Proving the possibility of physical removal of particulate matter with the SJAC-technology

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Particulate matter emissions from shipping affect air quality in port areas. Physical removal of particulate matter is difficult due to the small size of particles. In this article the so-called Steam Jet Aerosol Collector (SJAC) is introduced; a novel technique to enlarge particulate matter, facilitating its physical removal. Results are presented from experiments conducted on a pilot-scale test facility. The SJAC-technology shows potential in combination with a cyclone having a maximum number removal efficiency of 33%, as measured with an SMPS and a maximum mass removal efficiency of 24%, as measured with an absolute filter at 110°C (383K). Further system development is however necessary.

INTRODUCTION

Emissions of particulate matter from diesel engines are a growing concern, because particulate matter is classified as a probable carcinogen[1] and contributes to the concentration of fine particles in air, which are associated with detrimental health effects. One of the sources of diesel particulate matter emissions is shipping, whose impact is most pronounced in densely populated coastal and port areas. In the last decade emission limits for shipping have been implemented.[2,3,4] The Marine Environment Protection Committee of IMO agreed in July 2005 to review Annex VI and to study the possibilities of reducing particulate matter.[5]

Particulate matter is defined as measured according to ISO 8178-1[6], in which every component caught on a filter, after the exhaust gas is diluted and cooled to a maximum filter temperature of 52°C, or more precisely according to RL97/68 EC[7] after dilution with a filter temperature between 42 and 52°C.

Particulate matter in this definition is composed of four fractions. The first is ash stemming from fuel, lube oil and engine wear. The second fraction is elemental carbon from pyrolysis of fuel and lube oil. The third fraction is composed of semi-volatile hydrocarbons, some of which may contain oxygen or nitrogen. The fourth fraction is sulphuric acid with associated water. During combustion, sulphur in fuel forms sulphur dioxide and a smaller fraction of sulphur trioxide. Sulphur trioxide will combine with water to form sulphuric acid, H_2SO_4, which is, together with the associated water, a part of particulate matter.

Two fundamentally different approaches for reduction of particulate matter by after-treatment exist. The first approach is catalysed oxidation of particulate matter and the second is the physical removal of particulate matter.

Oxidation is suited for diesel engines running on low sulphur fuel, ie 15-500mg sulphur per kg fuel (15ppm to

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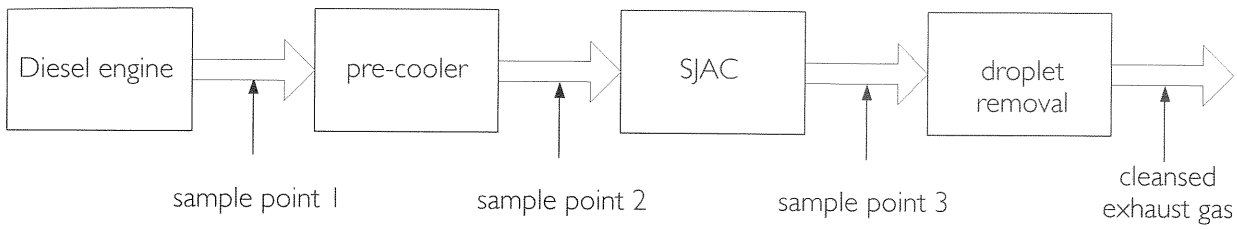


Fig 1: Schematic structure of the pilot-scale set-up

0.05%).[8,9] Oxidation is less suited for high sulphur fuels. Whilst oxidation by a catalyst reduces the carbon and hydrocarbon fraction of particulate matter, it converts a part of sulphur dioxide to sulphur trioxide, ultimately forming H_2SO_4.[10] At low sulphur concentrations in fuel the balance between the reduction of carbon and hydrocarbons and the creation of H_2SO_4 is tipped towards the reduction of particle mass, whilst at high sulphur concentrations in fuel the balance is tipped towards the creation of particle mass. This equilibrium sulphur concentration depends on catalyst composition.

For high sulphur fuels physical removal is the preferred option, since oxidation only leads to a marginal decrease or may even lead to an increase in particulate matter emissions.

In marine applications high sulphur fuels are used, containing up to 0.2% sulphur for inland shipping, up to 1.5% in a so-called SOx emission control area (SECA) and up to 4.5% sulphur for sea going vessels.[3,11] Therefore, physical removal is the preferred option for particulate matter reduction in shipping. Diesel particulate matter is so small however, that most commercial methods to remove particulate matter cannot be applied. Therefore, a technique, called SJAC (Steam Jet Aerosol Collector), is being developed at the Energy Research Centre of the Netherlands (ECN) to facilitate the physical removal of particulate matter by enlarging the particles.

