**VTT Technical Research Centre of Finland**

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*Published in:*
Proceedings of the 30th CIMAC World Congress 2023

Published: 12/06/2023

*Document Version*
Publisher's final version

*License*
Other

Link to publication

*Please cite the original version:*
Lehtoranta, K., Aakko-Saksa, P., Vesala, H., Järvinen, A., Peitz, D., & Jokiluoma, J. (2023). Reducing particle emissions from marine engines – fuel choices and technology pathways. In *Proceedings of the 30th CIMAC World Congress 2023* Article 555

BUSAN, JUNE 12 –16, 2023

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# Reducing particle emissions from marine engines – fuel choices and technology pathways

Emission Reduction Technologies - Exhaust Gas Aftertreatment Solutions


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This paper has been presented and published at the 30th CIMAC World Congress 2023 in Busan, Korea. The CIMAC Congress is held every three years, each time in a different member country. The Congress program centres around the presentation of Technical Papers on engine research and development, application engineering on the original equipment side and engine operation and maintenance on the end-user side. The themes of the 2023 event included Digitalization & Connectivity for different applications, System Integration & Hybridization, Electrification & Fuel Cells Development, Emission Reduction Technologies, Conventional and New Fuels, Dual Fuel Engines, Lubricants, Product Development of Gas and Diesel Engines, Components & Tribology, Turbochargers, Controls & Automation, Engine Thermondynamis, Simulation Technologies as well as Basic Research & Advanced Engineering.
 

## ABSTRACT

Particle emissions from marine applications have been receiving increasing attention in recent years, whether as black carbon for their impact in artic ice melting and global warming, as nanoparticles for their health impact or due to the general classification of soot as a carcinogenic substance by the World Health Organization. Fulfiling the global requirements of marine propulsion and power generation applications only a few technology paths are commercially available which have the potential to reduce particle emissions significantly.

SOX scrubber in combination with traditional HFO operated diesel engines represent one route trying to achieve this objective. Alternatively, the engines can be converted to dual fuel operation, including liquified natural gas (LNG) operation or the fuel can be changed to a distillate liquid fuel which can be combined with a diesel particulate filter (DPF).

In detail, these different approaches vary not only in terms of technical challenges, required onboard modifications and costs, but also with regards to their actual performance in reducing black carbon (BC), particle mass (PM) and nanoparticle-related particle number (PN) emissions. In the European Union the PN abatement performance will gain additional attention as in upcoming regulations a cut-off level for ultra-fine nanoparticle emissions of 10 nm will likely be introduced.

In this contribution we present a comparison of the different technological options for low BC, PM & PN with their respective challenges and performance characteristics. Measurements have been conducted on marine medium-speed and high-speed engines on both engine test beds and on board. The setups were chosen in a way to cover the range of commercially available paths to reduce particulate emissions. For the measurements a range of analytical devices for assessing particle-related emissions (together with gaseous emissions measurements) were employed. Results are set in context of current and upcoming emission regulation for international, near-coast and inland water marine applications.

# 1 INTRODUCTION

Particle emissions from marine applications have been receiving increasing attention in recent years. Especially at coastal areas, shipping emissions can significantly contribute to the air quality and human health [1], [2]. World health organization has classified the soot as a carcinogenic substance and the smallest particles, nanoparticles, are known to migrate deep into human body contributing e.g., to heart and pulmonary diseases. On a global scale even hundreds of thousand premature deaths annually are estimated due to shipping [3]. In addition, the soot, or black carbon (BC), is categorized as the second important anthropogenic species contributing to global warming (after $CO_2$ emission) [4]. The effect which is especially important at the Arctic Area, due to BC deposition on ice and subsequent albedo change.

The international Maritime Organization (IMO) has implemented regulations to reduce emissions from ships. Regulations consider emissions of nitrogen oxides ($NO_x$) and sulphur oxides ($SO_x$) to the air, the latter via fuel sulphur level limitation. However, there is no IMO regulation for particle emissions of ships, although IMO has been working on BC emissions from international shipping since 2011 (MEPC 68).

In EU, the emissions in inland water ways are regulated. Stage III A standards introduced emission limits for engines used in inland waterway vessels and Stage V regulation tightened the limits further. These emission limits for inland waterway vessels include CO, HC, $NO_x$ and also particles. Both particle mass (PM) and particle number (PN) are included in Stage V regulation.

