Ministry of Environment and Gender Equality
Environmental Protection Agency

Development of wet Electrostatic Precipitator for marine engines MUDP Project

MUDP Report

December 2024

Publisher: The Danish Environmental Protection Agency

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ISBN: 978-87-7038-691-3

Miljøteknologisk Udviklings- og Demonstrationsprogram

Projektet, som er beskrevet i denne rapport, er støttet af Miljøteknologisk Udviklings- og Demonstrationsprogram (MUDP) under Miljøministeriet, der støtter udvikling, test og demonstration af miljøteknologi.

MUDP investerer i udvikling af fremtidens miljøteknologi til gavn for klima og miljø i Danmark og globalt, samtidig med at dansk vækst og beskæftigelse styrkes. Programmet understøtter dels den bredere miljødagsorden, herunder rent vand, ren luft og sikker kemi, men understøtter også regeringens målsætninger inden for klima, biodiversitet og cirkulær økonomi.

Det er MUDP's bestyrelse, som beslutter, hvilke projekter der skal modtage tilskud. Bestyrelsen betjenes af MUDP-sekretariatet i Miljøstyrelsen.

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Denne slutrapport er godkendt af MUDP, men det er alene rapportens forfatter/projektlederen, som er ansvarlige for indholdet. Rapporten må citeres med kildeangivelse.

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1. Resume (In Danish)

Det kombinerede scrubber- og våde elektrostatisk partikelfilter (ESP) system, der blev testet i Alfa Laval's testcenter, kan effektivt rense udstødningsgasser fra skibsmotorer drevet af både dieselolie og tung brændselsolie. Desuden kan vaskevandet, der bruges til rengøring af scrubberen og den våde ESP, effektivt renses ved hjælp af et separationssystem. Testkampagnen opnåede følgende resultater:

1. Den kombinerede scrubber og våde ESP-system opnåede fjernelseseffektivitet på op til 96% for PM og 91% for BC, når motoren blev drevet med tunge brændselsolie ved en motor belastning, der varierede fra 25% til 100%.
2. Den kombinerede scrubber og våde ESP-system opnåede fjernelseseffektivitet på op til 98% for PM og 96% for BC, når motoren blev drevet med Dieselolie (DO) ved en motor belastning, der varierede fra 25% til 100%.
3. Vaskevandrensningssystemet demonstrerede en gennemsnitlig renseeffektivitet på ca. 99%, hvilket gør det meget effektivt.

Samlet set giver det kombinerede scrubber- og våde ESP-system, sammen med det effektive vaskevandrensningssystem, en robust og effektiv metode til at reducere PM- og BC-emissioner fra skibsforbrændingsmotorer. Dette system viser stort potentiale for at forbedre luftkvaliteten i marinen og overholde både nuværende og fremtidige emissionslovgivninger.

2. Resume (In English)

The combined scrubber and wet Electrostatic Precipitator (ESP) system tested can effectively clean exhaust gases from marine engines powered by both Diesel Oil (DO) and Heavy Fuel Oil (HFO). Furthermore, the washing water used for cleaning the scrubber and wet ESP can be effectively cleaned using a separator system. The test campaign achieved the following results:

1. The combined scrubber and wet ESP system achieved removal efficiencies of up to 96% for PM and 91% for BC when the engine was operated on Heavy Fuel Oil (HFO) with a load ranging from 25% to 100%.
2. The combined scrubber and wet ESP system achieved removal efficiencies of up to 98% for PM and 96% for BC when the engine was operated on Diesel Oil (DO) with a load ranging from 25% to 100%.
3. The wash water cleaning system demonstrated an average cleaning efficiency of approximately 99%, making it highly effective.

Overall, the combined scrubber and wet ESP system, along with the highly efficient wash water cleaning system, provides a robust and effective method for reducing PM and BC emissions from marine combustion engines. This system shows great potential for improving air quality and complying with stricter environmental regulations in the maritime industry.

3. Introduction

The following chapter introduces PM and BC emissions in the marine industry and outlines the current regulations governing these emissions.

3.1 Contribution of shipping to emissions

The influence of shipping on local air emissions depends on variables like wind direction, temperature, and distances traveled. Despite the dynamic nature of these factors, the current discussion offers an overview of recent initiatives aimed at quantifying or approximating this impact, which is summarized in TABLE 1. Regarding particulate emissions, especially $PM_{2.5}$ (referring to particles with a diameter below 2.5 micrometers), the average contribution accounts for around 14% of the total collected particle mass. PM_{10} and PM_1 are referring the same way as $PM_{2.5}$. The remaining fraction originates from land-based industries, vehicular operations, and natural sources like sea salt aerosols or volcanic emissions.

TABLE 1. Impact of shipping on local air emissions.

Country	Area	Component	Contribution*	Ref
Worldwide	Ports	PM	5-26%	[1]
Europe	Total area	PM_{10}	5.0%	[2]
Baltic sea region	Coastal	$PM_{2.5}$	3-6%	[3]
China	Ningbo Port	$PM_{2.5}$	11%	[4]
	Shanghai Port			
China	Shanghai	$PM_{2.5}$	20-30%	[5]
China	Shanghai port	$PM_{2.5}$	6%	[6]
China	YRD, port area	$PM_{2.5}$	35%	[7]
Italy	Venice	$PM_{1.0}$	7%	[8]
Italy	Civitavecchia	PM_{10}	33%	[9]
Japan	Coast of Seto	$PM_{2.5}$	17-21%	[10]
France	Calais, port	PM_{10}	2%	[11]
Sweden	Gothenburg	$PM_{2.5}$	10 %	[12]
Croatia	Rijeka	$PM_{1.0}$	2%	[8]
Greece	Thessaloniki City	$PM_{2.5}$	9-13%	[13]

*** The column "Contribution" is the percentage (mass) that originates from shipping in the mentioned locations.**

This overview shows the need for particle emission regulation to reduce the output from the shipping industry.

