

Article

Assessing Particulate Emissions of Novel Synthetic Fuels and Fossil Fuels under Different Operating Conditions of a Marine Engine and the Impact of a Closed-Loop Scrubber

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Abstract: Particle emissions from marine activities next to gaseous emissions have attracted increasing attention in recent years, whether in the form of black carbon for its contribution to global warming or as fine particulate matter posing a threat to human health. Coastal areas are particularly affected by this. Hence, there is a great need for shipping to explore alternative fuels that both reduce greenhouse gas emissions, as anticipated through IMO, and also have the potential to reduce particle emissions significantly. This paper presents a comparative study of the particulate emissions of two novel synthetic/biofuels (GTL and HVO), which might, in part, substitute traditionally used distillate liquid fuels (e.g., MDO). HFO particulate emissions, in combination with an EGCS, formed the baseline. The main emphasis was laid on particle concentration (PN) and particulate matter (PM) emissions, combining gravimetric and particle number measurements. Measurements were conducted on a 0.72 MW research engine at different loads (25%, 50%, and 75%). The results show that novel fuels produce slightly fewer emissions than diesel fuel. Results also exhibit a clear trend that particle formation decreases as engine load increases. The EGCS only moderately reduces particle emissions for all complaint fuels, which is related to the formation of very fine particles, especially at high engine loads.



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Keywords: novel fuels; synthetic fuels; marine engine; exhaust emissions; scrubber; particulate matter; emission factors; EGCS; exhaust aftertreatment

1. Introduction

Air pollution is a significant environmental hazard to human health, ranking as the fifth biggest risk factor for the global population in 2016 (after malnutrition, dietary risk, high blood pressure, and tobacco) and the fourth greatest/biggest in Europe [1]. Evidence on the harm caused by fine particulate matter (PM_{2.5}) and ultrafine particles (UFP) produced, e.g., through combustion processes, has been provided. Particles in this size range are easily inhaled and deposit themselves inside the lungs, causing cardiovascular or pulmonary problems or inflammation [2,3]. The WHO project “Health risks of air pollution in Europe” (HRAPIE) identified shipping as one of the top three air pollution emission source categories, together with road traffic, space heating and air conditioning, however its impact remains a significant concern, particularly for island nations and port cities. Estimates from the World Health Organization (WHO) suggest that in 2019, air pollution was responsible for 4.2 million premature deaths, across the globe [4]. The WHO project “Health risks of air pollution in Europe” (HRAPIE) identified shipping as one of the top three air pollution emission source categories, together with road traffic, space heating, and air conditioning; however, its impact remains a significant concern, particularly for island nations and port cities [5].

Yet, the shipping industry is an essential part of the global economy, responsible for transporting over 80% of the world's goods by sea. Consequently, it is without a doubt a significant source of unavoidable greenhouse gases and other air pollution posing a threat to human health and air quality and contributing to global warming [6–9]. Ships traditionally use fossil fuels, especially heavy fuel oil (HFO), causing them to emit gaseous components like SO_x , CO_2 , and NO_x , as well as particulates. These particulates consist of a complex mixture of black carbon (BC), organic carbons (OC), heavy metals, ashes, and other substances [10–12]. Many of these components interact with the water-atmosphere interface, gradually degrading the surrounding environment in different manners (acidification of soil and water, particulates facilitating the melting of the polar caps) and might have adverse effects on populations in coastal regions [13,14].

Through the International Convention for the Prevention of Pollution from Ships (MARPOL), the International Maritime Organisation (IMO) aims at a worldwide approach to reduce the exhaust emissions from shipping. This includes the internationally recognised IMO 2020 regulation, which specifically targets fuel sulphur content aboard ships. This regulation mandates that fuel sulphur content must be limited to less than 0.5% outside designated emission control areas (ECAs) [15]. Since 2015, the maximum fuel sulphur content permitted within ECAs is below 0.1%.

These limits became compulsory following an amendment to MARPOL's Annex VI. This fuel-related regulation affects particulate emissions indirectly [16]. Further fuel-related reduction in emissions is achieved when using distillate fuels instead of HFO. Winnes and Fridell et al. show the average PM values in a range of 0.18–0.48 g/kWh for marine diesel oil (MDO) and 0.56–2.12 g/kWh in contrast to HFO, depending on the sulphur content [17]. Zhao et al. report that emissions regarding PM in mg/kWh can be reduced by up to 60% when HFO is substituted with distillate fuels [10].

Under MARPOL Annex VI Regulation 4 "Equivalents", shipping companies may use state-approved alternative methods to reduce SO_x emissions, as long as these methods achieve similar outcomes to the use of low-sulphur fuel oil (LSFO). By incorporating these methods, ships are permitted to combust high-sulphur fuels. This has resulted in a rise in the adoption of exhaust gas cleaning systems (EGCS), especially wet scrubbers, as they offer a financially viable substitute to the pricier LSFO. In 2023, the global 20 port average bunker price of IFO 380 (Industrial fuel oil also referred to as HFO) was USD 512.00 per metric tonne [18]. Very low-sulphur fuel oil (VLSFO) on the other hand cost USD 638.00 per mt [19] and marine gas oil (MGO) USD 897.50 per mt [20].

Several studies have examined the effect of EGCS on particulate emissions, yielding varied results. Fridel and Salo report reductions of up to 75% for PM and 92% for PN concentrations [21]. Zhou et al. report PM reductions between 40% and 50% [22]. The Danish Environmental Protection Agency (EPA) found that an EGCS on the MV Ficcara Seaways reduced PN concentrations by 31% to 51% [23].

The far-reaching decision of the IMO to reach net zero of greenhouse gas (GHG) emissions by 2050 means that the world's future fleet will have to rely on a broader range of fuels and adopt novel propulsion solutions and energy efficiency measures [24–26]. Bio-based fuel blends may be a promising approach to meet decarbonization challenges in marine shipping [27]. The European Maritime Safety Agency (EMSA) concluded in a report that the most suitable drop in biofuels would be hydrotreated vegetable oil (HVO), Fischer–Tropsch diesel (FT), biomethane from gasification and fatty acid methyl esters (FAME) from fat oil and grease (FOG), bio-methanol, or dimethyl ether (DME) [28].