In United States, EPA regulations are in line with IMO for vessels engaged in international shipping. In addition, the EPA Tier 2-3, include a HC emission standard and a CO standard for a selection of new engines (category 3). Emission standards for category 1 and 2 engines are based on the land-based standard for non-road and locomotive engines. These engines are typically used in e.g., tugboats, supply vessels, fishing vessels and as stand-alone generators for auxiliary electrical power on many types of vessels. The strictest regulation is Tier 4, and this includes also a limitation for PM.

Legislation and/or limits for other emission components, particularly, the fuel sulphur level limitation, define the basis conditions for the particle emission reduction technologies as well. In order to meet current 0.5% or 0.1% (outside or inside ECA) fuel sulfur limits, ships are increasingly utilizing lower sulphur level fuels or, alternatively, scrubbers to reduce sulfur emissions from the combustion of sulfur-rich heavy fuel oil. These technology choices have effects on particle emissions [5] and the particle emission reduction technology can only be selected once the technology choice to fulfil the sulphur legislation is adopted.

In the current study we focus on three different pathways to investigate the possibilities to reduce particle emissions from ships. First, low sulphur level distillate fuel combined with a diesel particulate filter (DPF), second, nearly sulphur free gaseous fuel i.e., liquified natural gas (LNG) without any aftertreatment equipment, and third, high sulphur level heavy fuel oil (HFO) in combination with a scrubber and wet electrostatic precipitator (WESP) to remove particles.

In the presented paper the experiments are done in marine engine laboratories. We study the effectiveness of these fuels and after-treatment systems to reduce particle emissions, namely PM, PN and BC from marine engines.

# 2 EXPERIMENTAL

Experiments were done in two different marine engine laboratories. Altogether, three different setups with the engines, fuels and after treatment devices are presented in the following chapters.

## 2.1 DPF with low sulphur distillate fuel

Performance of DPF combined with low sulphur level distillate fuel was studied at Anglo Belgian Corporation (ABC) Engine laboratory. A 2000kW eight- cylinder in-line DZC medium speed engine from ABC with 256 mm bore was utilized, fitted with a single stage turbocharging system and a Pump Line Nozzle (PLN) injection system. From the turbocharger outlet, the exhaust gas entered the diesel particulate filter (DPF) system. Further downstream followed the SCR (selective catalytic reduction) reactor for NOx removal (Figure 1). DPFs have been widely utilized for decades in connection with high-speed diesel engines i.e., smaller engines in vehicles and the off-road sector, larger ones in locomotives, inland ships and selected open-see applications such as in luxury yachts, research, or work vessels. Wall-flow monoliths are the most common type of diesel exhaust particulate filter and utilized in the presented study as well. In wall flow monoliths the channel ends are alternatively plugged to force the gas flow through the porous walls acting as a filter. The SCR is placed downstream of the DPF to benefit from the removal of particles, thereby enabling a more compact setup. Another benefit of the DPF being as close-coupled to the engine as possible is the sound attenuation by the wall-flow filter, which reduces the need for a silencer.

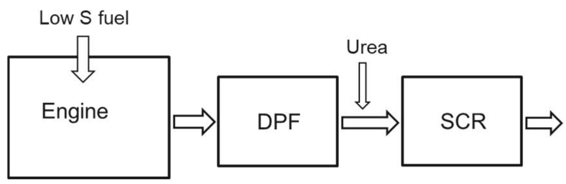



Figure 1. Simplified DPF testing setup

There were no noble metals in the catalyst coating of the DPF or SCR, which could also enable the usage of higher fuel sulphur levels in combination with the system. The soot particles collected on the DPF are removed in regular intervals by a built-in regeneration system; burners in the exhaust path elevate the exhaust temperatures in order for the catalytic coating to oxidize the soot. This concept has been in use on hundreds of marine high speed diesel engines in open see applications like luxury yachts, research and work vessels for improved air quality and clean decks.

In the presented study, the DPF setup was run according to the EU stage V certification requirements, detailing amongst others the official test cycles and mandating EN 590 diesel fuel (with sulphur level below 0.001%). The ISO 8178 test cycles E2, D2 and E3 were utilized in present study, covering engine load modes of 100%, 75%, 50%, 25% and 10%.