3.2 Legislation

In 1990, documents were submitted to the Marine Environmental Committee (MEPC) of the International Maritime Organization (IMO), detailing ship-related air pollution, particularly nitrogen oxides (NO_x) and sulfur oxides (SO_x) emissions. These submissions highlighted the long-range transport of these emissions, raising concerns about air quality over terrestrial areas.

These documents laid the groundwork for MARPOL Annex VI, effective on May 19, 2005, setting limits for NO_x and SO_x emissions, with Particulate matter (PM) being a by product of $SO_{x,}$ which and allowed for the creation of Emission Control Areas (ECAs).

Particulate matter (PM) emissions consist of various compounds, including black carbon (BC), metal sulfates, and water. Historically, PM regulations have been secondary to SO_x regulations. However, the link between SO_x content and PM emissions is complex and nonlinear, affected by factors such as engine type, fuel properties, and combustion conditions.

Accurate PM measurement is crucial, especially considering the health risks associated with smaller particles capable of penetrating lung alveoli. BC, a fine particulate matter, serves as an indicator of light-absorbing properties and plays a role in climate change. Methods for BC emission measurement include Filter Smoke Number (FSN) and photo-acoustic spectroscopy (PAS).

In addition to international regulations, domestic and territorial waters may have stricter national requirements, exemplified by China, Singapore, the EU, and California. Europe has implemented the strictest regulations for inland waterway engines concerning PM and particulate number (PN), as outlined in TABLE 2.

TABLE 2. Stage V emission limits for inland waterway vessels [14].

Engine Category	Equipment Type	Power Range (kW)	PM (mg/kWh)	PN (#/kWh)
IWP-v-1* IWP-c-1*	Inland waterway vessels	37≤P<75	300	-
IWP-v-2* IWP-c-2*		75≤P<130	140	-
IWP-v-3* IWP-c-3*		130≤P≤300	110	-
IWP-v-4* IWP-c-4*		300≤P≤1000	220	$1x10^{12}$
IWP-v-5* IWP-c-4*		P>1000	10	$1x10^{12}$
IWA-v-1** IWA-c-a**		560≤P<1000	20	$1x10^{12}$
IWA-v-2** IWA-c-2**		P≥1000	10	$1x10^{12}$

***IWP: Engines greater than or equal to 37 kW exclusively used in inland waterway vessels, for their propulsion or intended for their propulsion.**

**** IWA: Engines greater than 560 kW exclusively used in inland waterway vessels, for auxiliary purpose or intended for auxiliary purpose.**

A similar table can be made for inland China as seen in TABLE 3.

TABLE 3. Phase II emission limits for marine engines from 7/1/2021 in relation to inland China [15].

Engine type	Per-cylinder displacement (L)	Rated net power (kW)	PM (mg/kWh)
Category 1*	<0.9	≥37	300
	0.9–1.2		140
	1.2–5		120
Category 2**	5–15	<2,000	140

Engine type	Per-cylinder displacement (L)	Rated net power (kW)	PM (mg/kWh)
		2,000– 3,700	140
		≥3,700	270
	15–20	<2,000	340
		2,000– 3,300	500
		≥3,300	500

*** Category 1: net power greater than 37 kW and less than 5 L/cylinder.**

**** Category 2: 5–30 L/cylinder.**

To put the numbers in perspective, the 4-stroke marine diesel engine at Alfa Laval's test and training center has a rated power of 2000 kW. It produces a PM output of approximately 142 mg/kWh when using diesel oil (DO) and roughly 1206 mg/kWh when using Heavy Fuel Oil (HFO). Thus, particle removal is necessary for most engines. The inland waterways in the EU are home to approximately 15,561 vessels [16], marking a considerable market.

China has also taken significant steps towards further regulating PM and PN emissions, particularly through the establishment of Domestic Emission Control Areas (DECA) along its coastline. Since 2020, ships entering inland waterways are required to adhere to a maximum sulfur content of 0.1%. There are plans to expand the DECA to encompass all coastal waters of China by 2025 [17].

Various local initiatives also contribute to emissions reduction efforts. One such initiative is the Clean Shipping Index (CSI), which offers voluntary certification for shipowners [18]. The CSI aims to recognize vessels that undertake exceptional measures to reduce emissions beyond what is mandated by legislation. Points are awarded in different categories, with NOx, SOx, and PM earning a relatively high score if extraordinary reduction methods are implemented. Many ports in Scandinavia have tied their port fees to this index, offering discounts to ships with high scores.

3.3 Alfa Laval Test and Training Centre

The new wet ESP is installed as an addition to the existing engine test facility at the Alfa Laval Test and Training Centre in Aalborg, Denmark. The setup consists of the following equipment and can be seen in FIGURE 1:

1. A 4-stroke MAN 28/32 engine equipped with 9 cylinders with a max capacity of 1980 kW.
2. Six 50 kW electrical heaters to control the exhaust gas temperature.
3. A Selective Catalytic Reduction (SCR) for NO_x removal.
4. An exhaust gas boiler to recover heat from the exhaust gas.
5. A SOx scrubber for removal of SO_x.
6. A wet ESP for removal of particles, black carbon, and overall aerosols.
7. An exhaust gas funnel.