The goal of this paper is to show the potential of the SJAC-technology in a pilot-scale set-up by means of an experimental investigation.

Number and mass removal efficiencies of the SJAC are calculated from measured particle size distributions and particle masses.

SJAC-TECHNOLOGY

The concept behind 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 heat dissipated in the cooler can be used to generate the necessary low-pressure steam. The water could be made by a large water maker based on reverse osmosis, or the water could be distilled utilising 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 particle 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 growth of particles, as the condensed water needs to be divided over more particles. This reduces collection efficiency in a system that contains a size selective removal device, like a cyclone.

This concept was first described by Sun.[12] The development of the SJAC at ECN started as a measurement technique.[13] The conclusion of this work was that 99% of the aerosols could be captured with a particle concentration of 600 000/cm^3. The work of De Wilde et al.[14] 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 15kW diesel engine.

IMPLEMENTATION

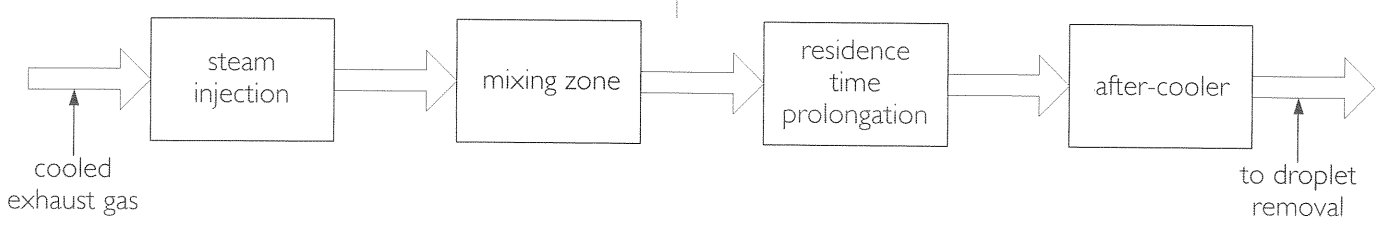
Pilot-scale SJAC

The pilot-scale SJAC was designed as an after-treatment device for an engine with a rated power of 15kW. The pilot-scale set-up is schematically shown in Fig 1.

The diesel engine used, is an ONAN 12.0 MDJF generator set delivering 12kW of electric power at full load. The generator set is running on commercially available automotive diesel fuel, which contains typically 50mg sulphur per kg fuel (50ppm). The exhaust gas flow is approximately 100kg/h (72m$_n^3$/h, ie volume at normal conditions, 273K and 1.013bar). The pre-cooler is realised by two spiral-type coolers. The used steam generator is of the make and type 'MK 5 Visual 10'. The droplet removal device is a so-called coalescer, ie 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 15-20h before reaching an unacceptably high pressure drop across the filter, it was decided not to determine the efficiency of this droplet removal device.

The SJAC itself, schematically represented in Fig 2, consisted of a steam-injection flange, followed by a mixing zone,

Fig 2: Schematic structure of the SJAC



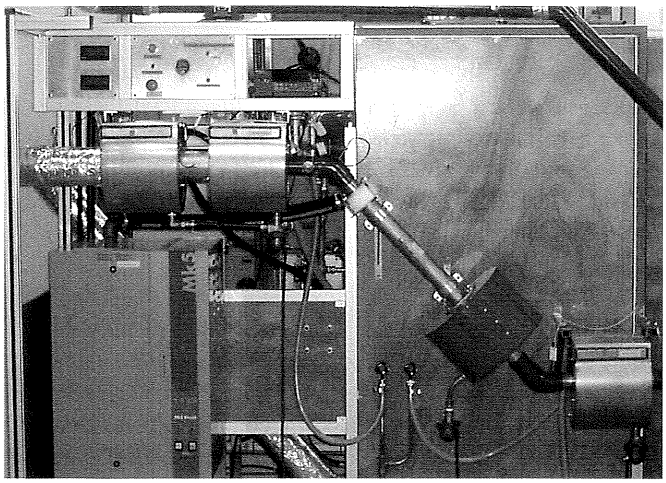


Fig 3: Realisation of SJAC. The hot exhaust goes through two coolers on the left. Steam is generated in a generator below the coolers and injected in the white injection chamber. Subsequently it is mixed and one can clearly distinguish the residence time chamber. The after-cooler is visible on the far right of the picture.

which contained a static mixer. The residence time was prolonged by 0.8s in a specially designed chamber. An after-cooler was present during all the experiments, but was switched on only during some of the experiments. The influence of this cooler turns out to be small and the effect will not be shown separately. The realisation of SJAC with pre-coolers is shown in Fig 3.