### 2.2 Natural gas as a fuel

Performance of natural gas as a fuel was studied at VTT Engine laboratory. A four-cylinder medium-speed 4-stroke marine engine that was retrofitted to enable operation with natural gas in dual fuel (DF) mode was utilized in experiments done in engine laboratory. In this DF mode, a small quantity of liquid fuel is first injected to pilot combustion, which is then sustained by delivery of the main quantity of natural gas. The maximum power of this engine in DF mode was 1400 kW. Engine loads from 30% to 85% were utilized in testing with natural gas as the main fuel (and very low S level marine gas oil as the pilot fuel). As the natural gas combustion, in general, is known to result in lower particle emissions than diesel type fuel combustion (since there is, in practice, no soot formation from natural gas combustion), no after-treatment system was included in the studies with the DF engine.

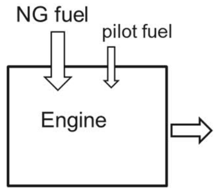



Figure 2. Simplified NG fuel testing setup

### 2.3 Scrubber and WESP with high sulphur heavy fuel oil

Performance of a scrubber combined with a wet electrostatic precipitator (WESP) was studied at VTT engine laboratory. The four-cylinder medium-speed 4-stroke marine engine was utilized in experiments. The maximum power of this engine was 1640 kW, and the engine was run with high sulphur level heavy fuel oil. A part of the exhaust was conducted through the scrubber followed by the WESP (Figure 3). The scrubber is designed to decrease $SO_x$ emissions and it relies on closed loop cycle. Sodium hydroxide (NaOH) was dosed into the process water to stabilize the pH in the device to reach efficient $SO_x$ reduction. The scrubber is followed by the WESP designed to decrease particle emissions. In the WESP, particles are negatively charged with a corona discharge created by a high-voltage electrical field. The ionized particles will migrate and are collected on the grounded walls of the device.

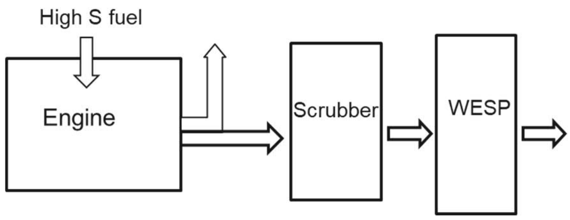



Figure 3. Simplified WESP testing setup

Engine loads of 30%, 50% and 75% were utilized in testing. Heavy fuel oil with high sulphur level was applicable since the scrubber was involved reducing the $SO_x$ emissions.

### 2.4 Fuels specification

Low sulphur level distillate fuel is one of the fuels to fulfil the IMO SECA requirements i.e., fuel sulphur level 0.1 %. Even lower sulphur content fuel is required when discussing EU stage V certification (also for inland waterway vessels) meaning the reference diesel fuel for testing compression-ignition engines has a sulphur content of 10 ppm (max), which is 1/100 fraction of the IMO SECA requirement. This fuel (Marine gas oil MGO) was utilized in the engine equipped with the DPF (ABC engine lab) and, in addition, as a pilot fuel when running in DF mode with NG as the main fuel (VTT engine lab) (Table 1). NG itself had high methane content of >95%. In comparison to NG, the engine was also run with marine diesel oil (MDO) having sulphur content closer to the maximum of SECA requirements i.e., 0.08% in our study. Heavy fuel oil, with high sulphur content, namely 2.75% in our study, was utilized in the engine when running the exhaust through a scrubber and WESP (VTT engine lab).

Table 1. Fuels specification

| | MGO * <0.001%S | MDO <0.1%S | HFO 2.75%S |
|---|---|---|---|
| | studies with DPF & pilot fuel in NG studies | studies in comparison to NG | studies with scrubber & WESP |
| Density (15°C) (kg/m3) | 836 | 879 | *N/A* |
| Viscosity (40°C, mm2/s) | 2.94 | 4.07 | *N/A* |
| Heating value, lower (MJ/kg) | 42.8 | 42.2 | 40.5 |
| Flash point (°C) | 66 | 78 | 113,5 |
| Sulphur (mg/kg) | 6.1 | 822 | 27500 |
| Ash % (m/m) | < 0.005 | < 0.005 | 0.059 |
| Carbon %(m/m) | 86.2 | 87.4 | 85.3 |
| Hydrogen %(m/m) | 13.9 | 12.5 | 11,0 |
| Nitrogen (mg/kg) | 40.6 | 367 | *N/A* |
| Ni (mg/kg) | < 0.50 | < 0.50 | 39,4 |
| V (mg/kg) | < 0.50 | < 0.50 | 199 |

**values from one fuel batch, different fuel batches in DPF tests and when operating with NG as pilot fuel – all batches however fulfilled the EN590 specification*