The experimental setup encompasses all essential apparatus required for emulating a functional maritime configuration. The engine's operational mode can be toggled between Marine Gas Oil (MGO) and HFO, enabling comprehensive equipment testing across varying fuel types. HFO was the primary fuel for this specific test campaign. The facility is designed to supply exhaust gas to the wet ESP, maintaining minimal concentrations of NO_x and SO_x, while adhering to a temperature range of 20-40°C.

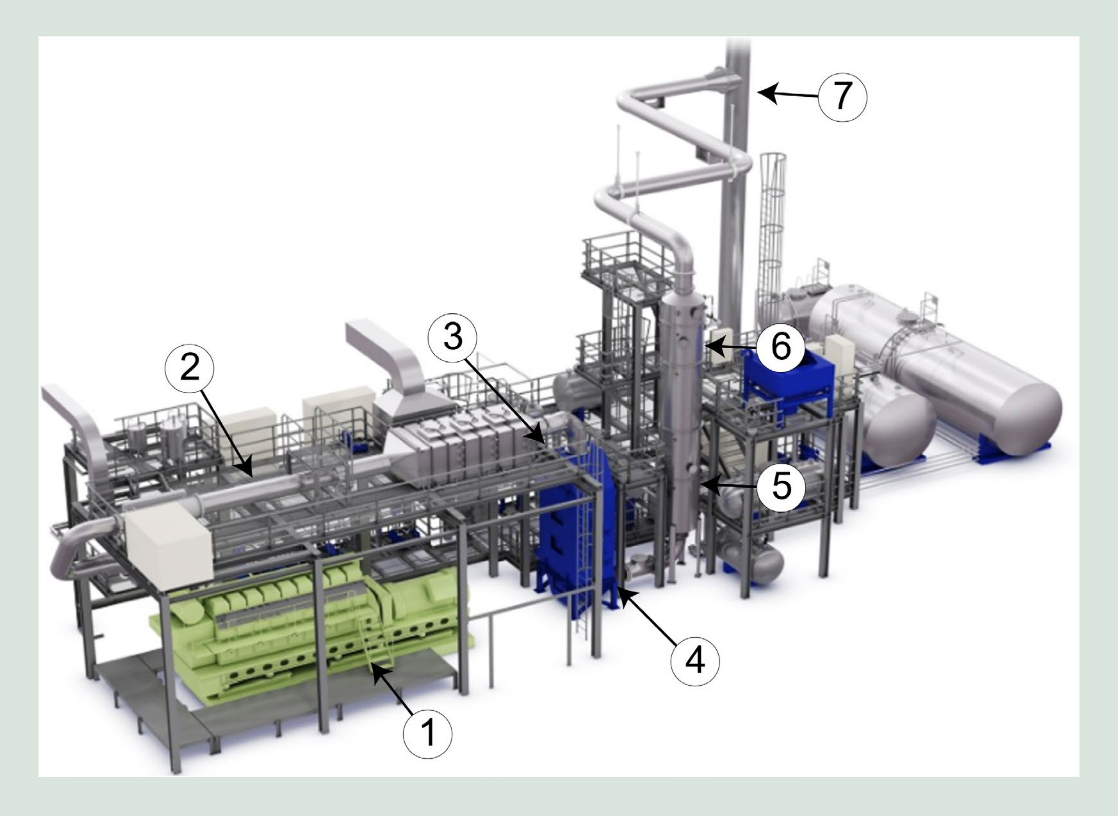


FIGURE 1. Illustration of the overall test setup from engine to exhaust gas funnel.

3.4 Wet electrostatic precipitator

The fundamental principle of an electrostatic precipitator, ESP (6 in FIGURE 1), is to electrically charge the particles and then force them to migrate towards collection plates, where they adhere. As particles accumulate on these plates over time, a layer forms. Two primary methods are employed to eliminate this particle layer: the first involves either hammering or vibrating the collection plates to dislodge the particles, known as a dry ESP. The second method entails using a water film or spray to remove the particle layer, termed a wet ESP. For this study, the wet ESP system has been chosen due to its increased removal efficiency of small particles, <1 µm, which constitute a large quantity of the particles generated by a marine engine. The higher removal efficiency is mainly achieved through the cleaning process of the plates, where a water film or spray removes all particles from the collection plates and distributes them to the bottom. In contrast, a dry ESP may reintroduce smaller particles to the gas stream as they are hammered or vibrated off the plates, potentially moving them back into the gas stream instead of allowing them to fall to the bottom.

3.5 Market Potential

The wet ESP technology demonstrates its capability to purify exhaust gases from various ship types and engines, whether in retrofitting existing vessels or integrating into newly constructed ones. As of January 2023, the world's merchant fleet comprised 105,500 ships of at least 100 gross tons, with 56,500 exceeding 1,000 gross tons, indicating a significant retrofit market potential [19]. Installing a filter in new ships is notably straightforward, thanks to the ample space available for installation.

Despite fluctuations in the new build market, assuming an average lifespan of 25 years and considering the previously mentioned fleet size, the market could encompass approximately 1,960 vessels ranging from 100 to 1,000 gross tons and 2,260 vessels exceeding 1,000 gross tons annually [19]. Another substantial market is the inland waterways in the EU, with approximately 15,561 vessels [16], and in China, with approximately 109,500 vessels operating on inland waterways by the end of 2022 [20].