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 changed parameter 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 1 illustrates the experimental conditions under which the tests were performed.

Two important efficiencies are distinguished. The particle removal efficiency of the total system (η_{tot}):

$$\eta_{tot} = 1 - \frac{x_{after\ SJAC}}{x_{before\ pre\text{-}cooling}} \qquad (1)$$

with $x_{after\ SJAC}$ and $x_{before\ pre\text{-}cooling}$ the number or (calculated) mass of particles at sample point 1 and 3 respectively, indicated in Fig 1, and the efficiency of the SJAC itself (η_{SJAC}):

$$\eta_{SJAC} = 1 - \frac{x_{after\ SJAC}}{x_{after\ pre\text{-}cooling}} \qquad (2)$$

with $x_{after\ SJAC}$ and $x_{after\ pre\text{-}cooling}$ the number or (calculated) mass of particles at sample points 2 and 3 respectively, indicated in Fig 1.

SMPS measurement

An SMPS (Scanning Mobility Particle Sizer), sometimes called a scanning electrical mobility spectrometer, (eg Wang and Flagan[15]), was used to determine the number of particles in selected diameter ranges after dehumidification of the exhaust gas. By dehumidification of the exhaust gas the water coating on the particles, created by SJAC, is removed, which means that

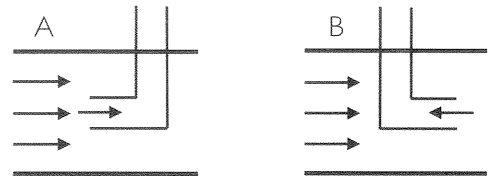


Fig 4: A. sample flow co-current; B. sample flow counter-current

dry particle diameters are measured. Exhaust gas was sampled by J-shaped tubes schematically illustrated in Fig 4.

The opening of the sampling tube is either facing towards the gas stream, where the sample flow is co-current to the gas flow or exactly towards the opposite site, where the sample flow is counter-current to the gas flow. The direction of the sample stream relative to the gas flow is given before each measurement for completeness. Because diesel particulate matter is of submicron sizes, it is expected to behave just like a gas, meaning that no substantial difference between the two measurement configurations is expected. This is investigated with absolute filter measurements. The configuration of the measurement equipment is shown in Fig 5.

The piping from sample points 2 and 3 was insulated to prevent additional water formation in the piping. The piping from sample point 1 towards the first silica-gel dryer was not insulated to reduce the temperature of the sample. The piping from the different sampling points was connected to a common tube by a valve-section, which enabled switching between the different sample points with the engine running. In order to investigate the removal efficiency of the SJAC a cyclone was mounted before the dehumidifying section to act as a droplet removal device. This cyclone had a cut-off diameter (point where 50% of particles is removed) of 1000 nanometre (nm). A small hose pump pumped the condensate and particles out of the cyclone.

Table 1: Measurement conditions

Temperature after cooler 1: (°C)	Amount of injected steam (kg/h):	Measurement methods:
20	8.3	SMPS
20	10	SMPS
25	10	absolute filter
30	8.3	SMPS, absolute filter