### 2.5 PM & PN Sampling

Exhaust PM was sampled following the ISO 8178-1:2006 standard. This is also the method specified for PM emissions sampling from inland waterway vessels in EU. According to this standard, the PM is determined as the mass of any material collected on a filter after diluting exhaust gas with clean, filtered air to a temperature higher than 42 °C and less than or equal to 52 °C, as measured at a point immediately upstream of the filter. The standard also defines a minimum dilution ratio of 4:1, but no maximum, before PM sampling is conducted. Since the dilution ratio variation can result to significant changes in PM [6], [7] the dilution ratio was kept constant during the measurements, on top of what the standard prescribed. We selected a DR of 10:1, which already significantly decreases sensitivity of semi-volatile material condensation while at the same time minimizing sampling duration. Samples were collected on TX40HI20-WW filters (Ø 47 mm) and collection times ranged from 5 to 30 minutes.

The PN measurement method, originates from the PMP (Particle Measurement Programme) work and considers only non-volatile particles with a diameter greater than 23 nm. This method is also mandated by the Stage V regulation for inland waterway vessels introduced 2020, which requires compliance with a non-volatile PN limit. A Dekati® Engine Exhaust Diluter (DEED) was used for PN sample conditioning in the current study. The system consists of two ejector diluters, providing two options for total dilution ratio, 100:1 or 1000:1, and an evaporation tube between the two dilution units. The temperature of the first ejector was ~200 °C and the temperature at the outlet of the DEED unit was below 35 °C. PN>23nm concentrations were determined with an Airmodus A23 Condensation Particle Counter (CPC).

In part of the experiments, the elemental carbon (EC) samples were collected on quartz filters and analyzed by the thermal optical method. While, in other part of the experiments, a micro soot sensor using photoacoustic spectroscopy (PAS) principle was utilized for black carbon (BC) measurement. Both these methods are considered as relevant methods to analyze black carbon from ship emissions [8], [9].

## 3 RESULTS AND DISCUSSION

### 3.1 DPF with low sulphur distillate fuel

The DPF setup was run according to the EU stage V certification requirements, meaning official ISO 8178 test cycles E2, D2 (both for generator curve) and E3 (for propeller curve). The PM, PN and BC measurement results, as measured engine out and downstream of the DPF are presented in the Figure 4 for all three test cycles.

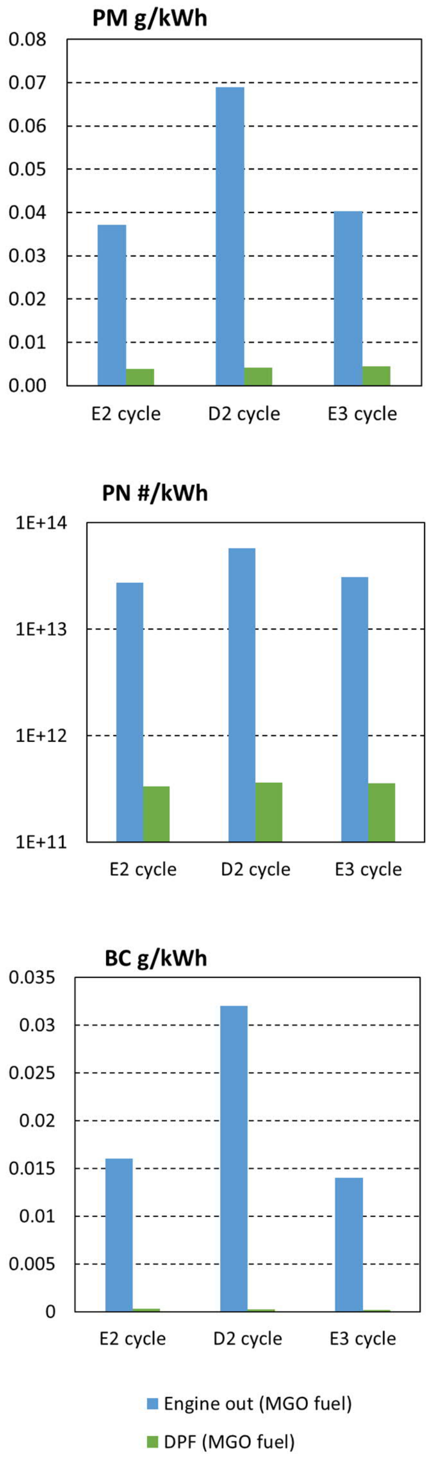



Figure 4. PM, PN and BC as measured engine out and downstream of a DPF (with low sulphur MGO as a fuel).