The legislation serves as the primary driving force behind this market, particularly regional regulations and initiatives targeting particle emissions from shipping in environmentally sensitive areas. Examples include the North European Emission Control Area (ECA), Californian ports, regions surrounding the Yangtze River Delta (YRD) in China, specific ports, and environmentally fragile areas such as the Arctic or tropical islands.

4. Objectives

The primary goal of this project is to create a solution that minimizes PM and BC emissions from a marine combustion engine. The system targets a removal efficiency of 80%, which is comparable to the reduction achieved by switching from HFO to DO. Initial tests have shown encouraging outcomes using a compact wet electrostatic precipitator (ESP) on a small scale. However, it is crucial to refine all design variables and establish a reliable cleaning system for both discharge and collection electrodes. Additionally, the efficacy of new insulator boxes, designed for stability, requires testing to determine their maintenance feasibility.

From a procedural perspective, the project's more specific aims encompass:

- Measure the removal efficiency of PM and BC particles within the wet ESP system.
- Evaluate the performance of the water cleaning unit for the combined scrubber and ESP wash water.

Drawing on the knowledge and outcomes, it becomes feasible to devise a novel wet ESP for commercial maritime vessel setups. Parameters such as gas velocity and the maximum permissible engine back-pressure are typically available through engine data sheets.

5. Installation

In Alfa Laval’s test and training center in Aalborg, the wet ESP system has been seamlessly integrated. This facility is fully equipped to replicate a standard marine vessel setup. Its notable feature is the enhanced operational flexibility, facilitating thorough equipment testing across diverse conditions.

5.1 Process

Within the test and training center, exhaust gas is generated by a 2 MW 4-stroke marine diesel engine. This gas then undergoes NO_x and SO_x removal via an SCR and a scrubber before entering the wet ESP. The overall process and setup are illustrated in FIGURE 1.

Initially, the engine's exhaust gas is heated electrically and then subjected to conventional selective catalytic reduction (SCR) to eliminate NOx. The gas subsequently passes through an exhaust gas boiler and a scrubber located beneath the ESP. Following this path, a wet electrostatic precipitator (ESP) is integrated after the existing scrubber. FIGURE 2 presents an image of the wet ESP setup.

FIGURE 2. Wet ESP in the Alfa Laval Test and Training Centre.

5.2 Mechanical

The experimental wet ESP unit is constructed with the capacity to manage the complete exhaust gas output produced by the 2 MW MAN marine diesel engine situated within the test and training centre. Notably, the wet ESP is placed atop the SO_x scrubber, as illustrated in FIGURE 3.

FIGURE 3. Wet ESP system layout at Alfa Laval Test and Training Centre.

A demister is installed downstream of the wet ESP as shown in FIGURE 3, to investigate the entrapment of water droplets under varying operational conditions, both with and without the ESP in operation. To ensure the precision of particulate and black carbon measurements, the demister will be emptied after evaluating the entrapment of water droplets.

The wet ESP system comprises a single rectangular enclosure housing two channels of equal size. Each channel accommodates a number of high-voltage discharge electrodes, each less than 1.8 meters. This length was chosen to ensure compatibility with the test and training center's crane clearance. The electrodes are secured by four insulator boxes, two at the top and two at the bottom of the system. The upper boxes contain the discharge electrodes, while the lower ones offer crucial stabilization. This stabilization is especially critical for maritime applications aboard vessels.

6. Procedure

The following section provides an overview of the procedure during the test campaign and the subsequent data processing.

6.1 Test scheme

Preliminary examinations were carried out to ensure the correct functionality of mechanical and electrical components, including valves, actuators, and the PLC control system. Furthermore, all sensors and transmitters were carefully inspected and calibrated. Four weeks before the main test campaign, the entire system underwent testing with the engine operating at 75% load to validate that all sensors were measuring as anticipated.

6.2 Data acquisition

All operational data concerning the engine and the wet ESP was automatically logged every second by the data logger within the test center. This encompassed various metrics such as temperature and pressure readings from transmitters, engine fuel flow, valve positions, data from gas analyzers installed in the facility, and the high voltage power supply status for the wet ESP system. Additionally, data generated from three measurements: PM, BC, and size distribution were separately recorded for further analysis.

6.3 Calculation of the velocity through the wet ESP

The volume flow and composition of the engine's exhaust gas are determined based on several inputs:

- Fuel flow meters.
- Fuel analysis.
- Scavenging air temperature (SW cooling temperature +4°C).
- Ambient temperature and humidity.
- Measured O_2 and CO_2 content in the exhaust gas. Either O_2 or CO_2 can be used but both signals have been used here to minimize possible errors.
- Exhaust gas temperature into the wet ESP.

To further assess the flow velocity through the wet ESP, the rinsing air within the insulator chambers is measured by gauging the pressure loss across hole plates within the chambers. Additionally, flow velocity is measured at specific points using a pitot tube to ensure isokinetic measurements.

6.4 Gas and particle measurements

PM and BC measurements were conducted on the exhaust gas following the wet ESP, and data were compared between measurements with the ESP turned off and on to evaluate the system's trapping efficiency. Focusing solely on post-ESP measurements allows for reduced equipment and personnel requirements. The three measurement positions for the test campaign are illustrated in FIGURE 4.