While these fuels offer the potential to lower the CO_2 -footprint of the marine sector, the particulate emissions of these fuels have yet to be researched in more depth. Especially in light of the fact that the IMO intends to regulate emissions of black carbon (BC) for marine engines [29]. Hence there are no worldwide regulations limiting PM or PN emissions at this time, nor is this under consideration. Specific regulations are in place within the European Union that apply to inland waterway vessels [30]. These regulations correspond to the limits already imposed on non-road engines.

A combination of alternative oil-type fuels and an EGCS, such as a wet scrubber, can be used for advanced particle removal, benefiting the coastal population, particularly if these aftertreatment methods are already installed on board.

Consequently, to study particulate emissions in exhaust gases originating from novel fuels, Flensburg's University of Applied Sciences has operated a full-scale closed-loop scrubber test bed. This enables conducting land-based research while closely simulating onboard conditions. The system was tested with exhaust from a medium-speed, 0.72 MW marine diesel engine.

The present study examines particulate emissions using four different fuels. Two fossil fuels, HFO with a sulphur content of 2.4 mass %, standard diesel oil (EN 590), and two synthetic fuels, gas-to-liquid (GTL), an FT-diesel and HVO. PN in the range of 6–523 nm and PM were measured as a function of engine load (25%, 50% and 75%). For PM estimation, a tailor-made method for measuring PM directly within the EGCS funnel without dilution was applied.

2. Materials and Methods

2.1. Engine and EGCS

The exhaust gas was produced by a MaK research engine (FOMO 4524). This engine is a modified version of the MaK 452 and MaK 282 series. It is a two-stage, supercharged, medium-speed, 4-stroke engine (Figure 1). The engine operates on 3-cylinders (6 in original configuration) with a 450 mm stroke and 240 mm bore. At its maximum continuous rating (MCR) of 100%, it generates 0.72 MW at 600 rpm. This engine can function on both residual and distillate fuels. The study results were generated during a measurement campaign between May and August of 2023, employing the ISO 8178 E3 test cycle, specifically targeting engine loads of 25% (0.18 MW), 50% (0.36 MW), and 75% (0.54 MW). The EGCS used in this study was built in 2019 in partnership with PureteQ A/S (Figure 1). It is a closed-loop inline turbo scrubber that utilises Baltic Sea water for SO₂ emission neutralization. To regulate pH levels during the use of HFO, a 50% NaOH feed was implemented. For further details, see Table 1.

Table 1. Specification of engine and EGCS.

Engine		EGCS	
Item	Specification	Item	Specification
Manufacturer	MaK	Manufacturer	PureteQ A/S
Model	FOMO 4524	Model	Inline Turbo Scrubber
Operation	Four-stroke diesel	Max. sulphur content [m/m]	3.5%
Rated Power [kW]	722	Max. engine Power [MW]	0.8
Speed [rpm]	600	Alkalization medium	NaOH, 50%
Cylinder	3	Loop wash water flow [m ³ /h]	21–36
Bore [mm]	240	Sections and nozzles	1 quench section, 16 pcs
Stroke [mm]	450		3 washing sections, 27 pcs
Air intake mode	Turbo charged		1 demister cleaning, 3 pcs
		Height [mm]	6800
		Diameter [mm]	750

2.2. Fuels

Two fossil fuels and two synthetic diesel equivalent fuels were used in this study. The specifications for these fuels are given in Table 2. The high-sulphur fuel (HFO) is the most commonly used fuel in shipping. The other fossil fuel, EN 590, is a distillate diesel fuel for cars, which is not widely used in shipping due to its price, but was chosen because of its stringent quality requirements, which allow for better replicability.

Table 2. Main fuel properties.

	GTL	HVO	EN 590	HFO
Net calorific value (MJ kg ⁻¹)	44.06	44.04	42.78	40.4
Density (kg m ⁻³) at 15 °C	781.0	783.0	840.0	990.3
Sulphur (m/m%)	0.0	0.0	0.009	2.4
Carbon (m/m%)	85.3	85.4	86.4	84.7
Hydrogen (m/m%)	14.7	14.6	13.2	9.9
Σ16 EPA PAH (mg kg ⁻¹)	9.6	190.7	1494.9	2970

GTL and HVO (produced by Shell) are synthetic diesel equivalent fuels. Gas-to-liquid technology based on Fischer–Tropsch synthesis is the origin and eponym of a synthetic low-sulphur fuel to be used. GTL is already being used as an alternative fuel for German inland vessels [31]. While GTL is based on natural gas and/or biogas, HVO is produced by hydrogenating vegetable oils and has recently been tested by the British Antarctic Survey as an alternative to conventional diesel fuels [32]. The HVO fuel uses waste and residues as feedstock, complies with EN15940, and is already used as a fuel for Deutsche Bahn’s diesel trains [33,34]. These synthetic fuels are fuel products synthesised from carbonaceous feedstocks with a paraffinic nature and contain virtually no sulphur or heavy metals. These “ultra-clean” fuels are the absolute counterpart to the heavy fuel oil used in this study.

2.3. Measurement Setup

Exhaust gas measurements, for PN, were performed both upstream (1) and downstream (2) of the EGCS. Through a combination of PM measurements at point 2 and in circulating wash water (3), the total PM emissions of the engine and EGCS were determined via filters and gravimetric analysis (Figure 2). Sea water filtered to 1 µm was used as wash water. The quantity of wash water used for each test day was precisely controlled and kept uniform at a minimum level, to account for any exhaust condensate and deliberately elevate the particulate concentration in the water for improved outcome.

Parallel PN and PM measurements were conducted over a four-hour period, after reaching stable engine conditions and temperatures, for each fuel and engine load. Injection nozzles and fuel rack adjustments were not performed for the different fuels. Continuous monitoring occurred for circulation tank level, pH, CO₂/SO_x, temperature and wash water density. Low-sulphur fuel tests were conducted before any HFO tests to prevent sulphur enriched soot contamination within the system. Real pictures and schematic of the measurement setup can be seen in Figures 1 and 2.



Figure 1. Measurement setup at Flensburg University of Applied Sciences: MaK Engine (left) and Scrubber (right).