The DPF was found to be very effective in collecting the particles over the entire test cycles for the generator and propeller curve with an efficiency of near 99% when discussing all studied parameters, i.e., PM, PN and BC. The measured PM levels downstream of the DPF were all below 0.005 g/kWh (over the test cycle) while BC levels were extremely low, below 0.0005 g/kWh. This DPF system together with the low sulphur distillate fuel have proven to reach EU Stage V PM and PN emission levels [10]. The SCR installed downstream of the DPF ensured also that the low levels of $NO_x$ required by the EU Stage V were reached.

For comparison, we present here also results from certification of a different 1920 kW 1800 rpm high speed marine diesel engine running on marine gas oil (MGO) (with similar very low sulphur level as shown in Table 1) as a representative example of DPF in marine open sea applications like luxury yachts, research, and work vessels. PM and BC results are presented in Figure 5 as measured engine out and DPF out.

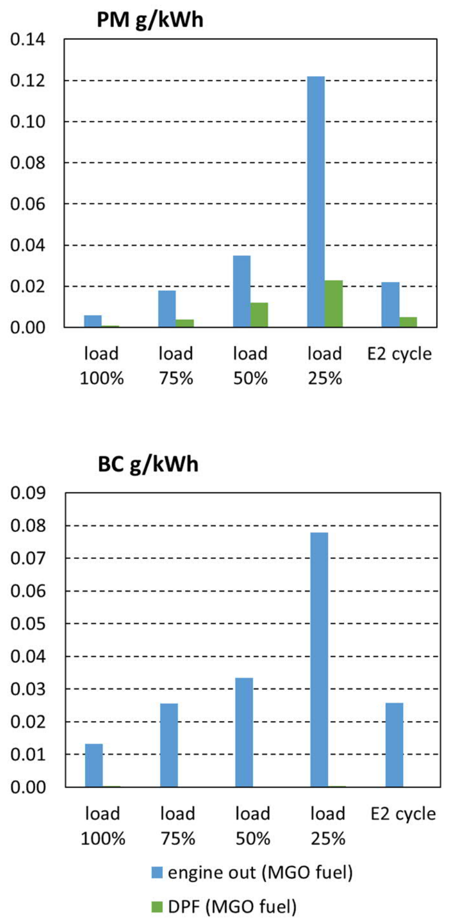



Figure 5 PM and BC results (from a high-speed engine) as measured engine out and DPF out at different engine loads and calculated over the E2 cycle.

In addition to the PM and BC results calculated over the 4 different load modes we also present the results as calculated according to E2 cycle where load conditions of 100%, 75%, 50%, and 25% are weighted with factors of 0.2, 0.5, 0.15, and 0.15 (according to the ISO 8178). These altogether in Figure 5 shows how the result over the E2 cycle in this case, is very close to the result achieved from the 75% load which is weighted with a factor of 0.5 in the cycle calculation.

When we compare the BC values measured DPF out to those measured engine out, we see that removal efficiencies of 98-99% and above are achieved. For PM, removal efficiencies are 77-83%, resulting to the level of 0.005 g/kWh as calculated over the test cycle. These results form the high speed application confirm that for both, medium and high speed marine engines soot can be effectively removed as is also known for on-road engine applications equipped with DPF for decades by now.

One important issue is the soot removal regeneration process of the filter. In present study the system was equipped with a burner system to periodically oxidize the soot collected on the filter. As the measurements were conducted according to the stage V requirements the emissions during regeneration were also measured and included in the results calculated over the reported test cycles.

Another issue in marine applications is the ash collection on the filter. In addition to fuel itself, lubricating oils used in marine engines contain ash and contribute to the ash collected on the filters, as well. Using distillate fuel and low ash-forming lubricating oil reduces the amount of ash collected in the filter and extends the operating time between required ash removal. The regeneration process should also support the ash removal from the filter over the filter lifetime.

### 3.2 Natural gas as a fuel

Natural gas was utilized as the main fuel in dual fuel (DF) mode while the high-quality and very low sulphur level MGO (marine gas oil) was utilized as pilot fuel (according to the engine manufacturer's instruction). In comparison the engine was run also with lower quality MDO (S < 0,1%) liquid fuel. The PM, PN and BC measurement results, from both the NG and MDO experiments at two different load modes (40% and 85%) are presented in the Figure 6.

