]; 25 euro per 1000 litres is used in this calculation. For time in operation and depreciation the same assumptions are used as those for the SJAC-ESP. This leads to an estimated OPEX and, since there are no revenues, yearly costs of €90 per kW installed per year. For the cost break-down see Table 7.11. The cost per kg PM not emitted is €136/kg PM not emitted, assuming that 90% is removed of an engine emission of 0.3 g PM/kWh.

Table 7.11 Predicted operational expenditure PM-filter with low-sulphur fuel [\*1000 euro/year]

<table>
<thead>
<tr>
<th>Share in OPEX</th>
<th>PM-filter low-sulphur fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Production Cost</td>
<td></td>
</tr>
<tr>
<td>Consumables</td>
<td>29%</td>
</tr>
<tr>
<td>Utilities (electricity)</td>
<td>0%</td>
</tr>
<tr>
<td>Waste water</td>
<td>0%</td>
</tr>
<tr>
<td>Maintenance &amp; Repairs</td>
<td>5% of FCI</td>
</tr>
<tr>
<td>Operating Supplies</td>
<td>1% of FCI</td>
</tr>
<tr>
<td>Fixed Charges</td>
<td></td>
</tr>
<tr>
<td>Capital Charge</td>
<td>$\beta \cdot$ FCI</td>
</tr>
<tr>
<td>Local Taxes</td>
<td>2% of FCI</td>
</tr>
<tr>
<td>Insurance</td>
<td>1% of FCI</td>
</tr>
<tr>
<td>OPEX</td>
<td>100%</td>
</tr>
</tbody>
</table>

An important prerequisite for the application of PM-filters is that low-sulphur is available everywhere. Note that if low-sulphur fuel is obligatory for inland ships the OPEX reduces to €73 per kW installed per year, of which only €9 per kW installed per year is related to consumption of consumables. Note that if the PM-filter is made in small series the costs will most likely reduce.

If the SJAC-ESP and a PM-filter with low-sulphur fuel are compared it is from economical and environmental perspective better to use a PM-filter with low-sulphur fuel.

§7.4 Ferry

§7.4.1 System dimensions

In order to dimension the SJAC-ESP for a ferry and estimate the costs the same example of a ferry is used as in [Brussen et al. 2006], where it is used to estimate the emissions from shipping. This ferry is powered by 4 MAN 9L40/54 main propulsion engines with a power output of 6480 kW each. The ferry has four diesel powered generators, which are left out of the considerations in this section.
Table 7.12 Engine data main propulsion ferry

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine power per engine</td>
<td>6480 kW</td>
</tr>
<tr>
<td>Number of engines</td>
<td>4</td>
</tr>
<tr>
<td>Fuel consumption</td>
<td>181 g/kWh</td>
</tr>
<tr>
<td>Exhaust gas flow</td>
<td>7.13 kg/kWh</td>
</tr>
<tr>
<td>Exhaust gas temperature</td>
<td>350°C</td>
</tr>
<tr>
<td>Overall air excess ratio</td>
<td>2.66</td>
</tr>
</tbody>
</table>

All four identified system options for cooling mentioned in Table 6.1 are studied.

As guidelines for dimensioning the system the following is assumed:

- The mass ratio between injected steam and exhaust gas flow is 0.03.
- Boiler feed water is 30°C and temperature of injected steam is 110°C for low-pressure steam, and 120°C when the steam is taken halfway the turbine.
- The exhaust gas temperature before steam injection is 30°C.
- The inlet temperature of the coolant is 25°C.
- The coolant exit temperature can be maximally 5°C higher than the inlet temperature.
- The overall heat transfer coefficient of all heat exchangers is assumed to be 50 W/(m²K).
- The condenser is assumed to be a plate-and-frame heat exchanger, all other indirect contact coolers are floating head shell-and-tube heat exchangers.
- The velocity through the ESP is 0.74 m/s. The flow and temperature of air along the insulators of the ESP are proportional to the experimental situation, i.e. a gas temperature of 60°C and an air flow of 0.83 l/s for each ESP with the size of a Euromate SFE 50.
- Heat capacity of the exhaust gas is calculated from the gas composition and temperature dependant heat capacity values from [Smith et al., 1996].
- The exhaust gas temperature after steam generation cannot be lower than 190°C, because of the possibility of condensation of sulphuric acid and hydrocarbons.
- The pressure of the “high-pressure steam” is assumed to be 10 bar at a temperature of 240°C. The name high-pressure steam is used to contrast with low-pressure steam at atmospheric pressure. In this case low-pressure steam is taken out of the power turbine at a temperature of 120°C. The steam pressure after expansion is determined by 90% vapour after isentropic expansion. Due to the non-ideal expansion the actual vapour content is slightly higher. Isentropic efficiency of the steam turbine is 85%. The electrical efficiency of the generator attached to the steam turbine is 85% as well.
- All pump duties are calculated assuming a head of 10 metres, an isentropic efficiency of 75% and an electric efficiency of 80%, unless noted differently.
- The direct contact cooler are calculated with a Sulzer Mellapak plus 452Y structured packing, with a surface of 452 m²/m³. The program Sulpak, which can be obtained from Sulzer, has been used to determine the diameter of the column within the operating window. A minimum packing height is subsequently calculated assuming an overall heat transfer coefficient of 5.2 W/(m²K). The actual packing height is then obtained by filling out the minimum packing height in Sulpak, and is used in the tables describing the components. The height used in
the economic calculation (see the next section) is the packing height plus 1 metre. Because no structured stainless steel packing was available in ICARUS, stainless steel cascade rings have been used instead for the economic calculation.

- Reverse osmosis is scaled from SWRO-series of General electric for water containing up to 45 000 ppm NaCl [GE, 2008].
- The cyclone dimensions are calculated based on scaling of a high-efficiency cyclone from [Sinnott, 1993]

A simple process flow diagram is shown in Figure 7.5. Because the exhaust gas flows of the engines cannot be combined, all components that are in the exhaust gas flow are needed four times, whereas the high-pressure steam cycle, air compressor and boiler feed water treatment can be executed once. The high-pressure steam cycle is shown in Figure 7.4.

![Figure 7.4 High-pressure cycle for four engines. Note that the capacity of cooler E-104 is the capacity of all four heat exchangers](image)
Figure 7.5 Overview of design for one engine of a ferry
Dimensions of the main components are summarised in Table 7.13, whereas the power consuming and producing devices are listed in Table 7.14. As a reference for dimensions for the heat exchangers heat duty and heat exchanger surface area are listed. For the direct contact cooler heat duty and approximate dimensions are given. Approximate dimensions are also given for the cyclone. Characteristic surfaces are given for the freshwater generator by reverse osmosis and the ESP; the membrane surface and collection surface respectively. Note that no equipment for the treatment of waste water treatment is included. It is assumed, that the water can be stored on board or is clean enough to be discharged after neutralisation.