FIGURE 4. Gas Measurement Connections From left to right, the following measurements were taken: Black carbon (BC), ELPI (Electrical Low-Pressure Impactor), and particle matter (PM).

6.4.1 Particulate Matter (PM)

Hot exhaust gas samples were extracted from the ducts before and after the filters following the guidelines of DS/EN 13284-1:2017 "Stationary source emissions – Determination of low range mass concentration of dust – Part 1: Manual gravimetric method." However, the measuring position before the filters did not meet the requirements for distance to obstructions before and after it. To address this, the number of measuring positions was increased.

6.4.2 Black Carbon (BC)

The content of BC in the exhaust gas was measured using a filter smoke meter (FSN) 415SE from AVL. The FSN 415SE is specifically designed for this purpose and provides accurate measurements of BC levels. FIGURE 5 depicts a visual representation of the system. This instrumentation plays a crucial role in understanding and monitoring BC emissions, contributing to efforts aimed at reducing environmental pollution and improving air quality.

FIGURE 5. AVL Smoke Meter applied for measuring before and after the ESP.

7. Results

In the following section, the results of the test campaign are presented. A primary outcome is the examination of the Current-Voltage Curves (CVC), which are crucial for the operational efficiency of the wet ESP system. Additionally, the results for the removal efficiencies of PM and BC are presented.

7.1 Current-voltage curve (CVC)

The Current Voltage Curve (CVC) stands as a crucial parameter for evaluating the effectiveness of the wet ESP, showcasing the volume of current discharged to the collection area. A heightened current signifies superior filter performance. FIGURE 6 displays the DO and HFO.

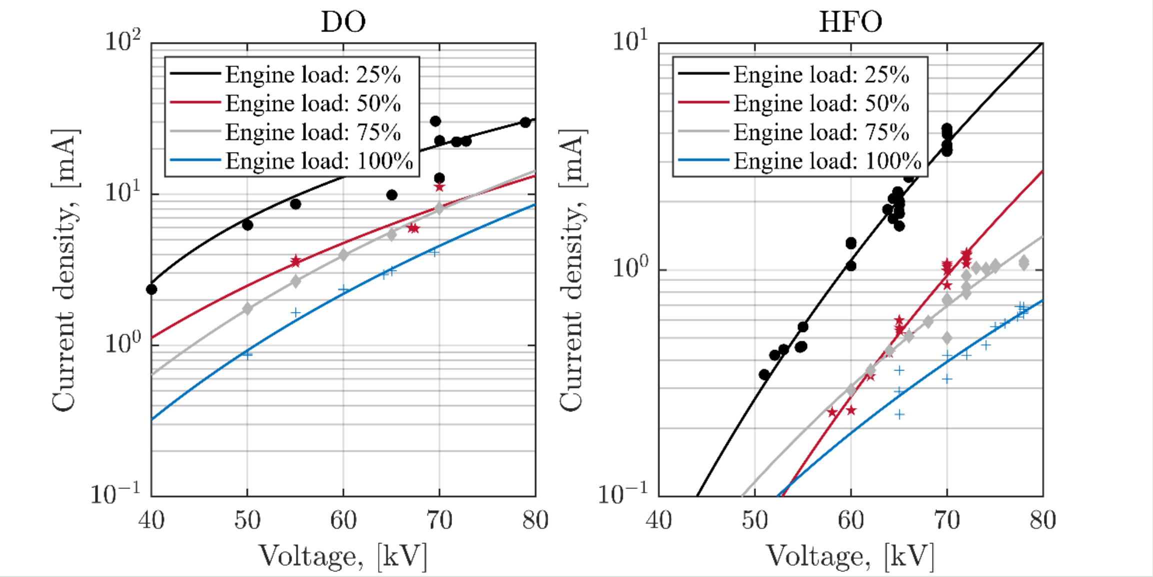


FIGURE 6. Current Density Curves (CVC) for the engine running on DO and HFO with a voltage input of 40-80 kV.

FIGURE 6 shows a clear trend, where the current decreases with increased engine load. This phenomenon occurs because the space current within the ESP increases with higher particle loads, which, in turn, escalate with higher velocities through the filter. Additionally, the current decreases when switching from DO to HFO. This is attributed to the increased particle load, where HFO generates a particle load ten times higher than DO. Maximizing the power input (Watt per gas flow rate) is essential to achieve the highest removal efficiency of particulate matter.

7.2 Removal Efficiency of PM and BC

During the tests of the wet ESP, a PM removal efficiency of 83-96% for DO and 49-92% for HFO was measured. Additionally, a BC removal efficiency of 80-91% for DO and 55-85% for

HFO was measured. When the removal efficiency of the scrubber is also considered, the PM removal efficiency increases to 91-98% for DO and 74-96% for HFO, whereas the BC removal efficiency increases to 88-95% for DO and 73-91% for HFO. For the scrubber itself, a average PM removal efficiency of approximately 49% and a BC removal efficiency of approximately 40% have been measured during previous test campaigns.

The combined scrubber and wet ESP PM and BC removal efficiencies are illustrated in FIGURE 7.