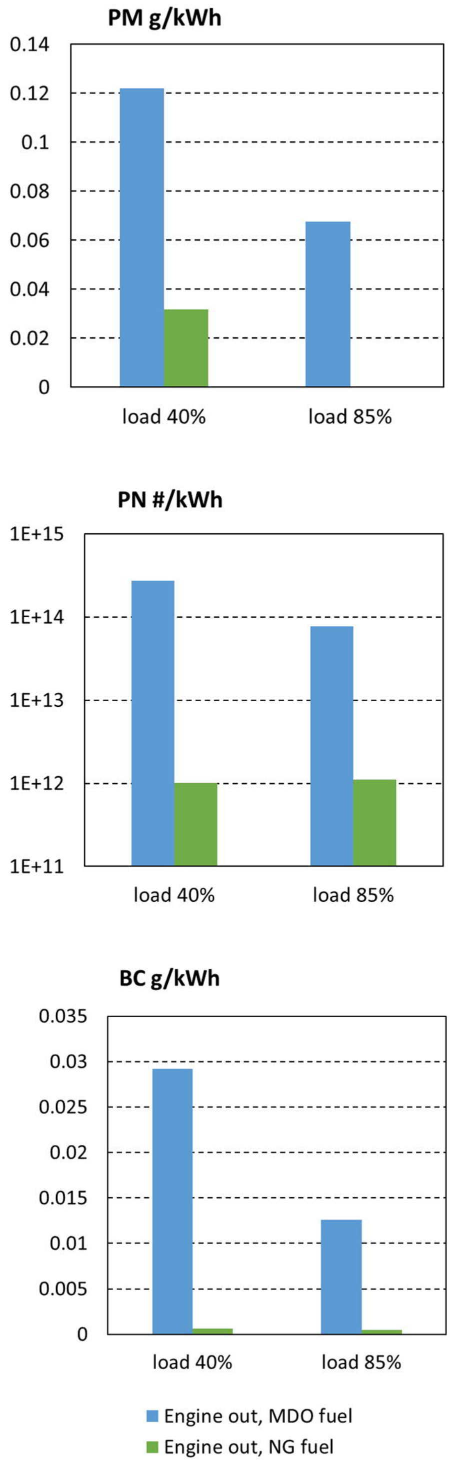



Figure 6. PM, PN and BC as measured engine out with MDO as a fuel and with natural gas (NG) as a fuel.

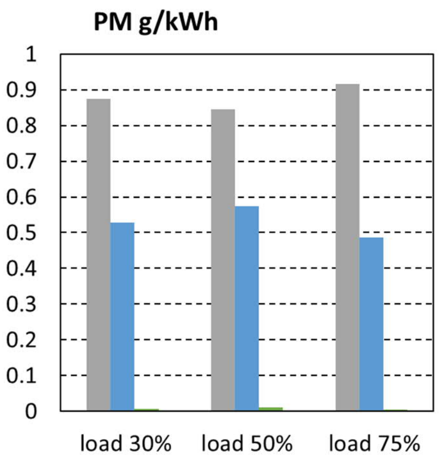
DF operation with NG as the main fuel resulted in low PM levels, at a level 72−75% lower than the MDO usage. And the impact of NG use was actually magnified when nonvolatile PN>23nm was considered, with PN levels 98−99% lower than when using MDO. When shifting to DF operation, only traces of black carbon were observed as values were well below 0,001 g/kWh at both load modes studies. These results were earlier published in refs. [5], [11] and they are comparable to studies onboard LNG-powered ships that have also shown low particle emission levels [12], [13].

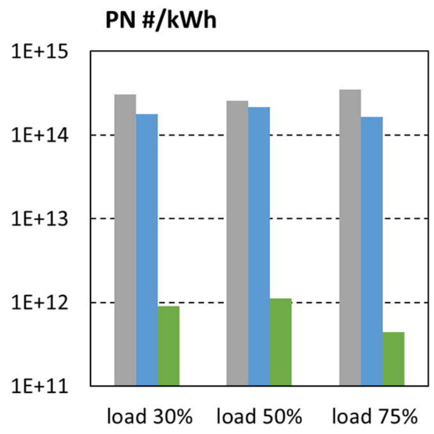
With natural gas combustion in dual fuel engines, namely low-pressure dual fuel engines, due to low temperature combustion, also low $NO_x$ levels can be achieved. However, the hydrocarbon emissions tend to be higher than from diesel engine and because natural gas is mainly methane, also the hydrocarbon emission is mainly methane. Since methane is a strong greenhouse gas, its emissions should be minimized.