Table 7.13 Main components and their size for a SJAC-ESP on board of a ferry

<table>
<thead>
<tr>
<th>Heat exchanger LP-steam</th>
<th>LP-steam HEX</th>
<th>Heat exchanger HP-steam</th>
<th>HP-steam HEX</th>
<th>Heat exchanger for temperature before steam injection</th>
<th>HP-steam HEX</th>
<th>Direct contact cooler</th>
<th>LP-steam direct contact cooler</th>
<th>HP-steam direct contact cooler</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4* 81 m², 4*990 kW</td>
<td></td>
<td>4* 365 m², 4*2254 kW</td>
<td>d=4 m, h=2.13 m, 4*3849 kW</td>
<td></td>
<td>d=3.5 m, h=2.556 m, 4*2254 kW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat exchanger LP-steam</td>
<td>4* 81 m², 4*990 kW</td>
<td></td>
<td>4* 365 m², 4*2254 kW</td>
<td>d=4 m, h=2.13 m, 4*3849 kW</td>
<td></td>
<td>d=3.5 m, h=2.556 m, 4*2254 kW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat exchanger HP-steam</td>
<td>4* 1228 m², 4*3849 kW</td>
<td>4* 365 m², 4*2254 kW</td>
<td>d=3.5 m, h=2.556 m, 4*2254 kW</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat exchanger for temperature before steam injection</td>
<td>4* 1228 m², 4*3849 kW</td>
<td>4* 365 m², 4*2254 kW</td>
<td>d=3.5 m, h=2.556 m, 4*2254 kW</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct contact cooler</td>
<td>d=4 m, h=2.13 m, 4*3849 kW</td>
<td></td>
<td>4* 365 m², 4*2254 kW</td>
<td>d=3.5 m, h=2.556 m, 4*2254 kW</td>
<td></td>
<td>d=3.5 m, h=2.556 m, 4*2254 kW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cyclone</td>
<td>12* d=1.5 m, h=6 m</td>
<td>12* d=1.5 m, h=6 m</td>
<td>12* d=1.5 m, h=6 m</td>
<td>12* d=1.5 m, h=6 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ESP</td>
<td>4* A_c=1562 m²</td>
<td>4* A_c=1562 m²</td>
<td>4* A_c=1562 m²</td>
<td>4* A_c=1562 m²</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air compressor</td>
<td>660 m³/h, 1.5 bar</td>
<td>660 m³/h, 1.5 bar</td>
<td>660 m³/h, 1.5 bar</td>
<td>660 m³/h, 1.5 bar</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steam turbine</td>
<td>10 bar steam, 954 kW</td>
<td>10 bar steam, 954 kW</td>
<td>10 bar steam, 954 kW</td>
<td>10 bar steam, 954 kW</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Condenser</td>
<td>1848 m², 4621 kW</td>
<td>1848 m², 4621 kW</td>
<td>1848 m², 4621 kW</td>
<td>1848 m², 4621 kW</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fresh water generator (reverse osmosis)</td>
<td>Am=394 m²</td>
<td>Am=394 m²</td>
<td>Am=394 m²</td>
<td>Am=394 m²</td>
<td>Am=394 m²</td>
<td>Am=394 m²</td>
<td>Am=394 m²</td>
<td>Am=394 m²</td>
</tr>
</tbody>
</table>

Note that three cyclones per engine were necessary, because one large cyclone per engine could not separate the droplets from the cooler effectively. Given the fact that the cyclones act as guards, it should be seriously considered to omit them.
Table 7.14 Electrical power consumption (+) and production (-) in kW for SJAC-ESP on board of a ferry

<table>
<thead>
<tr>
<th></th>
<th>LP-steam HEX</th>
<th>LP-steam direct contact cooler</th>
<th>HP-steam HEX</th>
<th>HP-steam direct contact cooler</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiler feed water pump</td>
<td>4*0.06</td>
<td>4*0.06</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Steam turbine</td>
<td>-5.4</td>
<td>-5.4</td>
<td>4*21</td>
<td>4*21</td>
</tr>
<tr>
<td>Cooling water pump</td>
<td>4*31</td>
<td>4*31</td>
<td>4*21</td>
<td>4*21</td>
</tr>
<tr>
<td>Pump for condenser</td>
<td>37</td>
<td>37</td>
<td>4*21</td>
<td>4*21</td>
</tr>
<tr>
<td>Pump for reverse osmosis</td>
<td>63</td>
<td>63</td>
<td>63</td>
<td>63</td>
</tr>
<tr>
<td>ESP</td>
<td>4*2</td>
<td>4*2</td>
<td>4*2</td>
<td>4*2</td>
</tr>
<tr>
<td>Air compressor</td>
<td>27</td>
<td>27</td>
<td>27</td>
<td>27</td>
</tr>
<tr>
<td>Tracing</td>
<td>4*20</td>
<td>4*20</td>
<td>4*20</td>
<td>4*20</td>
</tr>
<tr>
<td><strong>Total power consumption</strong></td>
<td><strong>302</strong></td>
<td><strong>302</strong></td>
<td><strong>-651</strong></td>
<td><strong>-651</strong></td>
</tr>
</tbody>
</table>

Again the power consumption is almost fully determined by energy required for pumps for cooling water and reverse osmosis and energy required for tracing. The energy for the latter can also be derived from engine coolant water or exhaust gas heat (in the case of low-pressure steam).

§7.4.2 Capital and operational expenditure

In order to investigate the financial implications of the SJAC-ESP first the price for the purchased equipment is determined. From this price the capital expenditure is derived. Subsequently operational expenditure and yearly costs are derived. Table 7.15 shows the price estimations for several devices. The prices listed are for one device, and for the total price of the equipment the price per device should be multiplied by the number of devices necessary. Almost all prices are stemming from Aspen Icarus Process Evaluator, a price estimation programme for chemical engineers. Exceptions are the price for the ESP, which is based on a quotation (for a different number of ESPs) and the price of the reverse osmosis for boiler feed water which is based on listed prices in [DACE, 2006].

Table 7.15: Price estimation for equipment of SJAC-ESP for main propulsion of a ferry in euro. Costs are given per device, except for the total price, which is for four engines.

<table>
<thead>
<tr>
<th></th>
<th>Number</th>
<th>LP-steam HEX</th>
<th>LP-steam direct contact cooler</th>
<th>HP-steam HEX</th>
<th>HP-steam direct contact cooler</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat exchanger LP-steam</td>
<td>4</td>
<td>51 900</td>
<td>51 900</td>
<td>4</td>
<td>146 600</td>
</tr>
<tr>
<td>Heat exchanger HP-steam</td>
<td>4</td>
<td>146 600</td>
<td>146 600</td>
<td>4</td>
<td>146 600</td>
</tr>
<tr>
<td>Heat exchanger to temperature</td>
<td>4</td>
<td>813 200</td>
<td>776 700</td>
<td>4</td>
<td>813 200</td>
</tr>
<tr>
<td>before steam injection</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct contact cooler</td>
<td>4</td>
<td>283 000</td>
<td>266 800</td>
<td>4</td>
<td>283 000</td>
</tr>
<tr>
<td>Cyclone</td>
<td>12</td>
<td>62 200</td>
<td>62 200</td>
<td>12</td>
<td>62 200</td>
</tr>
<tr>
<td>Steam turbine</td>
<td>1</td>
<td>577 600</td>
<td>577 600</td>
<td>1</td>
<td>577 600</td>
</tr>
<tr>
<td>Condenser</td>
<td>1</td>
<td>188 796</td>
<td>188 796</td>
<td>1</td>
<td>188 796</td>
</tr>
<tr>
<td>Fresh water generator (reverse osmosis, incl. pump)</td>
<td>1</td>
<td>183 536</td>
<td>183 536</td>
<td>1</td>
<td>183 536</td>
</tr>
<tr>
<td>Boiler feed water</td>
<td>4/1/1/1</td>
<td>3 450</td>
<td>3 450</td>
<td>14 200</td>
<td>14 200</td>
</tr>
<tr>
<td>Cooling water pump</td>
<td>4</td>
<td>18 000</td>
<td>18 000</td>
<td>4</td>
<td>18 000</td>
</tr>
<tr>
<td>Pump for condenser</td>
<td>1</td>
<td>47 700</td>
<td>47 700</td>
<td>1</td>
<td>47 700</td>
</tr>
<tr>
<td>ESP</td>
<td>4</td>
<td>315 087</td>
<td>315 087</td>
<td>4</td>
<td>315 087</td>
</tr>
<tr>
<td>Air compressor</td>
<td>1</td>
<td>14 600</td>
<td>14 600</td>
<td>1</td>
<td>14 600</td>
</tr>
<tr>
<td><strong>Total price equipment</strong></td>
<td><strong>5 751 085</strong></td>
<td><strong>3 630 285</strong></td>
<td><strong>6 772 881</strong></td>
<td><strong>4 735 281</strong></td>
<td><strong>6 772 881</strong></td>
</tr>
</tbody>
</table>