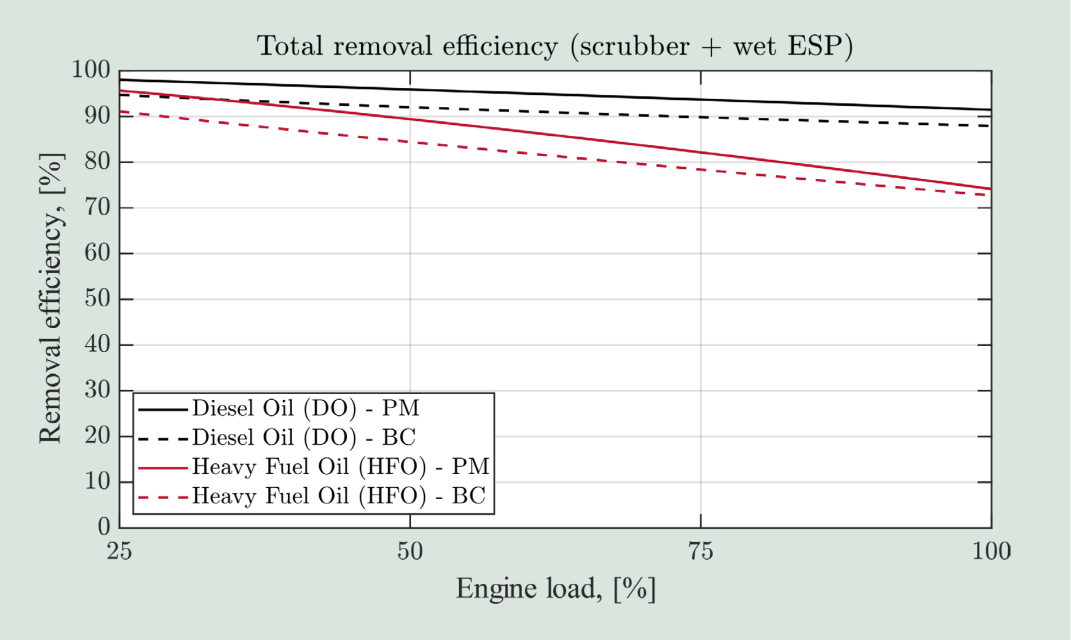


FIGURE 7. Illustration of the total PM and BC removal efficiency for the combined system containing a scrubber and a wet ESP.

FIGURE 7 shows an increase in both PM and BC removal efficiency when lowering the engine load from 100% to 25%. This is due to the particles having a longer residence time inside the wet ESP system.

The BC removal efficiency is lower than that of PM, partly driven by the lower BC removal efficiency inside the scrubber. Additionally, the slope of the PM removal efficiency is steeper than the one for BC, resulting in a larger gap between PM and BC removal efficiency at lower engine loads. The reason for this difference is mainly due to the size distribution of BC particles, which tend to be below 1 µm. The wet ESP has more difficulty removing these smaller particles from the gas stream.

The overall results of the test campaign were close to the expected targets for PM and BC removal, as based on previous tests conducted on a smaller setup. However, when the engine was operated on HFO at 100% load, removal efficiencies were 6-7% lower than anticipated. This reduction in efficiency is likely due to an increased amount of water droplets carried from the scrubber into the wet ESP system compared to the previous tests with the smaller setup.

These additional droplets, driven by the particle space charge effect, reduce the current density in the ESP. The presence of these excess droplets was visually confirmed using transparent plates mounted on the insulation boxes during system tests, both with the ESP activated and deactivated. This effect was most pronounced when hot exhaust gas was used, creating a clearer mist at the start of the ESP column compared to when only cold air was blown through the system.

However, the demister at the end of the ESP column could not confirm the increased quantity of water droplets, likely due to its lower efficiency at capturing droplets smaller than 50 µm. The formation of these fine droplets is likely due to the rapid cooling at the start of the scrubber, where the temperature drops from around 350°C to 60°C. This sudden cooling causes some water to evaporate, creating turbulence that breaks up remaining droplets into smaller ones, around 1 µm in size, resulting in the fine mist observed inside the scrubber.

Future experiments are needed to investigate this further, potentially by incorporating a finer demister after the ESP system to improve water droplet capture.

7.3 Cleaning of wash water from scrubber and wet ESP

During the test campaign of the ESP, water samples were taken to measure the separation efficiency of the water cleaning system. This system operates in parallel with the water system for the ESP and scrubber, continuously removing pollutants from the circulation tank. The water cleaning system consists of a pump, a pre-treatment system where a chemical coagulant and flocculant are dosed, and a high-speed centrifugal separator. The separator is a two-phase device that removes solid particles from the liquid phase, proving to be a highly efficient method for cleaning scrubber wash water.

During the test campaign, the separator operated at a nominal flow rate of 2 m^3/h with various dosing ratios of the chemicals. It was found that a mixing ratio of 125 ml/m^3 of coagulant combined with a dosing ratio of 4 ml/m^3 of polymer flocculant resulted in high separation efficiency.

After the test campaign, total suspended solids (TSS) concentration was measured in the water samples to determine the separation efficiency. Some of the measurements are shown in the table below.

TABLE 4. Overview of the wash water separation efficiency tests.

	Flow rate [m^3/h]	TSS of feed [mg/l]	TSS of effluent [mg/l]	Separation efficiency
#1	2	270	3.6	98.7%
#2	2	240	2.0	99.2%

The test campaign demonstrated that the installed water cleaning system can effectively clean water from both the scrubber and ESP, achieving a very high separation efficiency.
A picture of the two bottles of wash water before and after the cleaning process can be seen in FIGURE 8.