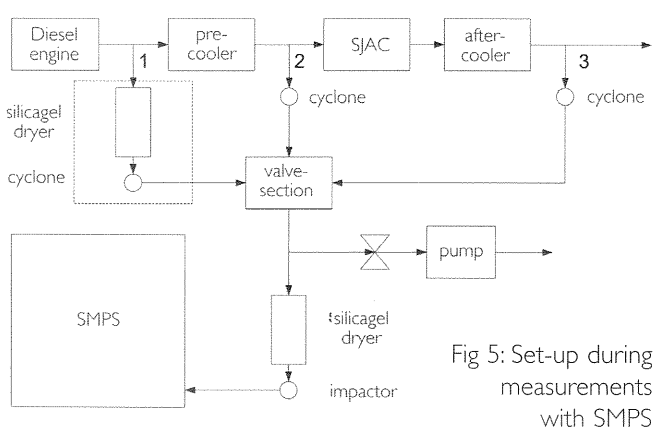


Fig 5: Set-up during measurements with SMPS

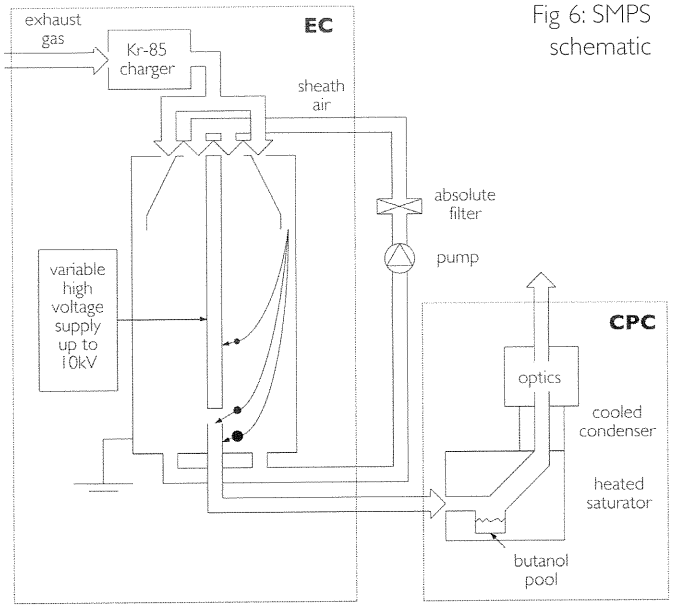


Fig 6: SMPS schematic

In order to obtain the required flow rate through the cyclone, and maintain the required flow through the SMPS it was necessary to split the flow after the cyclone. A pump in combination with a valve maintained the selected flow-rate through the cyclone. Another valve was mounted just in front of the SMPS to control the flow through the SMPS. The gas stream going towards the SMPS was first dried, as required by the SMPS. An impactor with a cut-off diameter of 800nm or 1000nm, which is specified at each measurement condition, subsequently removed particles that were larger than measurable in order to ensure correct measurements by the SMPS. Only during the first measurements the silicagel dryer and the cyclone were present in the piping from sample point 1 to the valve-section. They acted as a back-up for, although placed in front of, the silicagel dryer and impactor, because at the start of the experiments it was not certain that one silicagel dryer was enough to remove all water vapour in that sample. When it turned out that the capacity of one silicagel dryer and impactor was sufficient they were removed.

The SMPS 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, schematically represented in Fig 6.

This way the number of particles with particle diameters ranging from 19.1nm to 649nm and 930nm were measured. 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. A bandwidth independent of number concentration density is calculated by dividing the number concentration at a central diameter by the bandwidth around the central diameter.

From the number of particles in each diameter bandwidth it is possible to calculate a mass-distribution assuming that particles are spherical and assuming a density. It is known that diesel particles are not spherical. Diesel particles can be described as fractals as is frequently done.[16,17,18,19] Using fractal theory it is possible to find an empirical relationship between particle diameter measured with SMPS, often referred to as mobility diameter, and particle mass. In this work the relationship found by Park et al.[18] for high load will be used. It is:

$$m = 8 \cdot 10^{6} \cdot d_{m}^{2.33} \qquad (3)$$

With in this case mass in femtogram (10^{-15} g) and mobility diameter in nm the values calculated from equation 3 are quite similar to the values found by Maricq and Xu.[19] The effect of this correction will be illustrated by comparing the calculated mass assuming round particles with a density of 2200kg/m^3 and 1000kg/m^3 with the calculated mass after the conversion with the relationship found by Park et al.[18] in Fig 8.

Even with this conversion, calculated volumes and masses are indicative only. Mass measurements with absolute filters have been performed to measure real particle mass. Because the temperature of gas samples during SMPS measurements and absolute filter measurements were not equal it is not possible to compare the measurement results directly to obtain a relationship between the two.

Absolute filter measurement

The set-up for the absolute filter measurement used J-shaped sample tubes with a larger diameter than with SMPS measurements. They were mounted with a co-current gas flow as illustrated in Fig 4A. A heated valve was mounted between the sample point and the absolute filter which made it possible to change absolute filters with the engine was running. During measurements with a cyclone a peristaltic pump removed the condensate and particles from the cyclone. The absolute filters were mounted horizontally, with gas flowing down through the filter.