From Table 7.15 it becomes clear that the heat exchangers to cool the exhaust gas to the required temperature before steam injection determine the cost very significantly. It is
crucial to realise that by allowing a higher exhaust gas temperature the SJAC-ESP could be cheaper. The influence of the temperature before steam injection is elaborated in section §7.4.3.

From the price of the equipment the capital expenditure (CAPEX) and the fixed capital investment (FCI), i.e. the money that is permanently allocated to the project, can be derived. The approach is the same as the approach for inland shipping, which is discussed in section §7.3.2 and summarised in Table 7.4.

Table 7.16 Fixed capital investment and capital expenditure for SJAC-ESP for the main propulsion of a ferry [*1000 euro]

<table>
<thead>
<tr>
<th></th>
<th>LP-steam HEX</th>
<th>LP-steam direct contact cooling</th>
<th>HP-steam HEX</th>
<th>HP-steam direct contact cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>I. Direct Costs</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Purchased Process Equipment</td>
<td>5 751</td>
<td>3 630</td>
<td>6 773</td>
<td>4 735</td>
</tr>
<tr>
<td>Installation of Purchased Equipment</td>
<td>1 725</td>
<td>1 089</td>
<td>2 032</td>
<td>1 421</td>
</tr>
<tr>
<td>Instrumentation and Controls</td>
<td>748</td>
<td>472</td>
<td>880</td>
<td>616</td>
</tr>
<tr>
<td>Piping</td>
<td>3 796</td>
<td>2 396</td>
<td>4 470</td>
<td>3 125</td>
</tr>
<tr>
<td>Electrical</td>
<td>357</td>
<td>363</td>
<td>677</td>
<td>474</td>
</tr>
<tr>
<td>Service facilities</td>
<td>1 725</td>
<td>1 089</td>
<td>2 032</td>
<td>1 421</td>
</tr>
<tr>
<td><strong>II. Indirect Costs</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Engineering and Supervision</td>
<td>1 438</td>
<td>908</td>
<td>1 693</td>
<td>1 184</td>
</tr>
<tr>
<td>Construction General Expenses</td>
<td>1 146</td>
<td>723</td>
<td>1 349</td>
<td>943</td>
</tr>
<tr>
<td>Contractor's fee</td>
<td>430</td>
<td>271</td>
<td>506</td>
<td>354</td>
</tr>
<tr>
<td>Contingency</td>
<td>1 387</td>
<td>875</td>
<td>1 633</td>
<td>1 142</td>
</tr>
<tr>
<td><strong>III. FCI = I+II</strong></td>
<td>18 720</td>
<td>11 817</td>
<td>22 046</td>
<td>15 413</td>
</tr>
<tr>
<td><strong>IV. Working Capital</strong></td>
<td>2 246</td>
<td>1 418</td>
<td>2 645</td>
<td>1 850</td>
</tr>
<tr>
<td><strong>V. Start-up Costs</strong></td>
<td>1 498</td>
<td>945</td>
<td>1 764</td>
<td>1 233</td>
</tr>
<tr>
<td><strong>CAPEX</strong></td>
<td>22 464</td>
<td>14 180</td>
<td>26 455</td>
<td>18 496</td>
</tr>
</tbody>
</table>

The CAPEX for the SJAC-ESP with low-pressure steam and direct contact cooler is €547 per kW installed engine power.

From the fixed capital investment and the consumption of consumables and utilities the operational expenditure can be calculated. The used approach for OPEX calculation is shown in Table 7.5. Additional data for the OPEX calculation are shown in Table 7.17.

Table 7.17 Costs of variables in OPEX calculation for a ferry

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent of time operational</td>
<td>50%</td>
</tr>
<tr>
<td>Average engine power</td>
<td>85%</td>
</tr>
<tr>
<td>Fuel price IFO</td>
<td>€296 per 1000 kg [Bunkerworld.com, 2008]</td>
</tr>
<tr>
<td>Fuel price low-sulphur IFO</td>
<td>€317 per 1000 kg [Bunkerworld.com, 2008]</td>
</tr>
<tr>
<td>Efficiency electrical generator</td>
<td>85%</td>
</tr>
<tr>
<td>Price for waste water</td>
<td>€0.30 per litre waste water</td>
</tr>
<tr>
<td>Price neutralising agent (NaOH)</td>
<td>€266 per 1000 kg [ICIS, 2007]</td>
</tr>
</tbody>
</table>

Initially it is assumed that the ferry is outside a SECA and is fuelled with IFO. It is assumed that the water from the direct water contact cooler is clean enough to be discharged after neutralisation. It is assumed that water, which is not clean enough to be discharged, is disposed of on land after neutralisation. It is assumed that the waste water can maximally be as acidic as a pH of two, before it is discharged, see section §6.3.2. This means that more SOx will be emitted in the case of a heat exchanger than in the case of a direct heat exchanger, because the condensate formed in the heat exchanger will be saturated with
H₂SO₄. Therefore less H₂SO₄ needs to be neutralised with a heat exchanger than with a direct contact cooler, and the costs under consumables will be lower.

Table 7.18 Operational expenditure SJAC-ESP on board of a ferry [*1000 euro per year]

<table>
<thead>
<tr>
<th></th>
<th>LP-steam HEX</th>
<th>LP-steam direct contact cooling</th>
<th>HP-steam HEX</th>
<th>HP-steam direct contact cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Production Cost</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Consumables</td>
<td>1</td>
<td>348</td>
<td>1</td>
<td>348</td>
</tr>
<tr>
<td>Utilities (electricity)</td>
<td>71</td>
<td>71</td>
<td>71</td>
<td>71</td>
</tr>
<tr>
<td>Waste water</td>
<td>3 044</td>
<td>453</td>
<td>3 014</td>
<td>422</td>
</tr>
<tr>
<td>Maintenance &amp; Repairs</td>
<td>936</td>
<td>591</td>
<td>1 102</td>
<td>771</td>
</tr>
<tr>
<td>Operating Supplies</td>
<td>187</td>
<td>118</td>
<td>220</td>
<td>154</td>
</tr>
<tr>
<td>Fixed Charges</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capital Charge</td>
<td>2 665</td>
<td>1 682</td>
<td>3 139</td>
<td>2 195</td>
</tr>
<tr>
<td>Local Taxes</td>
<td>374</td>
<td>236</td>
<td>441</td>
<td>308</td>
</tr>
<tr>
<td>Insurance</td>
<td>187</td>
<td>118</td>
<td>220</td>
<td>154</td>
</tr>
<tr>
<td>OPEX</td>
<td>7 467</td>
<td>3 618</td>
<td>8 209</td>
<td>4 423</td>
</tr>
</tbody>
</table>

Table 7.18 shows that the majority of the OPEX is stemming from the capital charge and the waste water. Quite some financial space is available to install a waste water treatment plant. Even for the direct contact cooling case a financial space of 4 million euro is available, which means that 0.8 million euro is available for the equipment. This space gets larger when the ferry is used more than anticipated in this OPEX calculation.