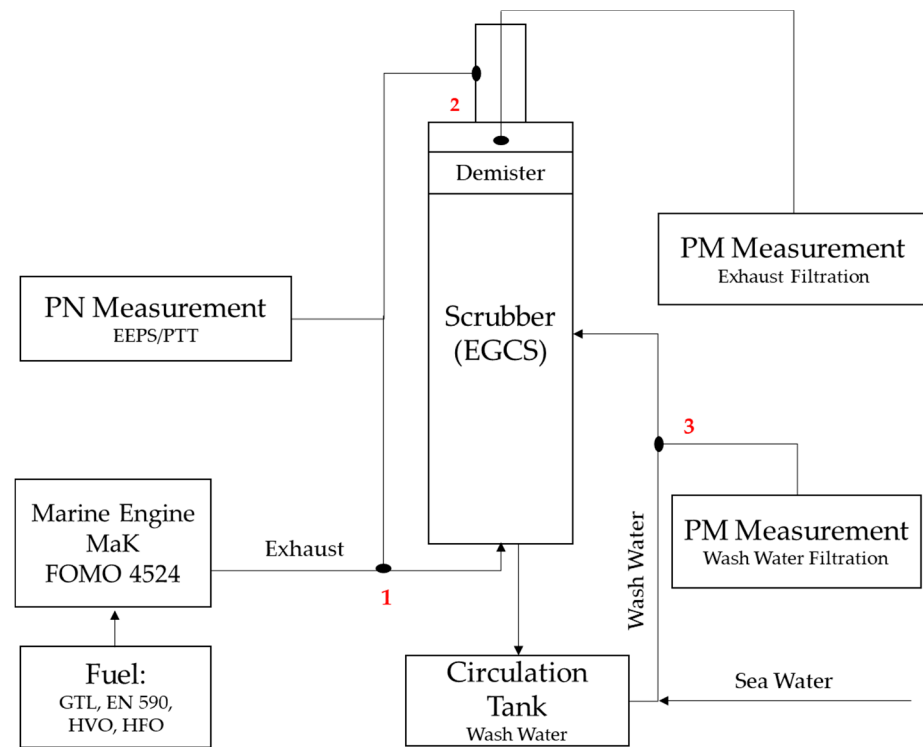


Figure 2. Measurement schematic. (1) Upstream of EGCS, PN measurement; (2) downstream of EGCS, PN and PM measurement; (3) PM measurement in wash water.

2.4. Particle Number Measurement in Exhaust Gas

Particle size measurements were conducted at points 1 and 2 (Figure 2) using an engine exhaust particle sizer (EEPS 3090) in conjunction with a porous tube thermodiluter (PTT 3098) and a heated (180 °C) polytetrafluoroethylene (PTFE) sample line manufactured by TSI. All measurements were carried out using the same instrument settings, with a dilution ratio (DR) of 100:1 and a catalytic stripper (CS) set at 350 °C to eliminate volatile particles. The dilution process included a hot dilution of 20:1, followed by a cold dilution of 5:1. This approach was chosen due to the fact that the dilution process, ratio, and temperature all affect the results [35,36]. Employing one consistent dilution ratio for all measurements guaranteed consistent error margins for all results. The sample was diluted with compressed and filtered air. The EEPS employs the principle of electromobility to measure particle size across 32 bins, ranging from 6.04 nm to 523 nm (referring to the bin mid-point). Four measurements, each lasting 3 min, were performed upstream and downstream of the EGCS. Results refer to EU-norm conditions (273.15 K and 1013.25 hPa), as indicated by the capital *N*.

2.5. Particle Matter Measurement in Exhaust Gas

To measure PM emissions after the EGCS (point 2 in Figure 2), a tailored filtration unit was designed and constructed, made feasible by easy access to the exhaust. Through this filtration unit, it was possible to filter a defined volume flow of undiluted exhaust gas directly from the exhaust funnel and maximise the captured particle mass on filter paper. This dilution-free method was beneficial since it avoids any dilution losses that might occur in typical PM measurement setups. To achieve this, two vacuum pumps (50 Hz and 0–75 Hz (frequency-regulated)) and a flow meter were installed. PM samples were collected using Frisette 110 mm diameter quartz fibre filters placed in a custom mount and suspended 1.3 m into the exhaust funnel. The exhaust temperature was between 15 and 25 °C, depending on sea water temperature and engine load. The exhaust gas volume flow and subsequent velocity required for isokinetic sampling were calculated using the carbon balancing method. Each measurement took between 20 and 25 min, until the vacuum

pump reached its maximum operating frequency of 75 Hz. The filters were dried at 100 °C for 24 h and then placed in an exicator for 5 min before being weighed.

2.6. Particle Matter Measurement in Wash Water

Wash water samples were taken once stable engine conditions were achieved, approximately two hours after engine start, and after a further four hours to calculate PM emissions captured by the wash water within these four hours. Together with the PM-measurement outcomes of the exhaust, the total particle emission of the engine could be estimated. Blank value samples of the wash water were taken before each measurement to determine background particulate concentrations. The samples were vacuum filtered using acetate membrane filters (47 mm) with a pore size of 0.45 µm, dried and weighed. This was performed with both empty and loaded filters. To improve the accuracy of this measurement, the seawater was filtered before being used as wash water. The goal of this measure was to eliminate rust, biological matter, and sediment particles that originated from the pipe system and the extraction point in the Flensburg firth. Turbulent currents were produced within the circulation tank to prevent particle sedimentation. PM values reported in this study are based on the average concentration of three filter samples.

3. Results

These experiments have been carried out to determine the emission behaviour of a marine engine when combusting traditional fossil fuels (HFO, distillate diesel) and novel, synthetic fuels (GTL and HVO) at different engine loads. The measured emission factors (PN in 1/Ncm³ and PM in mg/kWh) have been calculated for the different load points and corrected for dilution.

3.1. Effect of Engine Load and Fuel on Particle Number and Particle Size Distribution

Figures 3–5 show the particle number size distributions reflecting non-volatile particles within the raw exhaust at different engine loads. Corresponding total PN concentrations can be found in discussion paragraph.

Prior to the following discussion, it should be noted that the interpretation of certain results obtained during the PN measurement, particularly the origin of some peaks in the sub-nanometre size range, could not be determined with certainty. Similar challenges in this regard have been reported elsewhere [37,38]. It is suggested that the few detected high peaks of particles around the 10 nm size range, particularly during high engine load (75% MCR), may be a combination of artefacts within the measuring equipment and a result of dilution ratios and temperatures, rather than a reflection of a real species. The overall analysis of emitted particles within this size range, based on the employed methodology, is challenging and certain values will therefore not be taken into consideration.