Since the principle of SJAC is to enlarge particles by a water coating, the mass of particles is influenced by the water coating. In order to assess the influence of SJAC on the original particles the filter temperature needs to be higher than the dew point temperature of water.

The sample points and filter holders were heated by trace heating and kept at a temperature of 110°C (383K). The absolute filter itself was made of quartz-fibre, to allow sufficient loading. The filters were weighed after residing in an oven at 110°C. In this way the influence of SJAC on the solids and a part of the volatile hydrocarbons is assessed. The influence of SJAC on lighter volatile hydrocarbons cannot be assessed by a mass measurement of a quartz-fibre filter. The influence of SJAC on the sulphuric acid part of particulate matter cannot be assessed either.

After weighing the filters were put in an oven again, but

Table 2: Measurement results 20°C after pre-coolers, 8.3kg/h steam injection

Measurement no.	Efficiency total system (mass)	Efficiency SJAC (mass)	Efficiency total system (number)	Efficiency SJAC (number)	No. of particles at sample point 1 [#/cm^3]	Mass of particles at sample point 1 [mg/m^3]
1	49%	-	44%	-	1.5 x 10^7	25
2	-	43%	-	34%	-	-

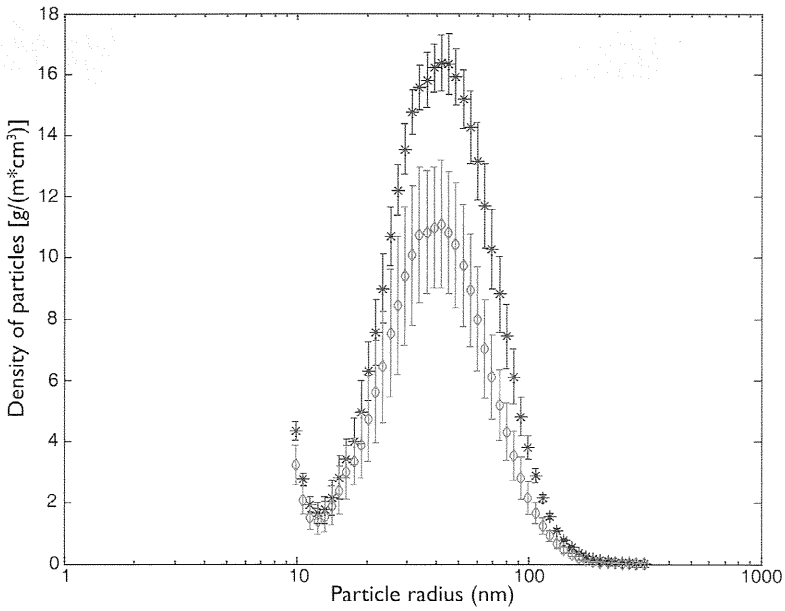


Fig 7: Measured particle size distribution at sample point 3 with a temperature of 20°C behind the pre-cooler. * is without steam, ◊ is with 8.3kg/h steam

this time at 300°C (573K) for more than one hour and weighed again in order to investigate the amount of volatile compound in the samples.

RESULTS AND DISCUSSION

SMPS measurement

The experiments started with measurements using an SMPS. The first set-up tested was with a temperature before the SJAC of 20°C and 8.3kg/h steam injection. The cut-off diameter of the impactor in front of the SMPS was 800nm, 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 626nm.

It is noticeable that a slight difference in efficiency between the SJAC and the total system is present. 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 since larger particles, which contribute more to the total particle mass, will remain bigger, and are therefore more easily removed than smaller particles.

In Fig 7 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 35nm, while the end of a small mode seems to be present at approximately 10nm. This small mode is associated with so-called secondary aerosol, like condensed hydrocarbons or sulphuric acid formed by homogeneous nucleation.[20,21]

As mentioned before the conversion of number measurements to particle mass is not straightforward. Fig 8 illustrates the effect of different densities and the effect of releasing the assumption of spherical particles by application of the formula of Park et al.[18] as mentioned before. It illustrates that the assumption of non-spherical particles shifts the particle radius with highest mass concentration density to smaller radii. This is expected as in fractal theory density decreases with increasing particle radius. The large difference in absolute value is most notable. Comparison of these data with data from absolute filter measurements, presented later in this paper, points out that the application of the formula from Park et al.[18] gives the best approximation of mass, although a large discrepancy is still present. For an indication of total particle mass in Tables 2 through 4 the formula of Park et al.[18] is used.