The operational expenditure is not equal to the yearly costs, which in this thesis are defined as the operational expenditure minus the yearly revenues. It is expected that the direct contact cooler will reduce the sulphur oxide emissions to a level below using a fuel with 1.5% sulphur. This is a fair assumption, because a direct contact cooler will act as a scrubber. This means that the SJAC-ESP with direct contact cooler will be earning some of its costs back, when a ship is sailing in a SECA. This is listed under revenues. On the other hand the costs are slightly higher for the SJAC-ESP with a heat exchanger when it is sailing in a SECA, because the electricity costs are slightly higher, because the fuel is more expensive. For this calculation the fuel prices are used as illustrated in Table 7.17.

Table 7.19 Yearly revenues and costs SJAC-ESP dependant on time spend in SECA [*1000 euro]

<table>
<thead>
<tr>
<th>% of operational hours in SECA-&gt;</th>
<th>0%</th>
<th>25%</th>
<th>50%</th>
<th>75%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>yearly revenues</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LP-steam HEX</td>
<td>0</td>
<td>-1</td>
<td>-3</td>
<td>-4</td>
<td>-5</td>
</tr>
<tr>
<td>LP-steam direct contact cooler</td>
<td>0</td>
<td>92</td>
<td>184</td>
<td>276</td>
<td>368</td>
</tr>
<tr>
<td>HP-steam HEX</td>
<td>224</td>
<td>227</td>
<td>230</td>
<td>233</td>
<td>235</td>
</tr>
<tr>
<td>HP-steam direct contact cooler</td>
<td>224</td>
<td>316</td>
<td>408</td>
<td>500</td>
<td>592</td>
</tr>
<tr>
<td><strong>yearly costs (first 10 years)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LP-steam HEX</td>
<td>7 467</td>
<td>7 468</td>
<td>7 469</td>
<td>7 470</td>
<td>7 472</td>
</tr>
<tr>
<td>LP-steam direct contact cooler</td>
<td>3 618</td>
<td>3 526</td>
<td>3 434</td>
<td>3 342</td>
<td>3 250</td>
</tr>
<tr>
<td>HP-steam HEX</td>
<td>7 985</td>
<td>7 982</td>
<td>7 980</td>
<td>7 977</td>
<td>7 974</td>
</tr>
<tr>
<td>HP-steam direct contact cooler</td>
<td>4 199</td>
<td>4 107</td>
<td>4 015</td>
<td>3 923</td>
<td>3 831</td>
</tr>
</tbody>
</table>

Policy makers are often interested in the cost per kg of an emission not emitted, as this is a good way to compare the effectiveness of spending a euro in very different applications. If it is assumed that 34% of the particulate matter is removed in the coolers and 70% in the ESP and if it is assumed that the engine emission is 0.5 g PM/kWh, the cost per kg PM reduced can be calculated. As the yearly costs are a function of time that is spent in the
SECA, the costs per kg PM not emitted are also a function of time spent in the SECA. Note that, since sea water scrubber manufacturers claim higher particulate matter removal efficiencies with their scrubbers than the assumed 34% used in this calculation, the actual costs per kg PM not emitted may be lower for concepts with direct contact coolers than calculated here.

Table 7.20 Costs per kg PM not emitted [€/kg PM not emitted]

<table>
<thead>
<tr>
<th>% of operational hours in SECA-&gt;</th>
<th>0%</th>
<th>25%</th>
<th>50%</th>
<th>75%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>LP-steam HEX</td>
<td>193</td>
<td>193</td>
<td>193</td>
<td>193</td>
<td>194</td>
</tr>
<tr>
<td>LP-steam direct contact cooler</td>
<td>94</td>
<td>91</td>
<td>89</td>
<td>87</td>
<td>84</td>
</tr>
<tr>
<td>HP-steam HEX</td>
<td>205</td>
<td>205</td>
<td>205</td>
<td>205</td>
<td>205</td>
</tr>
<tr>
<td>HP-steam direct contact cooler</td>
<td>108</td>
<td>105</td>
<td>103</td>
<td>101</td>
<td>98</td>
</tr>
</tbody>
</table>

IMO recently announced a time scale for much more stringent regulation with regard to sulphur percentage level in fuel, see section §2.5 and [IMO, 2008]. This will have an impact on the OPEX and yearly costs of the SJAC-ESP, starting from 2015. In 2015 the SOx-emission should be equivalent with a fuel with 0.1% sulphur in SECAs and in 2020 the global SOx-emission should probably be equivalent with 0.5% sulphur fuel. [Krystallon, 2008] claim that their sea water scrubber, which is a type of direct contact cooler, is so efficient that a 3.5% sulphur fuel can be reduced to an SOx-emission equivalent to a 0.1% sulphur fuel. If this is true for the direct contact cooler in the SJAC-ESP concept, the economic case for the different versions of the SJAC-ESP look significantly different, as is shown in Table 7.21. If more than 75% of the time is spend in a SECA the installation would actually be gaining money in the configuration with a direct contact cooler and low-pressure steam.

Table 7.21 Estimated yearly revenues and costs SJAC-ESP in a ferry in 2015-2020 period from 2008 prices and investments [*1000 euro 2008 value]

<table>
<thead>
<tr>
<th>% of operational hours in SECA-&gt;</th>
<th>0%</th>
<th>25%</th>
<th>50%</th>
<th>75%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>yearly revenues</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ferry LP-steam HEX</td>
<td>0</td>
<td>-19</td>
<td>-37</td>
<td>-56</td>
<td>-75</td>
</tr>
<tr>
<td>Ferry LP-steam direct contact cooling</td>
<td>0</td>
<td>1364</td>
<td>2728</td>
<td>4092</td>
<td>5455</td>
</tr>
<tr>
<td>Ferry HP-steam HEX</td>
<td>224</td>
<td>265</td>
<td>305</td>
<td>345</td>
<td>385</td>
</tr>
<tr>
<td>Ferry HP-steam direct contact cooling</td>
<td>224</td>
<td>1588</td>
<td>2952</td>
<td>4316</td>
<td>5680</td>
</tr>
<tr>
<td>yearly costs (first 10 years)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ferry LP-steam HEX</td>
<td>7467</td>
<td>7485</td>
<td>7504</td>
<td>7523</td>
<td>7541</td>
</tr>
<tr>
<td>Ferry LP-steam direct contact cooling</td>
<td>3618</td>
<td>2254</td>
<td>890</td>
<td>474</td>
<td>-1838</td>
</tr>
<tr>
<td>Ferry HP-steam HEX</td>
<td>7985</td>
<td>7945</td>
<td>7904</td>
<td>7864</td>
<td>7824</td>
</tr>
<tr>
<td>Ferry HP-steam direct contact cooling</td>
<td>4199</td>
<td>2835</td>
<td>1471</td>
<td>108</td>
<td>-1256</td>
</tr>
</tbody>
</table>