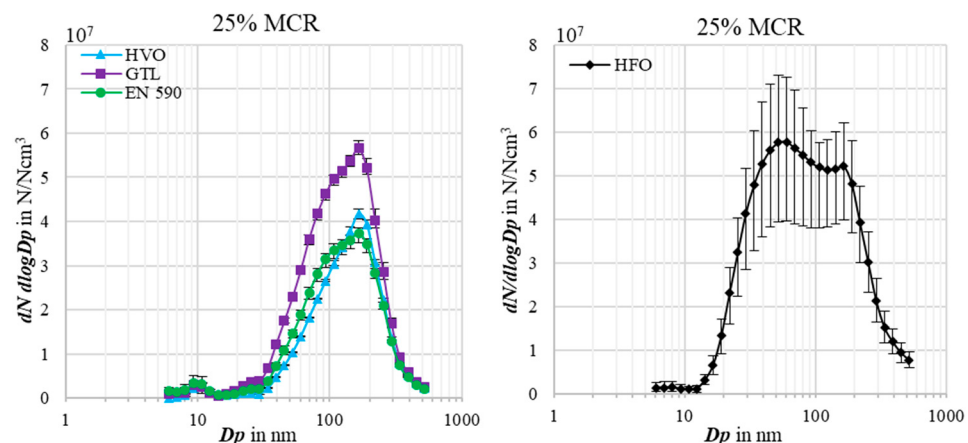


Figure 3. Particle number size distribution of raw exhaust gas for 25% MCR; **left:** HVO, GTL, and EN 590; **right:** HFO.

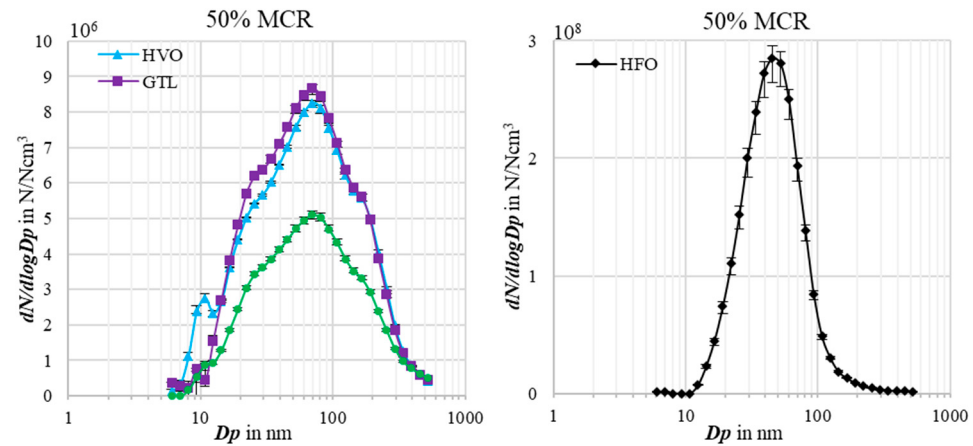


Figure 4. Particle number size distribution of raw exhaust gas for 50% MCR; **left:** HVO, GTL, and EN 590; **right:** HFO.

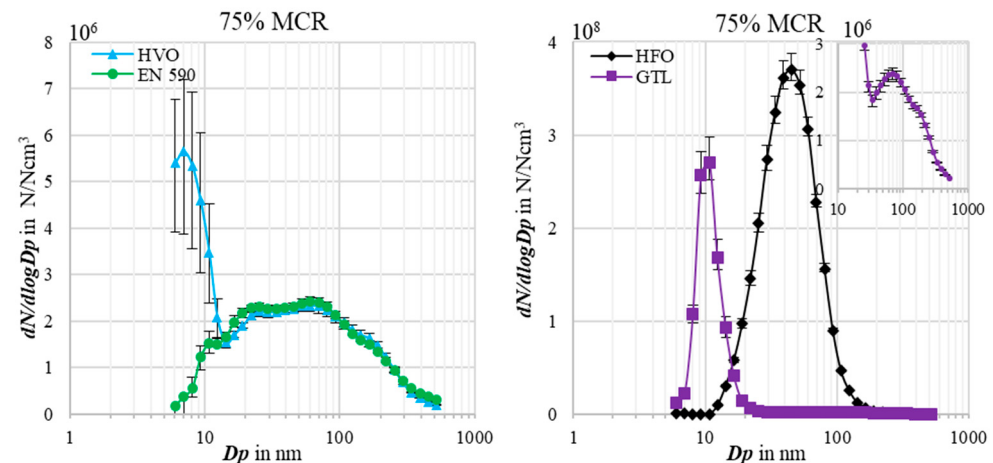


Figure 5. Particle number size distribution of raw exhaust gas for 75% MCR; **left:** HVO, EN 590; **right:** HFO, GTL.

The size distributions for the compliant fuels indicate that an increase in engine load reduces particle concentration and main particle mode. At 25% and 50% MCR, the size ranges of detected particles are similar to each other within their respective engine loads; however, the concentration drops by an order of magnitude at 50% MCR. At the same time, the mode decreases from 165 nm at 25% MCR to 69.8 nm at 50% MCR. At 75% MCR, the peak is at 10.8 nm; when combusting HVO, the main size distribution agrees exactly with EN 590. The main size peak occurs at 69.8 nm for both fuels. In the case of GTL, the interpretation of the particle concentration and modes is not as obvious for the reason mentioned above. Figure 5 (right) shows a clear peak at 10.8 nm with a concentration magnitude making it appear that only particles in this size range are present. The extra magnification of concentration range for this fuel and engine load presents a more reliable particle size distribution with the main mode at 70 nm.

HFO shows the same propensity to produce smaller particles with an increase in engine load, going from 165 nm and 60.4 nm at 25% and 50% MCR to 45.3 nm at 75% MCR. Unlike the compliant fuels, the particle number concentrations do not drop but increase with the engine load.

Because this is a turbocharged engine, combustions at lower engine loads tend to be of lower quality since not enough exhaust is produced for the turbo charges, which in return do not produce enough compressed air for combustion. Low quality combustion leads to the production of larger particles in higher concentrations. As the engine load increases, more exhaust, and consequently more compressed air, is available for the combustion

process. In addition, the FOMO 4524 has a steep miller angle for NO_x reduction and early closing of the inlet valve, which exacerbate the lack of combustion air in lower engine load points. Combustion quality is indicated by the exhaust gas temperature, as it decreases with an increase in quality. This is reflected in the measured temperatures, which ranged between 460 and 490 °C, 380 and 400 °C, and 310 and 325 °C for 25%, 50%, and 75% MCR, respectively.