One advantage of the NG is that its combustion produces less $CO_2$ than diesel combustion. At 40% load a 24% and at 85% load 31% lower $CO_2$ levels were recorded [5]. For comparison, onboard measurements by Peng et al. [13] showed a $CO_2$ reduce of 18% when switching a dual-fuel marine vessel from diesel to natural gas operation. However, if the methane emissions are not minimized these $CO_2$ benefits maybe lost due to the high global warming potential (GWP) of methane [14].

### 3.3 Scrubber and WESP with high sulphur heavy fuel oil

When studying the WESP system, emission measurements were conducted from three different measurement points: engine out, downstream of the scrubber (but upstream of the WESP) and downstream of the WESP. PM, PN and BC results from those three locations at the studied engine loads of 30%, 50% and 75 are shown in the Figure 7.



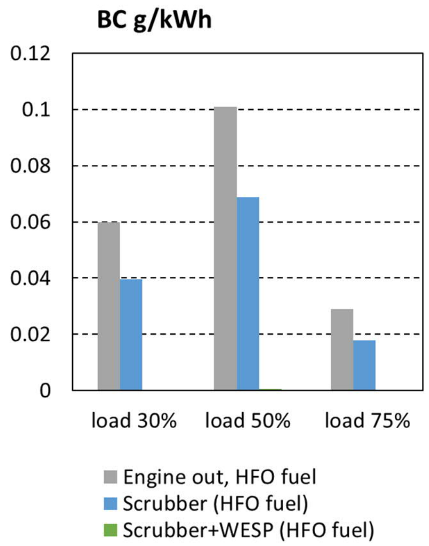




Figure 7. PM, PN and BC as measured engine out (with HFO as fuel), downstream of the scrubber (but upstream of the WESP) and downstream of the WESP.

The results indicate that a combination of a scrubber and a WESP decreases particle emissions very efficiently. The scrubber can only have moderate reduction in particle emissions, based on current study as well as previously reported studies with scrubbers [5], [15]. The WESP makes a remarkable addition to this, resulting in total particle emission reduction of 97-99%, when discussing all studied parameters, i.e., PM, PN and BC. The measured PM levels downstream of the WESP were all below 0,012 g/kWh while BC levels were below 0.001g/kWh.

The combination of the scrubber and the WESP does not have any significant effect on the $NO_x$ levels. If $NO_x$ reduction is needed, the system must be equipped with e.g., an SCR system to reduce $NO_x$ emissions. The SCR would then need to be fit upstream of the scrubber to ensure high exhaust gas temperature required by the $NO_x$ reduction reactions.

To the authors' knowledge there are only two studies done with the WESP connected to marine sized engine, the present study is fulfilling the one by *Järvinen et al.* [16] and the other one is by *Jeong et al* [17]. These two different setups show that with a WESP connected downstream of the scrubber particle emissions can be significantly reduced.

In addition to particle emissions WESP removes efficiently also water mist, oil mist and acid mist, which results in efficient reduction of visible plume and other exhaust emissions. Remarkable reduction in plume visibility was also observed in the tests [16]. Visible plume is a downside of using wet exhaust gas treatment systems, such as $SO_x$ scrubbers.

### 3.4 Discussion of the three technologies, regulation, and prospects

When thinking of the regulations concerning particle emissions from ships, we investigate the EU regulation for inland waterway vessels. The low sulphur level distillate fuel combined with a diesel particulate filter was run over the official test cycles and proved to fulfill the requirements i.e., PM limit of 0.015 g/kWh and PN limit of $1x10^{12}$ #/kWh.

The NG fuel studies as well as the WESP studies were conducted on couple of different load modes but not over any entire test cycle. However, we can use the results from the studied load modes as indications whether the limit values could be reached. In the case of PM, the NG usage led to higher levels (0.02 and 0.03 g/kWh) compared to the limit value of 0.015 g/kWh. However, there might be room to improve this as shown earlier by the lower PM level recorded from the exhaust of another engine with NG usage [5]. Additionally, a recent review reported median PM emission of only 0.0003 g/kWh for marine LNG DF engines (> 1 MW and engine load > 40%) [18]. The PM levels downstream of the WESP were all well below the limit value of 0.015 g/kWh indicating there could be possibilities to reach the level over test cycles as well.