§7.4.3 Sensitivity analysis of yearly costs

In this section it is analysed how sensitive the estimation of the yearly costs, i.e. the operational expenditure minus the revenues, of the ferry is to a number of assumptions. A large number of assumptions were made, and the yearly costs are only tested against some of the variables. Those are the temperature after cooling to the goal temperature, the allowed temperature increase of the cooling water, the fuel price, the price of the waste water, the price of the ESP, the price of the steam turbine and the influence of the operational hours. They are elaborated below.
The influence of the exhaust gas temperature on the costs is interesting as the exhaust gas temperature can be freely chosen within a certain operating window. For this calculation it is assumed that the characteristic parameter is kept constant, i.e. the ratio between particulate matter mass and condensate is constant. This means that at a higher exhaust gas temperature more steam needs to be injected, see also section §4.4.2. In this case a lower exhaust gas temperature of 26°C has been chosen. Note that this is very close to the assumed coolant temperature of 25°C, which is kept constant. The upper temperature for the exhaust gas was 40°C. At this temperature still enough steam could be produced to yield a constant condensate to particulate matter mass ratio, however the exhaust gas has a temperature of only 108°C after the creation of steam. Therefore this heat exchanger is constructed of C20-steel. At a temperature of 40°C the exhaust gas is not yet saturated, excluding the effect of sulphur oxides. It is assumed that no water is coming from the heat exchanger, and hence less water needs to be cleaned. Only the influence of the temperature on the two low-pressure options is studied. This has to do with the fact that at an exhaust gas temperature of 40°C no additional steam capacity is present to create power. The sensitivity of the yearly costs, i.e. OPEX minus revenues, to the exhaust gas temperature after cooling is shown in Figure 7.6. For the case with the heat exchangers, cooling to 40°C leads to a cheaper system than cooling to the standard temperature of 30°C, which in its turn leads to a cheaper system than with an exhaust gas temperature after cooling of 26°C. For the case of a direct contact cooler both options are slightly more expensive, with cooling to 40°C the most expensive. Figure 7.6 shows that the variant with a heat exchanger is very sensitive to the exhaust gas temperature, whereas the direct contact cooler is not.

If the cooling water is allowed to be discharged at a higher temperature, two things happen. On one hand the required amount of water decreases significantly, leading to smaller pumps and hence less power consumption. On the other hand the logarithmic temperature difference in the cooler decreases and as a result the cooler needs to be slightly larger. In Figure 7.7 the influence of a temperature difference between the inlet and outlet of cooling water of 10°C is investigated and compared to the standard temperature difference of 5°C.
From Figure 7.7 it becomes clear that the sensitivity of the price is not high, and that the yearly costs of the SJAC-ESP are either slightly higher or slightly lower.

![Figure 7.7 Sensitivity of yearly costs to a higher allowed temperature difference of the cooling water](image)

Figure 7.8 shows the influence of a variation of 50% in the fuel price on the yearly costs. From this figure it becomes clear that the fuel price has barely no influence on the yearly costs. In case of an increase in fuel price the yearly costs increase slightly for the options with low-pressure steam, whereas the yearly costs decrease slightly for the options with high-pressure steam as the revenues of the steam turbine increase.

![Figure 7.8 Sensitivity of yearly costs to a 50% increase or decrease of the fuel price](image)

Subsequently the influence of the waste water price is investigated. This price is possibly the biggest uncertainty in the calculation. Figure 7.9 shows the influence of a 50% increase or decrease of the waste water price. Especially the options with heat exchangers are very sensitive to this price. The price of the option with heat exchanger will always be higher,
because the capital expenditure of the option with heat exchanger is higher, and it is assumed that less water needs to be treated in the case of direct contact cooler.

![Figure 7.9 Sensitivity of yearly costs to a 50% increase or decrease of the waste water price](image)

If it is assumed that for the water from the direct contact cooler the same price per kg needs to be paid as for the waste water from the ESP or heat exchanger, the yearly costs become €3.0 billion euro per year for the low-pressure steam option and €2.0 billion euro per year for the high pressure steam option. These costs are totally unrepresentative as for this amount of money several plants could be build to clean the waste water. However, it is important to realise the impact of the waste water price and the obligation to clean the water from the direct contact cooler on the calculated yearly costs.

To put the costs of waste water cleaning in a different perspective, a comparison with the operational expenditure of sea water scrubbers is useful. The calculation is shown in the next section, but the operational expenditure is estimated at approximately 1.4 million euro per year, including waste water treatment, see Table 7.22. The amount of waste water from a sea water scrubber is higher than the amount of water from the heat exchanger and ESP. Therefore the costs for waste water should be lower than 1 million euro. That is lower than used in the present economic calculations, as can be seen in Figure 7.9 and Table 7.18.

Additionally the sensitivity of the yearly costs to the price of the ESP is analysed. Figure 7.10 shows that the yearly costs are influenced by the price of the ESP to some extent.
The sensitivity of the costs to the steam turbine price, is interesting for judging the potential of the high-pressure options. Figure 7.11 clearly shows that the yearly costs are not so sensitive to the steam turbine price that the high-pressure option earns itself back.

Lastly an analysis of the effects of the operational time on both yearly costs and cost per kg particulate matter not emitted is performed. Interestingly the yearly costs are not extremely dependant on the operational period for the direct contact coolers, indicating that the fixed costs are a significant part of the costs. The heat exchanger options are more strongly
dependant on the operational period, because cleaning of waste water is a significant cost factor. Figure 7.13 shows that the costs per kg PM not emitted are strongly dependant on the operational period. The longer the operational period the lower the costs per kg PM avoided.

Figure 7.12 Sensitivity of the yearly costs to a 50% increase or decrease of the operational period

Figure 7.13 Influence of a 50% increase or decrease of the operational period on costs per kg PM not emitted
§7.4.4 Comparison with competitive technologies

If it is assumed that a regular ESP is not suited for sea shipping, basically one of the reasons to start the SJAC-ESP development, two technologies remain as potential competitors for SJAC-ESP. The first competitor is a sea water scrubber. The second competitor is a particulate matter filter in combination with low-sulphur (max. 50 ppm) fuel.

A sea water scrubber is designed for the removal of sulphur oxide from exhaust gas. It removes particulate matter as well. However, the amount of particulate matter removed is not particularly clear, see the discussion in section §2.6.4.2. For the calculation a minimum of 40% and a maximum of 80% particulate matter removal is assumed. [MES, 2005b] give an indicative price for a scrubber of US$200 per kW, which they use to calculate the pay back time of the installation. Given the large fluctuations of the US Dollar compared to the euro it is hard to give a very exact price in euro. In this calculation €173 per kW is used for the fixed capital investment in 2008. The consumables for sea water scrubbers consist of a neutralising agent. In the calculation NaOH is assumed. Electricity use for pumps is not specified for sea water scrubbers. It is probably 1 to 2% of engine power, but for the calculation it is assumed to be zero.