Examining the total number concentrations of the compliant fuels, which range between 1.20×10^{10} 1 N/cm³ (GTL) and 8.34×10^9 1 N/cm³ (EN 590) at 25% MCR, between 1.75×10^{10} 1 N/Ncm³ (GTL) and 1.73×10^9 1 N/Ncm³ (HVO) at 50% MCR and between 2.13×10^9 1 N/Ncm³ (GTL) and 5.72×10^8 1 N/Ncm³ (EN 590) at 75% MCR, it becomes clear that they have similar emission factors. The higher total PN for GTL at 75% MCR is due to the high concentration of measured particles in the 10 nm size range. In Figure 4, it is shown that the size distributions of HVO and EN 590 are more similar to each other than different if the peak around 10 nm is not considered. The total PN for HFO goes from 9.87×10^9 1 N/cm³, to 1.56×10^{10} 1 N/cm³, to 2.10×10^{10} 1 N/cm³, for 25%, 50%, and 75% MCR, respectively.

3.2. Effects of Fuel and Engine Load on Particle Matter

Due to the configuration of the testbed and the chosen measurement method, the PM emission factors in the exhaust gas were determined by adding particle masses captured through the wash water and at the scrubber outlet. Figure 6 depicts respective cumulative values as emission factors in relation to the engine load and fuel type.

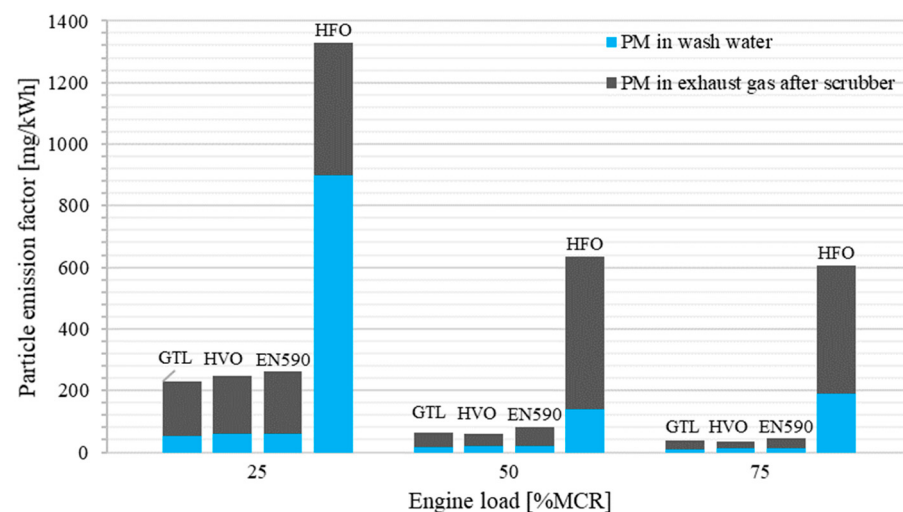


Figure 6. Load- and fuel-related emission factors.

The results indicate that particle mass concentrations of the exhaust are affected mainly by fuel type, regardless of engine load. The main reduction in particle matter discharge takes place when changing from HFO with 2.4% sulphur to any sulphur-free fuel. Particle mass emissions show a decreasing trend for HFO with 1330.1 mg/kWh, 625.8 mg/kWh and 607.6 mg/kWh under the three engine loads (25% MCR, 50% MCR, 75% MCR). More than double the reduction in particle emissions was achieved when the engine operation was changed from manoeuvring mode to the transient mode (50% MCR). With an increase in engine load, from 50% MCR to 75% MCR, only a slightly smaller emission factor was measured. The reason for high PM production rates, regardless of engine load, is the general composition of HFO. Particulate matter produced during the combustion of HFO is substantially a mixture of fuel impurities (heavy metals, ashes, and asphaltenes), primary PM (e.g., soot) and secondary PM (crystalline sulphate salts) formed from SO₂. The overall lower calorific value also means that more fuel must be combusted to generate the same amount of energy, resulting in higher emissions.

Using diesel oil (EN 590) as an equivalent to the typical very low-sulphur distillate fuel, the exhaust PM concentrations were 262 mg/kWh, 82 mg/kWh, and 44 mg/kWh for their respective engine loads.

When considering the emission factors of novel fuels with no sulphur, such as GTL and HVO, it was found that their values are lower than those of diesel oil, although very similar. Engine operation with GTL resulted in PM levels of 229.6 mg/kWh, 62.0 mg/kWh, and 37.1 mg/kWh at engine loads of 25%, 50%, and 75%, respectively. With HVO, the levels were 249 mg/kWh, 59.1 mg/kWh, and 35 mg/kWh at the same engine loads. Table 2 shows that the compliant fuels, GTL, EN 590, and HVO, are generally similar in their specification, which is also reflected in the produced particulate emissions.

3.3. Impact of the EGCS on PN Emissions

Figures 7–9 include particle size distributions measured both upstream and downstream of the scrubber and illustrate the potential of the EGCS for particle reduction for the various fuels and engine loads. The closed-loop scrubber is able to reduce particle emissions in the sub-micron range (6.04 nm to 523 nm). In all investigated cases, particle size distribution downstream of the EGCS is lower than those from upstream of the EGCS, though the curves move closer together with an increase in engine load.

The use of HFO results in a significantly greater emission of particles compared to compliant fuels. These emissions are characterised by a broad size distribution and a large number of coarse particles. The probability of washing out larger particles is higher than for very small particles. This effect is particularly noticeable at low engine loads, 25% MCR, where the scrubber achieved more than 40% reduction of PN (Figure 9).

Studying the impact of the scrubber on particle concentrations resulting from compliant fuels (EN 590, HVO, and GTL), which are lower than for HFO, it can be concluded that the reduction efficiency of the EGCS decreases when the particle concentration magnitude within the raw exhaust gas decreases. The overall reduction of PN oscillates between 5% and 15%.