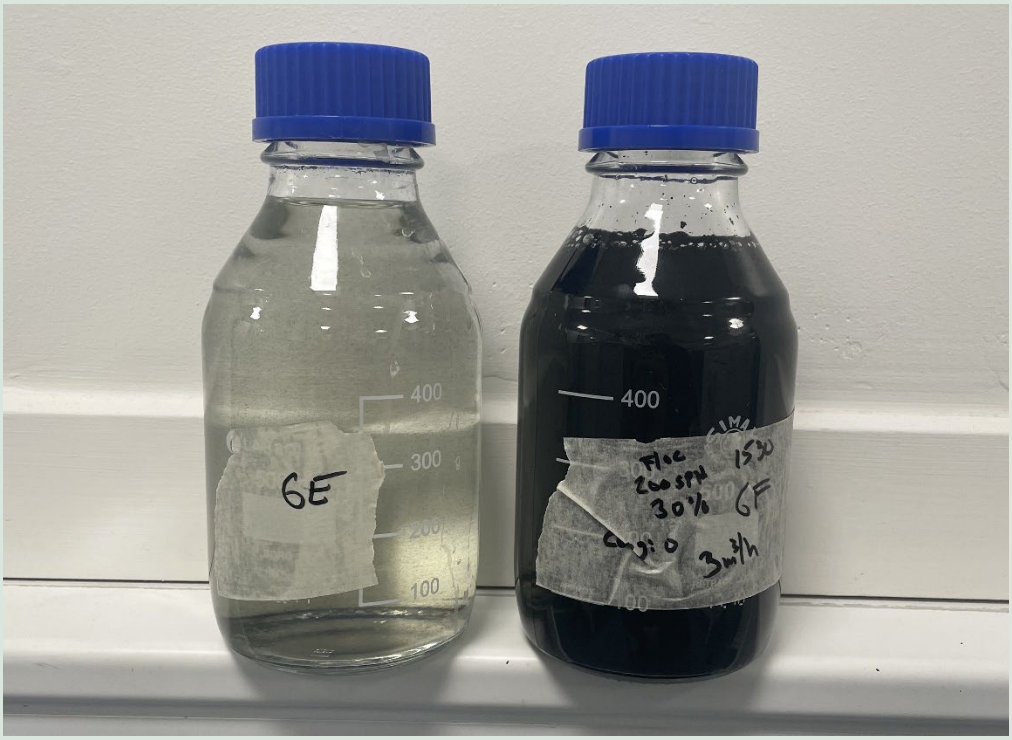


FIGURE 8. Bottles of wash water from the combined scrubber and wet ESP systems, with a sample before cleaning on the right and after cleaning on the left.

8. Conclusion

The test campaign resulted in several significant findings:

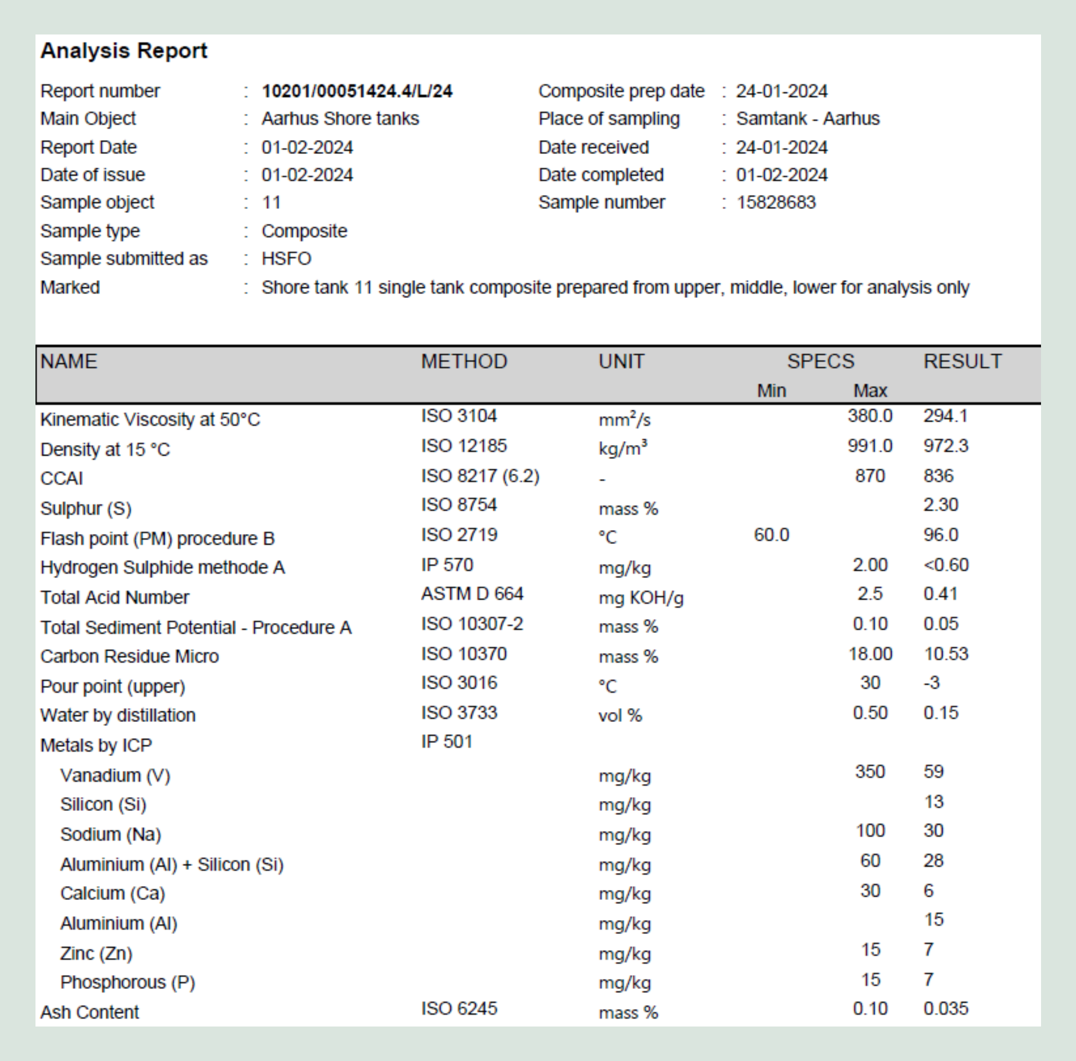
1. The combined scrubber and wet ESP system achieved removal efficiencies of up to 96% for PM and 91% for BC when the engine was operated on Heavy Fuel Oil (HFO) with a load ranging from 25% to 100%.
2. The combined scrubber and wet ESP system achieved removal efficiencies of up to 98% for PM and 96% for BC when the engine was operated on Diesel Oil (DO) with a load ranging from 25% to 100%.
3. The wash water cleaning system demonstrated an average cleaning efficiency of approximately 99%, making it highly effective.