The PN levels from both, the NG and WESP usage were very close to the limit value of $1x10^{12}$ #/kWh. This gives indication of what the operation over the test cycles could be, however, keeping also in mind, that to reach the official limit value some improvements are needed since e.g., the results calculation over the official test cycles also takes into consideration of deterioration factors.

For all three technologies studied (DPF, NG and WESP), black carbon emissions were low (below 0.001 g/kWh).

We note that the usage of the scrubber combined with the WESP is not actually an option for EU inland waterway vessels but more a choice for oceangoing vessels that prefer to utilize the less costly heavy fuel oil with higher fuel sulphur level. In present study, we only compare this to the EU regulation for inland waterway vessels since that is the regulation where PM and PN limits already exist and this regulation might also give indication about the possible global regulation in future.

Even though the NG or WESP usage were not proven to reach stage V PM and PN levels in the present study, the particle emission reduction achieved by their usage were remarkable and their usage would have an impact, namely benefit on the air quality and human health. In addition, since black carbon has also warming impact on climate, reducing BC has benefits for climate as well. These benefits are obviously true also for the DPF usage since the stage V approval was achieved confirming even lower particle emissions levels.

In near future, and already today, GHG emissions reduction is a key issue leading the technologies development. IMO's 4th GHG study (2020) shows that emissions are projected to increase while IMO's target is that total annual GHG emissions from international shipping should be reduced by at least 50% by 2050. This calls for new fuels. NG can be considered as a transition fuel which facilitates the decarbonization of maritime transport. Ideally, existing engine solutions and tank arrangements can be used with the future fuels (very low or zero carbon fuels) with minimal modifications [19]. The utilization of LNG in DF engines together with liquid fuel for ignition also allows fuel flexibility for the ship operators.

Fossil marine fuels can be switched to non-fossil counterparts that are chemically similar but produced differently. These "drop-in" fuels resemble diesel, LNG, or methanol. Also, in the case of these carbon-neutral drop-in fuels, exhaust emissions are expected, meaning e.g., that particle emission formation occurs. Therefore, these future fuels also need particle emission reduction technologies [18].

In addition, new carbon-free fuels, like hydrogen and ammonia are considered as options for future marine applications. These might still also need some particle reduction, e.g., if these are to be used in dual fuel engines which still require diesel-type fuel for ignition. For example, DPF already combined with $H_2$ DF engines for meeting lowest

PM & PN targets (EU Stage V) in one commercial application [20]

## 4 CONCLUSIONS

Even though the particle emissions from ships are not globally limited, they have effects on climate as well as on human health, and therefor their limitation would be important. This study shows that there are technologies applicable, for both low sulphur level fuels as well as high sulphur level fuels, that can significantly reduce particle emissions from ships. DPF combined with low sulphur level distillated fuel is proven to reach the very low PM and PN levels required by the EU stage V regulation. NG usage as a fuel (without any after treatment system) leads to remarkably lower particle emission levels than the usage of low sulphur level liquid fuel. In addition, in the case of utilizing high sulphur level heavy fuel oil, the scrubber combined with the WESP can reach significant PM reductions of 98-99%.

When considering climate, and the targets to reduce GHG emissions in near future, new carbon neutral fuels are being developed and demonstrated. Combining these emission reduction technologies with the new carbon-neutral fuels could enable (near-)zero-emission shipping and these could be adaptable in near future.

## 5 DEFINITIONS, ACRONYMS, ABBREVIATIONS

**BC:** Black carbon

**$CH_4$:** methane

**CO:** carbon monoxide

**$CO_2$:** carbon dioxide

**DF:** dual fuel

**DPF:** diesel particulate filter

**EC:** elemental carbon

**ECA:** emission control areas

**GHG:** greenhouse gas

**GWP:** global warming potential

**HC:** hydrocarbon

**HFO:** heavy fuel oil

**IMO:** International Maritime Organization

**LNG:** liquefied natural gas

**MDO:** marine diesel oil

**MGO**: marine gas oil

**NaOH:** sodium hydroxide

**NG:** natural gas

**$NO_x$:** nitrogen oxides

**PM:** particle mass

**PN:** particle number

**SCR:** selective catalytic reduction

**SECA:** $SO_x$ emission control areas

**$SO_x$:** sulphur oxides

**WESP:** wet electrostatic precipitator

## 6 ACKNOWLEDGMENTS

This work was supported by several projects coordinated by the authors' organizations and participating companies. The staff at the engine laboratories is gratefully acknowledged for handling the engines, fuels, and related equipment during the measurement campaigns.

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