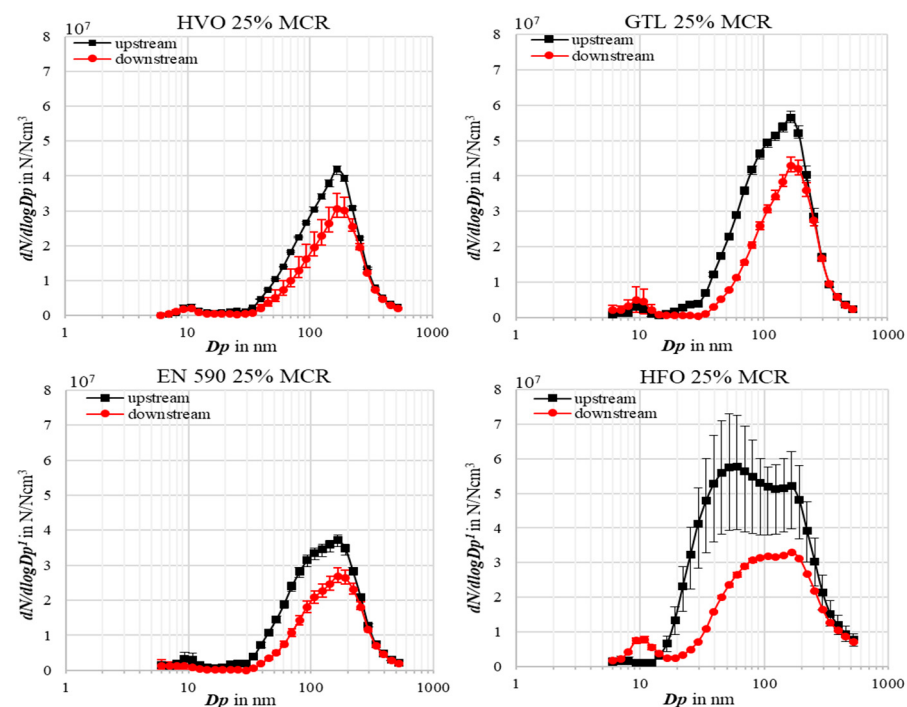


Figure 7. Particle size distribution in exhaust gas, upstream (black line) and downstream (red line) of the EGCS for 25% MCR.

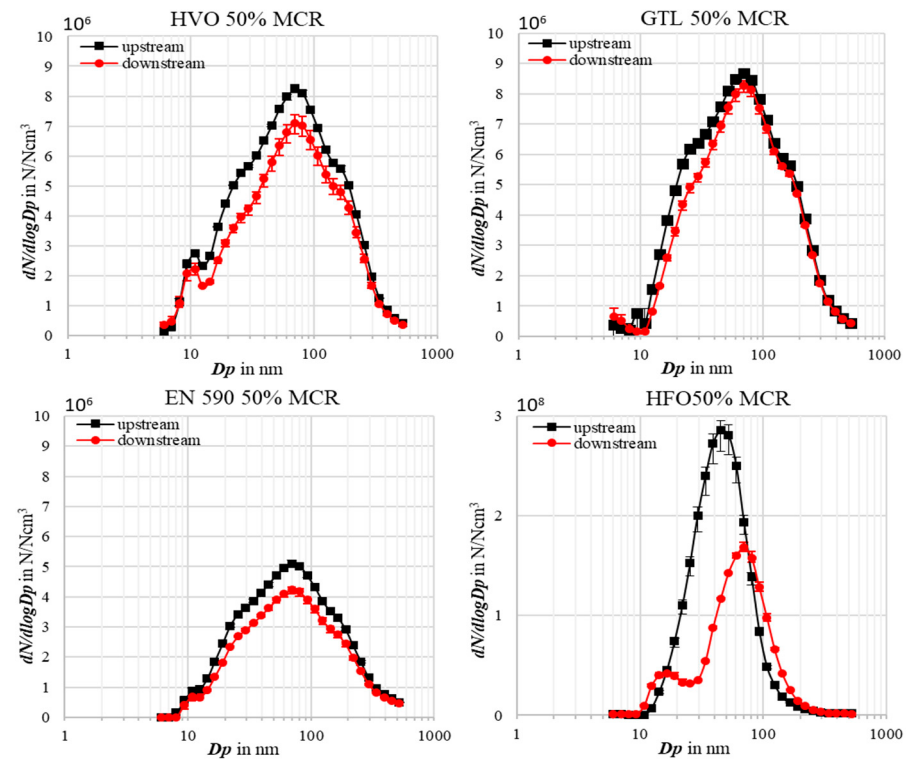


Figure 8. Particle size distribution in exhaust gas, upstream (black line) and downstream (red line) of the EGCS for 50% MCR.

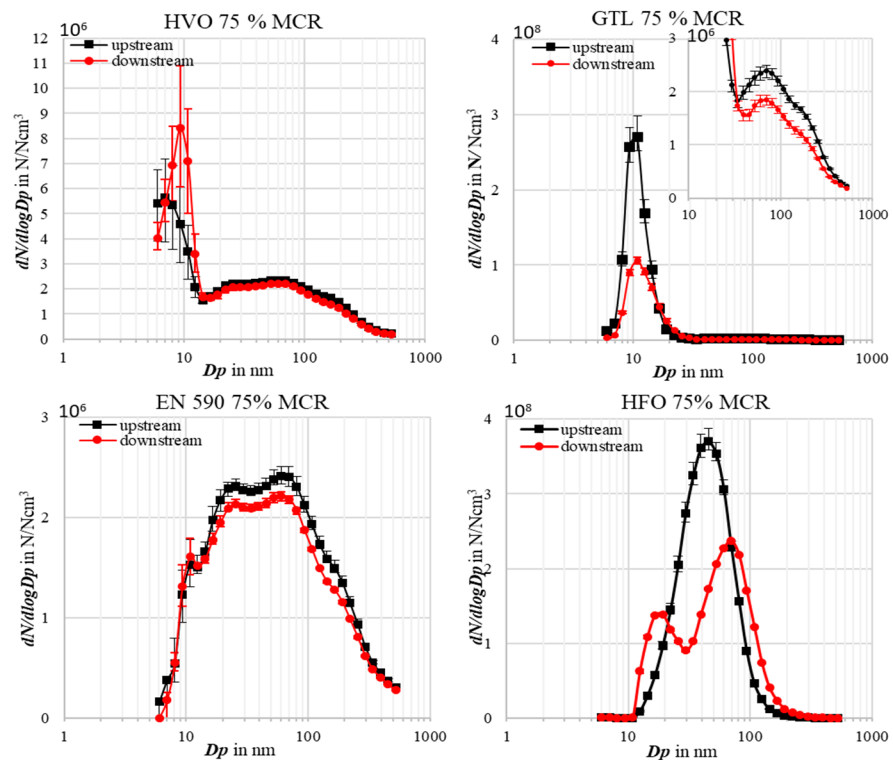


Figure 9. Particle size distribution in exhaust gas, upstream (black line) and downstream (red line) of the EGCS for 75% MCR.