A particulate matter filter will only regenerate properly if low-ash fuel is used, because otherwise accumulation of incombustible matter becomes problematic. In the calculation of the operational expenditure it is assumed that low-ash fuel contains 2.5% more energy per kg than HFO. Therefore the fuel consumption reduces to 97.5% of the original fuel consumption. The (remaining) fuel consumption increases with 2%, however, for regenerating the filter. The overall fuel consumption (in g/kWh) reduces therefore with 0.6%. The depreciation and other assumptions are similar to the case of the SJAC-ESP. Used fuel prices are €0.30 per kg fuel for IFO 180/380, and €0.635 per kg fuel for low-ash fuel (max. 50 ppm S). The operational expenditure for the sea water scrubber and PM-filter are shown in Table 7.22.

Table 7.22 Operational expenditure for sea water scrubber and PM-filter with low-sulphur fuel for the main propulsion of a ferry [*1000 euro per year]

<table>
<thead>
<tr>
<th></th>
<th>Sea water scrubber</th>
<th>PM-filter low-sulphur fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Production Cost</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Consumables</td>
<td>348</td>
<td>5 851</td>
</tr>
<tr>
<td>Utilities (electricity)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Waste water</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Maintenance &amp; Repairs</td>
<td>5% of FCI</td>
<td>225</td>
</tr>
<tr>
<td>Operating Supplies</td>
<td>1% of FCI</td>
<td>45</td>
</tr>
<tr>
<td>Fixed Charges</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capital Charge</td>
<td>β \cdot FCI</td>
<td>640</td>
</tr>
<tr>
<td>Local Taxes</td>
<td>2% of FCI</td>
<td>90</td>
</tr>
<tr>
<td>Insurance</td>
<td>1% of FCI</td>
<td>45</td>
</tr>
<tr>
<td>OPEX</td>
<td>1 392</td>
<td>7 526</td>
</tr>
</tbody>
</table>

In the case of sea water scrubbing the operational expenditure is not equal to the yearly costs, because the system has some revenues when it is being used in a SECA, similar to the SJAC-ESP with direct contact cooling. The additional fuel costs are slightly lower for a particulate matter filter with low-sulphur fuel, because normally when sailing in a SECA a more expensive fuel should be used than the heavy fuel oil.
Table 7.23 Yearly costs for different particulate matter removal devices as a function of time spent in a SECA [*1000 euro]

<table>
<thead>
<tr>
<th>% of operational hours in SECA -&gt;</th>
<th>0%</th>
<th>25%</th>
<th>50%</th>
<th>75%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sea water scrubber</td>
<td>1 392</td>
<td>1 300</td>
<td>1 208</td>
<td>1 117</td>
<td>1 025</td>
</tr>
<tr>
<td>PM-filter with low-sulphur fuel</td>
<td>7 526</td>
<td>7 434</td>
<td>7 342</td>
<td>7 250</td>
<td>7 158</td>
</tr>
</tbody>
</table>

Table 7.24 Costs per kg PM not emitted [euro per kg PM not emitted]

<table>
<thead>
<tr>
<th>% of operational hours in SECA -&gt;</th>
<th>0%</th>
<th>25%</th>
<th>50%</th>
<th>75%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sea water scrubber</td>
<td>36-72</td>
<td>34-67</td>
<td>31-63</td>
<td>29-58</td>
<td>27-53</td>
</tr>
<tr>
<td>PM-filter with low-sulphur fuel</td>
<td>156</td>
<td>154</td>
<td>152</td>
<td>150</td>
<td>148</td>
</tr>
</tbody>
</table>

Table 7.24 shows that a sea water scrubber is a cheaper option to reduce particulate matter than the SJAC-ESP. It is questionable, however, if a sea water scrubber is capable of removing large quantities of submicron particles efficiently. A PM-filter with low-sulphur fuel is more expensive than the SJAC-ESP. This is due to the large difference in price.

The yearly costs will be considerably different from 2015 on, when the measures announced in [IMO, 2008], come into force. (see also §2.5 for a discussion on those measures). The effect of these measures is illustrated in Table 7.25. In this case the sea water scrubber will be gaining more money than the SJAC-ESP case, because the investment in the SJAC-ESP is higher.

Table 7.25 Yearly costs for different particulate matter removal devices in 2015-2020 based on 2008 prices [*1000 euro (2008 value)]

<table>
<thead>
<tr>
<th>% of operational hours in SECA -&gt;</th>
<th>0%</th>
<th>25%</th>
<th>50%</th>
<th>75%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sea water scrubber</td>
<td>1 392</td>
<td>28</td>
<td>-1 355</td>
<td>-2 699</td>
<td>-4 063</td>
</tr>
<tr>
<td>PM-filter with low-sulphur fuel</td>
<td>7 526</td>
<td>4 798</td>
<td>3 434</td>
<td>2 070</td>
<td></td>
</tr>
</tbody>
</table>

§7.5 Conclusions

In this chapter first the most interesting markets were investigated for particulate matter removal devices. Inland shipping was identified as an interesting market from market point of view. For sea shipping the four most interesting markets were ferries, cruise ships, yachts and naval vessels. Of those four, ferries are the most interesting market for market implementation. For inland shipping and sea-going ferries process flow diagrams were made for the main components. They have been used as the basis for economic analyses. For inland shipping the costs per kg PM not emitted with SJAC-ESP were estimated at 498 euro. The cheapest version of the SJAC-ESP comprised of a cooler in which low-pressure steam was made, and a direct contact cooler to cool the gas down to the goal temperature. The combination of a particulate matter filter and a low-sulphur fuel is significantly cheaper. The costs per kg PM not emitted is in this case 136 euro. As the SJAC-ESP is at best as good as a particulate matter filter with low-sulphur fuel with regard to PM, the combination of low-sulphur fuel and a particulate matter filter is the best option for inland shipping.

For ferries the costs were estimated at minimally €94 per kg PM avoided with the SJAC-ESP. The cheapest version of the SJAC-ESP again comprised of a heat exchanger in which low-pressure steam was made and a direct contact cooler. This number is strongly dependant on the assumed costs for waste water treatment, operational period and economic
life-time. A particulate matter filter with low-sulphur fuel is much more expensive with €156 per kg PM not emitted. Sea water scrubbers reduce particulate matter emissions as well. It is unclear how well particulate matter is removed. The costs of removing a kg PM with a sea water scrubber range between 36 and 72 euro. A SJAC-ESP with direct contact cooling will always be more efficient in removing particulate matter than a sea water scrubber. The measures announced by IMO for 2015 will have large implications on the presented costs. Both the SJAC-ESP and sea water scrubber will actually be gaining money under the assumptions for the cost calculation. The sea water scrubber will be gaining more money than the SJAC-ESP, however. For sea shipping the SJAC-ESP is the cheapest option with 80% particulate matter removal efficiency. The SJAC-ESP is the cheapest option that removes sub-micron particles well.
Chapter 8. Conclusions and recommendations
In order to develop a technology to reduce the particulate matter emission from diesel engines on ships regardless of the used type of fuel, a measurement method, called SJAC, was used as a starting point for the development. The idea was to enlarge the particles by condensing water on them. Subsequently the particles should be captured with a size-selective removal device like a cyclone. Water vapour was forced to condense on the particles by supersaturating exhaust gas by injecting steam in cold, preferably saturated, exhaust gas. It was concluded from measurements that less than 25% of particulate matter mass was removed by this technology, most of which was removed in the exhaust gas coolers and not in the cyclone. From a calculation it was concluded that the limited removal efficiency was due to the particle concentration. The SJAC-technology will not be able to remove large quantities of particulate matter for typical particle concentrations in the exhaust gas of diesel engines.