Overall, the test campaign showed results close to the expected targets for PM and BC removal. However, the removal efficiencies were 6-7% lower than expected for tests with the engine running on HFO at a load of 100%. This lower removal efficiency is likely related to the higher amount of water droplets dragged into the wet ESP system from the scrubber. The compact design of the scrubber, with an absorber height of only 1.1 meters compared to the typical 3.2 meters found in a standard Alfa Laval scrubber, may be a contributing factor.

Despite this, the wet ESP system proved to be an effective solution for PM and BC removal, even with its relatively small height and overall footprint. This compact design offers a significant advantage for applications where space is limited.

In conclusion, the combined scrubber and wet ESP system, along with the highly efficient wash water cleaning system, provides a robust and effective method for reducing PM and BC emissions from marine combustion engines. This system shows great potential for improving air quality and complying with stricter environmental regulations in the maritime industry.

Appendix 1. Fuel Analysis



Analysis Report

Report number	: **10201/00051424.4/L/24**	Composite prep date	: 24-01-2024
Main Object	: Aarhus Shore tanks	Place of sampling	: Samtank - Aarhus
Report Date	: 01-02-2024	Date received	: 24-01-2024
Date of issue	: 01-02-2024	Date completed	: 01-02-2024
Sample object	: 11	Sample number	: 15828683
Sample type	: Composite		
Sample submitted as	: HSFO		
Marked	: Shore tank 11 single tank composite prepared from upper, middle, lower for analysis only		

NAME	METHOD	UNIT	SPECS		RESULT
			Min	Max	
Kinematic Viscosity at 50°C	ISO 3104	mm^2/s		380.0	294.1
Density at 15 °C	ISO 12185	kg/m^3		991.0	972.3
CCAI	ISO 8217 (6.2)	-		870	836
Sulphur (S)	ISO 8754	mass %			2.30
Flash point (PM) procedure B	ISO 2719	°C	60.0		96.0
Hydrogen Sulphide methode A	IP 570	mg/kg		2.00	<0.60
Total Acid Number	ASTM D 664	mg KOH/g		2.5	0.41
Total Sediment Potential - Procedure A	ISO 10307-2	mass %		0.10	0.05
Carbon Residue Micro	ISO 10370	mass %		18.00	10.53
Pour point (upper)	ISO 3016	°C		30	-3
Water by distillation	ISO 3733	vol %		0.50	0.15
Metals by ICP	IP 501				
Vanadium (V)		mg/kg		350	59
Silicon (Si)		mg/kg			13
Sodium (Na)		mg/kg		100	30
Aluminium (Al) + Silicon (Si)		mg/kg		60	28
Calcium (Ca)		mg/kg		30	6
Aluminium (Al)		mg/kg			15
Zinc (Zn)		mg/kg		15	7
Phosphorous (P)		mg/kg		15	7
Ash Content	ISO 6245	mass %		0.10	0.035

FIGURE 9. Fuel Analysis Report.

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Development of wet Electrostatic Precipitator for marine engines
The combined scrubber and wet Electrostatic Precipitator (ESP) system tested can effectively clean exhaust gases from marine engines powered by both Diesel Oil (DO) and Heavy Fuel Oil (HFO). Furthermore, the washing water used for cleaning the scrubber and wet ESP can be effectively cleaned using a separator system. The test campaign achieved the following results:

1. The combined scrubber and wet ESP system achieved removal efficiencies of up to 96% for PM and 91% for BC when the engine was operated on Heavy Fuel Oil (HFO) with a load ranging from 25% to 100%.

2. The combined scrubber and wet ESP system achieved removal efficiencies of up to 98% for PM and 96% for BC when the engine was operated on Diesel Oil (DO) with a load ranging from 25% to 100%.

3. The wash water cleaning system demonstrated an average cleaning efficiency of approximately 99%, making it highly effective.

Overall, the combined scrubber and wet ESP system, along with the highly efficient wash water cleaning system, provides a robust and effective method for reducing PM and BC emissions from marine combustion engines. This system shows great potential for improving air quality and complying with stricter environmental regulations in the maritime industry.

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