During the second set-up the temperature after the pre-cooler was 30°C and 8.3kg/h steam was injected. The sample-flow through the EC and CPC was 0.2 l/min. The measured midpoint diameters range from 19.8 to 897nm. The impactor had a cut-off diameter of 1μv. Sampling was co-current, besides the samples at sample point 1, which were counter-current. Table 3 shows the results of this measurement.

An increase in measured particle emissions of the engine as compared to the number of particles shown in Table 2, both in number and mass, is notable. The slightly larger measurement range in the former measurement 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 the SJAC than the first set-up. This also means that the difference between the measured concentration at sample point 1 and 2 has increased over time.

The third condition measured was expected to be the most beneficial condition with a temperature before the SJAC of 20°C and 10kg/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 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 8.3kg/h steam injection), which can be explained by the larger number

Table 3: SMPS measurement with a temperature of 30°C and 8.3kg/h steam injection

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

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

Table 4: SMPS measurement with a temperature of 20°C and 10kg/h steam injection

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 Figs 9 and 10.

The difference in measured value between sample points 1 and 2 has gradually increased from the first condition to the third condition. This ostensible retention of particles between sample points 1 and 2 is in fact a real retention in the pre-cooler (for position see Figs 1 and 5). After 40h 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 Fig 11. 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 which was not surprising. The remaining space between the windings was reduced that much that there was barely any space left between the first windings, making them virtually useless and forcing most gas to stream at a higher than normal velocity through the last windings.

Using a design of a cooler less prone to fouling or not having such a critical passage could avoid this complication.

	Measurement 1 (mg/mn³)	Measurement 2 (mg/mn³)	Average (mg/mn³)
Sample co-current	37	45	41
Sample counter-current	44	41	43

Table 5: Result measurement influence of sample point direction at 110°C

Absolute filter measurement

In order to verify the mass-results as measured by an SMPS, absolute filter measurements were performed. First the influence of sampling direction was investigated. 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 5.

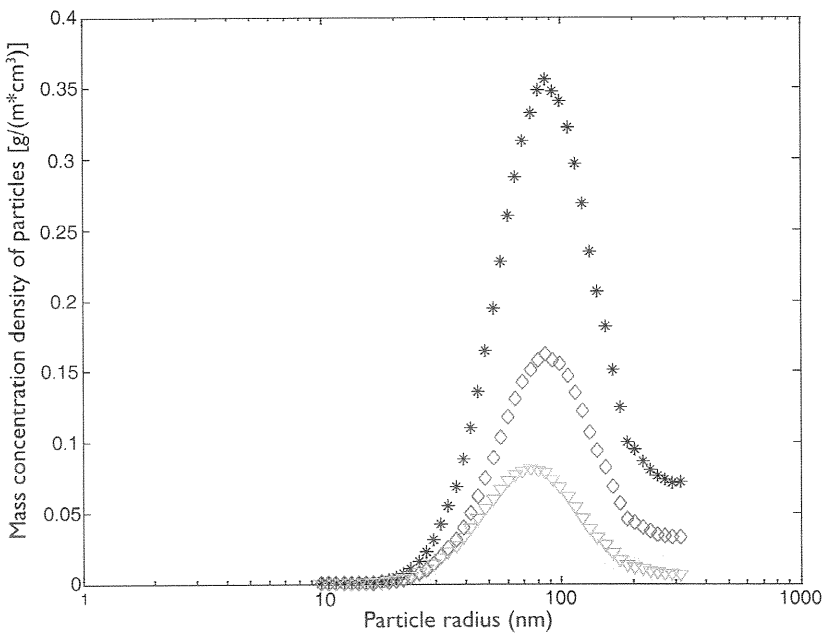
The mass of accumulated dust can be determined with an accuracy of 0.4mg. The volume during sampling can be determined with an accuracy of 2%. The sampled volume of these measurements differed slightly but is approximately $0.27 m_n^3$. For the measurement conditions in this report the maximum measurement error is $\pm 2 mg/m_n^3$.

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.[6]

Note that the mass-concentration of particles measured with the absolute filter measurement is smaller than the mass-concentration calculated from SMPS-measurements, despite the correction for non-spherical particles. Other measurements, presented in Table 6 and 7, show mass concentrations of the same order as those in Table 5. Measurement number 5 at the inlet of the pre-cooler in both Table 6 and 7 was treated as an erroneous measurement as this measurement is larger than the average plus two standard deviations.