It was found that a shift to distillate fuels with a sulphur level of 0.1 or 0.16% sulphur instead of an intermediate fuel oil with 1.5% reduces the emission of particulate matter by 20 to 30% by mass and up to 60% by number over the propeller load profile. A shift to distillate fuels would mainly reduce the number of particles with a mobility diameter around 50 nm. It was found that an SMPS should be able to measure particles larger than 562 nm in diameter in order to give a good determination of the total particle mass, because with the presently used conversion factors a significant amount of particle mass seems to be outside the measurement window.

The goal of the SJAC-ESP is to create a robust self-cleaning electrostatic precipitator (ESP) in order to remove particulate matter from the exhaust gas of a diesel engine in a ship regardless of the used type of fuel. It is hypothesized that by condensation of a small water layer on the particles, the particles will no longer stick to the electrostatic precipitator, but stream off the plates of the collection section. Up to 82% of particulate matter mass was removed during investigation of the operating window of the SJAC-ESP in the exhaust gas of a 15 kW diesel generator. The optimal settings were found to be 3% steam (as a fraction of exhaust gas flow) in exhaust gas of 30°C with a velocity of 0.74 m/s through the ESP. Voltages in the ESP were 10 kV in the charging section and -2 kV in the collection section. It was found that reducing the velocity did not increase the removal efficiency significantly. Decreasing the voltage in the collection section decreased the removal efficiency by approximately 10%. It is recommended to expand the operational window of the SJAC-ESP to higher velocities through the ESP, which was not possible with the present set-up. Improved insulator design solved the problem of instable voltages in the ESP. Key improvement was the injection of warm pressurised air along the insulators.

The SJAC-ESP removed between 41 and 70% of the mass of particulate matter from an exhaust gas slipstream of a 350 kW engine. The engine was operated on three different fuels; two distillate fuels and one intermediate fuel oil (RMA-30) with 1.5% sulphur. According to SMPS measurements, between 70 and 83% of the number of particles was removed from this slipstream. More importantly these measurements showed that particles smaller than 1 micrometer are removed very efficiently.
An endurance test was performed with the SJAC-ESP behind a 15 kW generator running on a distillate fuel. The system ran unmanned, and automatically shut down in case of an emergency. During the endurance test the installation was 142 hours operational over a 500 hour-period. Most problems were related to the heat exchangers, which did not have sufficient capacity. This resulted in exceeding the maximum pressure drop over the exhaust gas system. Problems with gas leakage from the ESP were stemming from the fact that the commercial ESP was not designed to be gas tight. A future ESP should be designed specifically for reducing particulate matter from exhaust gas and should hence be gas tight. It was found that the heat exchangers only have a minor effect on the total removal efficiency during the measurements in the slipstream of the 350 kW engine. Over the propeller cycle approximately 28% of particulate matter was removed in the heat exchangers. Most particulate matter was removed in the heat exchangers at high engine loads.

However, the endurance test did not yet prove that particulate matter streams off the ESP satisfactorily, nor did it prove the contrary. It is recommended to perform a new and longer endurance test, with the focus on a particulate matter balance, and long-term trends in the particulate matter removal efficiency in the ESP.

A developed model of the SJAC-ESP does not predict all the correct trends. Most importantly it predicts a different sensitivity to the velocity through the ESP. The biggest uncertainty in the present model is the ion concentration in the charging section of the ESP and as a result the charge on the particles that enter the collection section of the ESP. It is recommended to improve this model by making a proper description of the ion concentration in the charging section. Measuring the current in different parts of the ESP can give additional information on the ion concentration. A new description of the ion concentration in the charging section should include the decrease in ion concentration due to the charging process. Additionally the influence of collected particulate matter with water coating on the removal efficiency should be incorporated in the model. It is recommended to verify the calculation of the water coating on the particles by measurement.

In the present set-up approximately 30% of SOx is removed in the SJAC-ESP with a fuel of 1.5% sulphur and approximately 50% with MGO with 0.2% sulphur. This removal efficiency can be significantly increased if a heat exchanger is substituted by a direct contact cooler (i.e. a wet scrubber). This will also result in reduced costs of the SJAC-ESP, because direct contact coolers are cheaper than regular heat exchangers, which should be constructed of a strongly corrosion resistant material. Additionally the yearly costs of the SJAC-ESP are reduced with a direct contact cooler if the ship is sailing in a sulphur oxide emission control area. The system efficiency with regard to particulate matter could be slightly increased as well with direct contact coolers, because scrubbers reduce some particulate matter.

A market analysis identified inland shipping and ferries as interesting markets for first implementation of particulate matter removal devices. The conclusions for those two cases are significantly different, however. For inland shipping it is more economic to use a low-sulphur fuel with low ash-content in combination with an actively regenerated particulate matter trap. For ferries however, the preferred option to remove sub-micron particles is to use the SJAC-ESP. The costs are estimated at 94 € per kg PM avoided.
Appendix A Particle transport in grid collection section

The approach for calculating the concentration in each block is based on a steady state, i.e. the particle fluxes are in equilibrium as expressed in formula A.1.

\[ \dot{N}_{in} = \dot{N}_{out} \]  

Formula A.1

The particle flux for one block with these assumptions and the axes as defined in Figure A.1 is illustrated in Figure A.2.

\[ \dot{N}_{in} \] \(\rightarrow\) \[ \dot{N}_{out} \]

Figure A.1 Illustration of collection section

\[ \dot{N}_{x\_out} \] \(\rightarrow\) \[ \dot{N}_{x\_in} \]

\[ \dot{N}_{y\_out} \] \(\rightarrow\) \[ \dot{N}_{y\_in} \]

Figure A.2 Illustration particle streams in a block without Brownian motion

\(\dot{N}_{x\_out}\) and \(\dot{N}_{y\_out}\) can be defined as functions of the number of particles in a block, as illustrated in formula A.2 and A.3.

\[ \dot{N}_{x\_out} = -N_{n,m,r_p} \frac{\vec{u}_x}{x_b} \]  

Formula A.2

\[ \dot{N}_{y\_out} = N_{n,m,r_p} \frac{\vec{u}_y}{y_b} \]  

Formula A.3

with \(x_b\) and \(y_b\) the length of the block in x- and y-direction respectively, and \(N_{n,m,r_p}\) the number of particles with radius \(r_p\) in block \((n,m)\). This can be determined by using formula A.1.
\[ N_{n,m,r_p} = \frac{\dot{N}_{in}}{(-\dot{u}_x / x_b + \dot{u}_y / y_b)} \]

As the flux of particles from block \((n,m)\) in x-direction must equal the input from particles from x-direction of block \((n-1,m)\) and the flux of particles from block \((m,n)\) in y-direction must equal the input of particles from y-direction of block \((n,m+1)\) it is possible to solve the problem with the right boundary conditions. The flux \(\dot{N}_{y\_in}\) for blocks with \(n=1\) is given by the flow through the block multiplied by the concentration outside the block. At the same time the particle flux from x-direction into block \((200,n)\) has to equal zero, because no particle flux is coming from the electrode. Starting from block \((200,1)\) the whole problem is solved.
Curriculum Vitae

Geert van Rens was born on December 7th 1980 in Tilburg, the Netherlands. He attended secondary school at St.-Willibrord Gymnasium in Deurne (The Netherlands). In 1998 he graduated and started his study Mechanical Engineering at Delft University of Technology. A year later he obtained his propedeuse cum laude. In 2002 he obtained his Bachelor degree. In 2003 he was member of the “Opleidingscommissie werktuigbouwkunde” (Education committee mechanical engineering). In 2004 he spend a year of his Masters study at Chalmers University of Technology in Göteborg, Sweden. He graduated in 2005 with a thesis on the removal of particulate matter from diesel engines by means of a scrubber, with a specialisation in technology in sustainable development.