In contrast, the change from a mono-modal to a bi-modal distribution for HFO after EGCS at 75% MCR, with seemingly more particles smaller than 19.1 nm and larger than

69.8 nm, suggests that the scrubber emits secondary particles, affecting the reduction efficiency of particle concentration to a very low range of only 3%.

Moreover, the reduction effect of the EGCS on the particulate number is dependent on the velocity with which the exhaust gas travels through it and on the size of the particles. This is evident from the fact that, at 25% MCR, the reduction rates are the highest, between 24% and 27% for the compliant fuels and 41% for HFO, as the exhaust gas velocities are the lowest and the particle sizes the largest among the measurements taken. PN-reduction rates of GTL and HVO for 75% MCR have not been included in Figure 10 due to the high concentration of 10 nm-sized particles and their unclear origins.

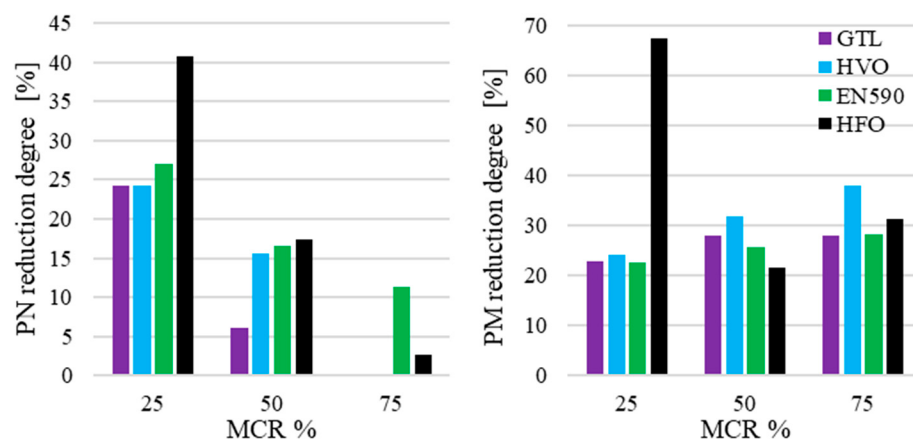


Figure 10. PN and PM reduction efficiency of the EGCS.

3.4. Impact of the EGCS on PM Emissions

The effectiveness of the EGCS in reducing solid masses can be better assessed by examining the ratio of particulate matter that can be washed out by the scrubber and that which remains downstream. From Figure 6, it is clear that most of the particle matter is carried into the atmosphere by the exhaust gases. An exception to this is the impact of the EGCS on particle emissions for low engine loads, particularly for HFO at 25% MCR. The calculated PM reduction rates for all conducted tests are shown in Table 3.

At 25% MCR, when operated with HFO, the EGCS exhibits the highest PM reduction with 67.5%. In comparison, with an increase in engine load to 50% MCR, the PM reduction decreases to approximately one third (21.7%) and nearly half (31.3%) for 75% MCR. The reasons for this phenomenon have been mentioned in Section 3.1: the production of coarser particles within the maneuvering mode due to combustions of lower quality and a fuel with a high ratio of incombustible residues. Moreover, the higher residence time of the exhaust gas within the EGCS supports the overall probability of washing out particles. Consequently, the overall PM emission factors, regardless of engine load, after the EGCS are similar to one another (Table 3).

The PM reduction rate of the compliant fuels shows only slight variations for the different engine loads, ranging from 22.7% to 24.2% for 25% MCR, 25.7% to 31.8% for 50% MCR, and 27.9% to 38.1% for 75% MCR. The study confirms the hypothesis that the use of scrubbers has a moderate impact on particulate emissions resulting from the combustion of compliant fuels.

4. Discussion

The study aimed to investigate particulate emissions in the form of emission factors (PN and PM) related to marine engine loads (kWh) of two potential future fuels for carbon-free shipping: GTL and HVO. Traditional marine fossil fuels were used as a benchmark due to their well-established emission factors in the relevant literature. However, comparing measurement studies on particle emissions yields a large spread depending on the research

environment. Therefore, only research engine outcomes will be considered as they are the most comparable.

The study also tested the EGCS as a particle abatement technology to determine its capability for particle reduction. It is acknowledged that this technology is a measure for oceangoing vessels that prefer to operate with less expensive heavy fuel oil in order to comply with IMO regulations. The removal of particles through an EGCS is a welcome side effect of the main objective of neutralising gaseous sulphur components. A full list of all emission results attained during this study is presented in Table 3.

Table 3. Particle number PN ($dp > 6$ nm) and particulate matter (PM) emissions measured for different fuels and engine loads; (us = upstream, ds = downstream) and the reduction achieved by EGCS (scrubber); PN for GTL and HVO at 75% MCR is listed but not interpreted because the particle counts of EEPS 3090 with the used gas dilution settings are probably unreliable.

Fuel	Load [%]	Total PN us [1 N/cm ³]	Total PN ds [1 N/cm ³]	PN red. [%]	PM ds [mg/kWh]	PM Wash Water [mg/kWh]	Total PM us [mg/kWh]	PM red. [%]
GTL	25	1.20×10^{10}	9.08×10^9	24.3	176.7	52.9	229.6	23.0
HVO	25	8.49×10^9	6.44×10^9	24.2	188.7	60.4	249.0	24.2
EN 590	25	8.34×10^9	6.09×10^9	27	202.3	59.4	261.7	22.7
HFO	25	1.66×10^{10}	9.87×10^9	40.7	431.9	898.2	1330.1	67.5
GTL	50	1.75×10^9	1.64×10^9	6.1	44.7	17.4	62.1	28.0
HVO	50	1.73×10^9	1.46×10^9	15.5	40.3	18.8	59.1	31.8
EN 590	50	1.11×10^9	9.30×10^8	16.5	61.1	21.1	82.2	25.7
HFO	50	1.89×10^{10}	1.56×10^{10}	17.3	498.1	138.0	636.1	21.7
GTL	75	2.13×10^9	1.30×10^9	-	26.8	10.3	37.1	27.9
HVO	75	5.79×10^8	5.29×10^8	-	22.0	13.6	35.6	38.1
EN 590	75	5.72×10^8	5.07×10^8	11.3	31.6	12.4	44.0	28.2
HFO	75	2.15×10^{10}	2.10×10^{10}	2.6	417.5	190.1	607.6	31.3

First, the assessment of particulate emissions at the lowest engine load of 25% MCR serves as a standardized measuring point in the E3 cycle. This mode of operation is typical during manoeuvring conditions near coastal areas, harbours, or when passing through sea channels. These are the regions where the population is most exposed to harmful exhaust emissions, a fact that is further compounded by the density of operating ships. Only high-quality, compliant fuels are allowed to be used in these areas.