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

Fig 8: Conversion assuming round particles and density of 1000 (◊) and 2200 (*) kg/m³ versus formula from Park et al.[18] (▽) for high load



Position \ Measurement		1 mg/m$_n^3$	2 mg/m$_n^3$	3 mg/m$_n^3$	4 mg/m$_n^3$	5 mg/m$_n^3$	Average mg/m$_n^3$
Inlet pre-cooler (engine out)	(1)	37	45	44	41	(56)	42
After pre-cooler **with** cyclone	(2)	37	40				38
After pre-cooler **without** cyclone	(2)						-
After SJAC, 25°C, 10kg/h steam	(3)	29	35				32
After SJAC, 30°C, 8.3kg/h steam	(3)	34	37				35

Table 6: Measurements from absolute filter at 110°C, between brackets sample point number

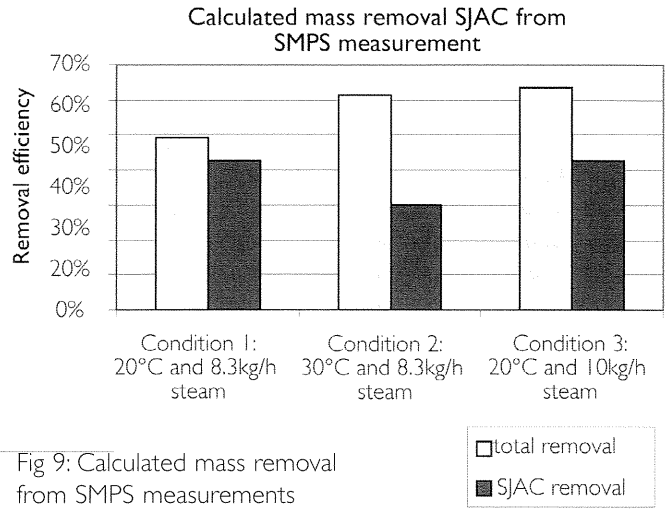


Fig 9: Calculated mass removal from SMPS measurements

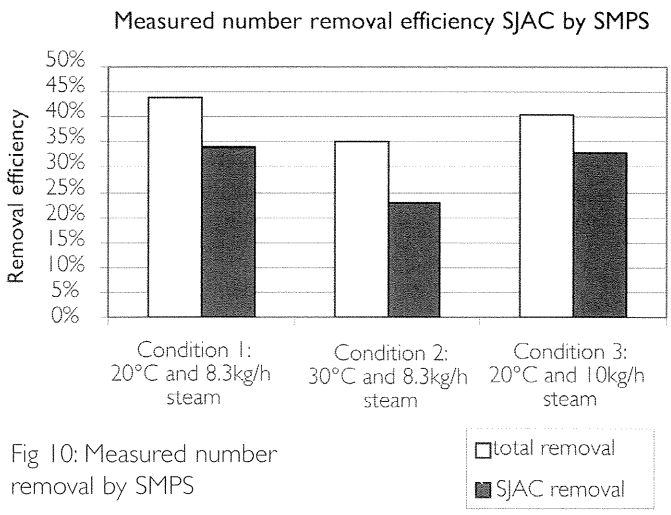


Fig 10: Measured number removal by SMPS

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 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 points 1 and 2.

It can be seen that the average results are relatively close to each other, although there is quite some scatter between the individual measurement points.

The share of volatile components in the measurement at 110°C can be determined by equation 4, because the sample at 300°C does not contain any volatile material anymore.

$$share_{volatile} = \frac{m_{110°C} - m_{300°C}}{m_{110°C}} \quad (4)$$

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, ie 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). In Fig 12 the standard deviation between measurements results are shown as bars, not the maximum measurement error. It can be concluded that volatile components are present on the particles when measured at 110°C, but in relatively small amounts, as in Fig 12.