From 2005 till 2008 he was employed by Energy research Centre of the Netherlands (ECN) as a PhD-student (in collaboration with Delft University of Technology) with the initial task to develop the SJAC-technology to a particulate matter reduction technique for shipping. When it became obvious that the SJAC-technology did not fulfil the expectations, a new technology was developed for particulate matter reduction for shipping. The newly developed technology is patented by ECN (P6021505NL). Besides working on several governmentally funded research projects, Geert also contributed to the European research project CREATING on particulate matter reduction in inland shipping. In 2006 Geert participated in an international design competition of Royal Haskoning on sustainable solutions for delta areas, together with fellow students Anne Loes Nillesen, Carianne Schamhart and Nadia Lugt. They won second prize.

Peer-reviewed publications:


Other recent publications and reports:


Van Rens, G., Nillesen A.L., Schamhart, C., Lught, N., Sustainable growth in urbanised delta areas, the opportunities of a geographical approach to the pearl river delta, Published in Innovative solutions for the delta, also available at http://www.deltacompetition.com/en-us/deltastories/Documents/DeltaSync02%20Pearl%20River%20Delta.pdf, Royal Haskoning, 2006

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Dankwoord (Word of thanks)

Zo’n project als in dit proefschrift beschreven doe je niet in je eentje. Ik heb dan ook veel steun gekregen gedurende de jaren van verschillende personen, die ik in dit stukje wil bedanken.

Allereerst wil ik mijn promotoren bedanken voor hun begeleiding en coaching. Zij hebben mij met raad en daad bijgestaan, ook toen de eerste versie van de SJAC niet bleek te werken. Daarnaast daagden ze me uit om steeds iets dieper op de materie in te gaan. Zonder hun rol had mijn proefschrift er vermoedelijk anders uitgezien. Verder wil ik prof. Stapersma extra bedanken omdat hij mij op de (op dat moment mogelijke) promotieplek bij ECN heeft gewezen.

In de beginperiode bij ECN kwam ik terecht in de groep van Ger Beckers (tegenwoordig allen ENATEC). In de beginperiode heeft Ruud van der Woude mij onder de vleugels genomen, als projectleider. Van hem heb ik misschien wel het meeste geleerd tijdens mijn verblijf bij ECN. De bijdrage van Gerard Broers is heel belangrijk geweest binnen dit project. Hij heeft in iedere fase van het project een belangrijke bijdrage geleverd bij de realisatie. Als er iets veranderd moest worden aan de opstelling was hij altijd beschikbaar. Ik heb in de tussentijd geleerd dat je Gerard niet hoefde te vertellen hoe je iets precies wilde hebben, je kon beter vertellen wat je wilde dat het deed en hoeveel ruimte je beschikbaar had en Gerard kwam dan met een veel betere oplossing, dan die ik in mijn hoofd had en maakte dat dan.

Belangrijk was ook de bijdrage van de “bedrijfsgroep” van biomassa. Het voert te ver om op te sommen hoe ze hebben bijgedragen hebben aan dit project omdat dit feitelijk bij alles was wat te maken heeft met (ver)bouwen van de opstelling, het in bedrijf stellen, bedrijven en in bedrijf houden van de opstelling. Ik denk dat ze zelf weten hoe belangrijk ze zijn geweest voor mijn onderzoek, en meer nog hoe belangrijk ze zijn voor het biomassa-onderzoek in brede zin. Ik durf zelfs te stellen, dat zonder hen nauwelijks of geen biomassaonderzoek plaats kan vinden. Ik denk dat ze dat zelf wel weten, maar ik gebruik deze plaats om dat nog eens te benadrukken. Ook wanneer er een probleem was, kwamen deze heren altijd met een goede en snelle oplossing.

Mijn ex-collega’s en in het bijzonder, Marco Geusenbroek, Johan Kuipers, Gerard Kos en Aline Kraai hebben allen een grotere of kleinere rol gespeeld in het vergaren van de meetgegevens. De afdeling Engineering and services van ECN en dan in het bijzonder Marcel Hoede en Ruud de Moel hebben wezenlijke bijdrages geleverd bij de P&ID en automatisering van de opstelling. Ruud moet ik nog extra bedanken voor het meermals op korte termijn komen opdraven als er een probleem was, veroorzaakt doordat de situatie toch anders was dan ondergetekende had verwacht.

Door de tijd heen heb ik veel verschillende projectleiders gehad, Ruud van der Woude, Hein de Wilde, Sander van Paasen, Fred Verhoeff, Robin Zwart en Luc Rabou, die allen op hun manier een bijdrage leverde aan het project. Interessant was ook om het verschil te zien in de leidinggevende stijlen tussen de verschillende personen. Luc Rabou moet ik nog extra bedanken voor zijn inzet om het patent rond te krijgen.
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There’s more to live than work, though. And although it is extremely weird thanking your friends and family, basically for the persons they are, I am going to give it a try. The reader may have noticed that I switched to English again. This time to help my foreign friends to understand the text slightly better, than when I would have written it in Dutch.

I consider myself very lucky to have met such loyal friends throughout the course of my live.
I still keep in touch with my friends from secondary school, and although the times we meet became less frequent throughout the years, it is always nice to meet each other.
During my education at Delft University of Technology I met several good friends. But I am probably the closest with Bart-Jan and Matthijs. I know they still cannot believe that my thesis is longer than 100 pages (it is in fact twice that amount), as they know me as a writer of (very) short reports.
When I moved to Alkmaar for my PhD, one of the first things I did was applying for the local hockey club. Throughout time I found my present team, Alkmaar heren 6, which is for me the perfect combination of sport and relaxation.
Almost last but not least, I like to thank my national and international friends (formerly) from (Jong-) ECN and JRC for all the good times during holiday trips (Mont St-Michel, Berlin, Serre Chevalier, and hopefully much more in the future), parties and other good moments, but as well for the understanding when I was (once again) not able to make it because I had to finish some part of my thesis.

In the end I decided for Bart-Jan and Berend to be my “paranimfen”, persons who accompany and assist me during my thesis defense. Because I consider them good friends, and they represent two major phases in my life. I was very happy that they said yes immediately.

Tot slot wil ik mijn ouders en zusjes bedanken voor hun steun. Niet alleen gedurende mijn promotie, maar ook toen ik besloot een jaar in Zweden te gaan studeren, en ook nu ik besloten heb om straks naar Zuid-Amerika te gaan om te gaan reizen.

Geert
Alkmaar, 16 september 2008
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