The comparison of particle number size distributions and resulting PN and PM emission factors revealed different patterns. At manoeuvring load (25% MCR), the number of emitted particles was of a similar order of magnitude regardless of the fuel type. However, HFO appears to be slightly ahead with 6.45×10^{16} 1/kWh and this number is much higher for PN at the similar engine conditions reported elsewhere [39,40]. Emitted species by HFO are characterized by a broader size distribution. Lyyrinen et al. [41] and Wu et al. [42] postulated that the HFO particles generally have a heterogeneous morphological characteristic, which is reflected in broad distribution towards a larger size range. In comparison, the novel fuels (GTL and HVO) seem to produce slightly higher particle concentration than distillate diesel fuel [43,44], but less than HFO (Table 3). The size distribution of raw exhaust particles from all compliant fuels was mainly mono-modal in the nanometre scale with main peaks, centred around 165 nm (25% MCR), which mainly reflect the soot mode [11]. These numbers contrast with studies of Ushakov et. al, who found most GTL and HVO particles in the accumulation mode (about 60–70 nm) at 25% MCR [43,44]. The soot-accented findings in this study most presumably resulted from unfavourable combustion conditions of the research engine. This mode is usually characterised by low-quality combustions and disproportionately high particle discharge reported for other marine distillate fuels [45].

When comparing mass emission factors at low engine loads, the differences in particle morphology in terms of size and density become clearer. Despite similar number concen-

trations, HFO emits 1330 mg/kWh of particulate matter into the atmosphere via the raw exhaust gas, which is in line with studies performed by Jeong et al. [39] and Wang et al. [46], while novel fuels such as GTL and HVO emit only 229 mg/kWh and 249 mg/kWh respectively. Diesel fuel emits 262 mg/kWh, which is slightly more than HVO and GTL. Ushakov et al. reported lower values for GTL and HVO in E2 and E3 cycles [43,44]. However, it is generally agreed that distilled fuels emit more in this configuration.

At 50% MCR engine load, the total PN in the exhaust gas for all compliant fuels is comparable and decreases compared to 25% MCR, ranging between 1.11×10^9 1 N/cm^3 and 1.75×10^9 1 N/cm^3 , which is one order of magnitude less than for HFO with 1.89×10^{10} 1 N/cm^3 . At the same time, the emitted particles from compliant fuels are smaller. The main mode is 69.8 nm (Figure 7). The PN and the main mode for GTL and HVO match the findings of Ushakov et al.

The data indicates that higher loads result in more favourable fuel combustion conditions in the testbed, leading to fewer emissions. This is particularly evident in the PM emission factors (Figure 5), which decreased significantly to approximately 60 mg/kWh for GTL and HVO. In contrast, EN 590 emitted PM at a rate of about 80 mg/kWh. PM emissions from Ushakov for GTL and HVO were consistently lower than MGO.

A further reduction in particulate emissions was observed while operating in the open sea mode (75% MCR). The particle number concentration for HVO and diesel fuel decreased by one order of magnitude, with no changes in the size mode (Figure 9). The PN for GTL, at 2.13×10^9 1 N/cm^3 was higher than that for 50% MCR. This suggests that the majority of emitted particles, with a main peak at 10.8 nm, belong to the nucleation mode. Other studies have classified particles in this range as non-volatile fuel-originated core particles [11]. However, in this study, it is assumed that concentration peaks in nucleation mode may more likely be attributed to the measurement modalities with analyser used.

It is a fact that HVO and GTL fuels tend to produce very fine particles, with the lowest mass emission factors during combustion, due to their lower fuel aromatic content; however, further investigation of this issue is needed.

5. Conclusions

This study compares particulate emissions from a full-scale marine engine testbed resulting from the combustion of various marine fuel alternatives. The focus was on assessing the particulate emission potential of novel fuels, such as GTL and HVO, which are of increasing interest to the marine industry as transitional or future fuels for zero-carbon shipping. Conventional fuels, including diesel and HFO 2.5% S, were used as a baseline. Additionally, the potential benefits of using classical EGCS (closed-loop scrubbers) for particulate reduction were investigated. The experiments were conducted using propeller law test cycles E3 at 25%, 50%, and 75% MCR. The determined emission values tended to be lower than those found in comparable studies. It is especially difficult to determine how differences in engines and measurement setups affect the results compared to real ship operation.

- The use of new fuels (GTL and HVO) results in the production of particulates, although their formation is on average 20% lower than that caused by the use of distillate fuel (diesel) and up to 90% lower than that caused by heavy fuel oil at any engine load tested. This is due to the lower aromatic content of the fuel, the absence of sulphur, a higher cetane number, as well as a better ratio of carbon to hydrogen.
- In the case of fossil fuels, switching from residual fuels (HFO) to distillates results in a reduction of more than 80% of particulates emitted at all engine loads, aligning with the objectives of the IMO as fixed in the MARPOL regulations.
- There is a clear trend showing the reduction in particulate emissions increases with engine load due to the more favourable fuel/air ratio for combustion. The highest values for measured PN and PM emission factors are observed at low engine loads, while medium loads achieve PM reductions of more than 50% for HFO and up to 70% for compliant fuels. High engine loads resulted in significant reductions in PM

emissions, averaging 40% for new fuels and diesel. However, for HFO, only a 3% improvement in PM emissions was observed.

- According to current IMO regulations, the use of scrubbers in combination with compliant fuels is not an ideal option. The impact of scrubbers on the reduction of particulate matter was in the range between 20% and 40%. It is believed that the feasibility of scrubbing is downgraded by a higher presence of finer particle sizes and a decreasing residence time in the scrubber channel. The results suggest that the scrubber is more effective with coarse particles from HFO and to an even more limited extent with compliant fuels.
- In light of the high levels of PN and PM emissions—particularly respirable particles—during low engine loads typical of coastal ship operations, the use of an EGCS would, however, be advantageous for air quality and human health, especially considering the upcoming IMO regulations for further limiting particulate emissions such as soot. In this context, it is expected that EGCS equipment, such as scrubbers, will need to be optimized to reduce not only sulphur emissions but also particulate and soot emissions from marine engines.

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