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 Fig 13; 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. It has to be kept in mind that the conversion

Fig 11: Schematic illustration of used cooler

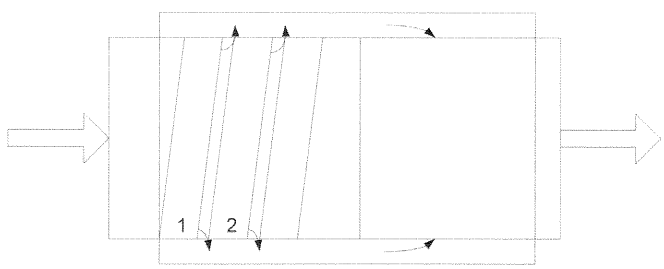


Table 7: Measurements from absolute filter at 300°C, between brackets sample point number

Position \ measurement		1 mg/m$_n^3$	2 mg/m$_n^3$	3 mg/m$_n^3$	4 mg/m$_n^3$	5 mg/m$_n^3$	Average mg/m$_n^3$
Inlet pre-cooler (engine out)	(1)	34	43			(58)	38
After pre-cooler with cyclone	(2)	33	37				35
After pre-cooler without cyclone	(2)	39	34				37
After SJAC, 25°C, 10kg/h steam	(3)	22	30				26
After SJAC, 30°C, 8.3kg/h steam	(3)	32	34				33

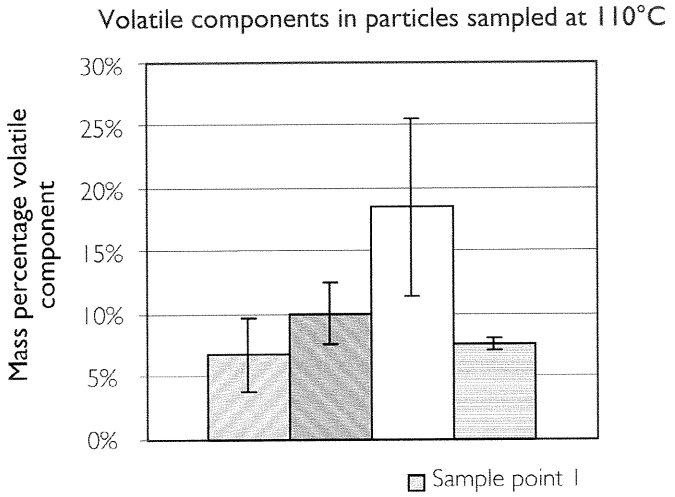


Fig 12: Share of volatile component in sampled mass at 110°C; bars indicate standard deviation between measurement results

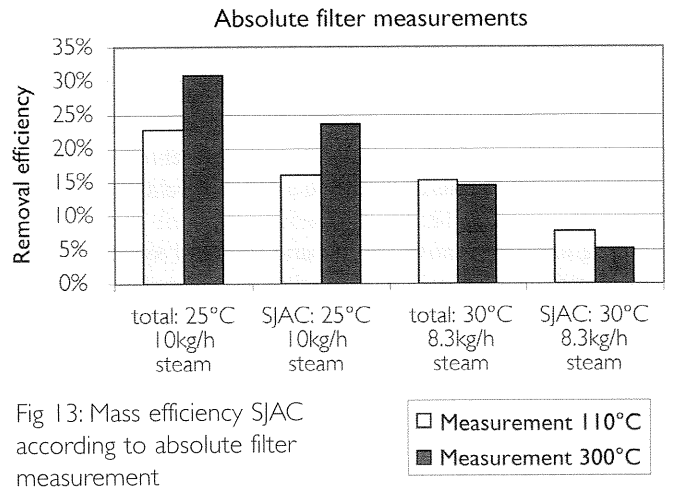


Fig 13: Mass efficiency SJAC according to absolute filter measurement

of SMPS measurements to mass is still an approximation, as well as that the measurement conditions of SMPS measurement and absolute filter measurement are not equal.

CONCLUSION

Measurements performed with an absolute filter and calculated mass from an SMPS measurement do not necessarily lead to the same absolute or relative results. If particle mass is important absolute filter measurements are recommended, as no assumptions are necessary and interpretation of the measurement is rather 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 work show that particle accumulation in the cooler can seriously affect the conclusions of an experiment.

Measurements show that the SJAC-principle works. Using a cyclone with a cut-off diameter of 1µm up to 24% of particle mass can be collected as measured with an absolute filter and up to 33% of the number of particles as measured with a SMPS can be collected. New improvements in the technique and the possibility for better removal efficiency than a cut-off diameter of 1µm give reason to expect better removal efficiencies in future concepts.

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NOMENCLATURE

η_{tot}	Particle removal in total system as defined by equation 1
η_{SJAC}	Particle removal by SJAC as defined by equation 2
x	Variable indicating mass or number at point specified by subscript
m	Mass (in equation 3 in fg, in equation 4 in kg)
d_m	Mobility diameter