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Scrubbers: Closing the loop
Activity 3: Task 1
Air emission measurements

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Preface

This is a project report covering exhaust gas emission measurements on Stena Britannica as part of the project Scrubbers: Closing the loop.

This report covers Task 1 Air emission measurements of Activity 3 (Integrated Life Cycle Balance) in the CEF funded project "Scrubbers – Closing the loop". Together with this report the Activity is presented in:

- Scrubbers: Closing the loop; Activity 3. Summary; Environmental analysis of marine exhaust gas scrubbers on two Stena Line ships. IVL report B2317, by Winnes H., Granberg M., Magnusson K., Malmaeus M., Mellin A., Stripple H., Yaramenka K., and Zhang Y., 2018
- Scrubbers: Closing the loop; Activity 3. Task 2; Risk assessment of marine exhaust gas scrubber water. IVL report B2319, by Magnusson K., Thor P., and Granberg M., 2018
- Scrubbers: Closing the loop; Activity 3. Task 3; Cost benefit analysis. IVL report B2320, by Yaramenka K., Mellin A., Malmaeus M., and Winnes H., 2018
- Scrubbers: Closing the loop; Activity 3. Task 4; Evaluation of exhaust gas scrubber systems for ship applications in a system perspective. IVL report B2321, by Zhang Y and Stripple H. 2018

IVL Swedish Environmental Research Institute has been the leading organisation of the activity and has performed the studies in this report with support from representatives from the project partners Lloyd's Register EMEA and Wärtsilä Sweden AB, and the project coordinator Stena UK Ltd.

We greatly acknowledge our funders at Connecting Europe Facility, and the insightful and dedicated support from the project coordinator Stena, our partners Lloyd's Register and Wärtsilä. Especially acknowledged are Andy Wright at LR who has supported with his specialist knowledge regarding air emissions measurements and Stian Aakre at Wärtsilä who has supported with technical knowledge of the system. The project coordinator has been much involved in the task with appreciated efforts from Per Stefenson and Björn Asplind at the Gothenburg office. Warm thanks also to the captains, chief engineers and crew on Stena Britannica for their support during emission measurements and water sampling, as well as the Stena Line personnel on shore in Hook of Holland for their assistance.

Contents

APPENDIX:

APP_A: Data from measurements on LSFO

APP_B: Data from measurements on HFO

APP_C: Determination of SFOC

APP_D: Fuel analysis report, 1st Feb

APP_E: Fuel analysis report, 2nd Feb

APP_F: Fuel analysis report, 3rd Feb

APP_G: Fuel analysis report, 4th Feb

APP_H: Lub oil analysis report, Feb

APP_I: Fuel analysis report 19th Sep

APP_J: Lub oil analysis, Sep

APP_K: Hourly log scrubber parameters 19th -20th of September

APP_L: Hourly log scrubber parameters 20th -21st of September

APP_M: Hourly log scrubber parameters 21st of September

APP_N: Pitot tube measurements and calculations of exhaust flow

Summary

This report covers two emission measurement campaigns on Stena Britannica, a RoPax ferry in traffic between Hoek van Holland and Harwich. The first set of trials is benchmark measurements for emissions from operations on low sulphur fuel oil (LSFO). The second set of trials is conducted after the fitting of an exhaust gas cleaning system on the ship. We compare emissions from LSFO combustion with HFO combustion downstream a scrubber. Both are alternatives that can be used to comply with the existing regulations in the area. The comparison is interesting from an environmental point of view since the number of installations of scrubbers on ships rapidly increases. We also analyse emission reductions over the scrubber, as measurements were conducted both upstream and downstream the installation.

An SO_2 scrubber is fitted in the exhaust channel in order to reduce SO_2 emissions to levels corresponding to the combustion of 0.1% sulphur fuel or lower, as described by the MARPOL Annex VI Regulation 14 on sulphur content in marine fuels used for operations in a SECA.

The main purpose of installing an exhaust gas scrubber on a ship is to reduce emission of sulphur dioxide to levels equivalent to emission levels from combustion of a fuel with 0.1% sulphur. The closed loop scrubber system on Stena Britannica was shown to accomplish and outperform the emission limit. SO_2 emissions are reduced significantly with the exhaust gas cleaning system (EGCS) on board Stena Britannica.

The specific emission factor for SO_2 downstream the scrubber was 83% lower than at combustion of low sulphur oil at 75% engine load. The emission factor is specific for the engine and represents mass of emission per unit of work produced by the engine, often expressed as g/kWh. Also specific emission rates of total hydrocarbons were lower downstream a scrubber compared to emissions from LSFO combustion, approximately 40% lower at 75-76% engine load. Other emission levels are increased. At 75-76% engine load, specific emission rates for PM were 0.27 g/kWh downstream the scrubber compared to 0.12 g/kWh at LSFO combustion. Also emission rates of polycyclic aromatic hydrocarbons, elemental carbon and black carbon, and sulphur in particles were significantly higher downstream the scrubber compared to the LSFO, while results are less clear on emissions of organic carbon. No significant differences in specific emission factors of CO_2 and NO_x could be concluded from the measurements, while the specific emission for CO was around 50% higher downstream the scrubber than at LSFO combustion. Tests at lower engine loads in large indicate a similar situation although the SO_2 removal seems even more efficient at lower engine loads, and the differences in PM emissions are less manifested.

Uncertainties of the results include the particle emission measurement methods used that are little tested on cold exhaust gases, the gases downstream the scrubber are approximately 20° C. No applicable standard for such measurements exists.

1 Introduction

The project 'Scrubbers – Closing the loop' includes two emission measurement campaigns within the scope of the project Activity 3 on Integrated Life Cycle Balance. Both campaigns take place on Stena Britannica in traffic between Hoek van Holland and Harwich. The first set of trials is benchmark measurements for emissions from operations on low sulphur oil. The second set of trials is conducted after the fitting of exhaust gas cleaning system on the ship. An SO_2 scrubber is then fitted in the exhaust channel in order to reduce SO_2 emissions to levels corresponding to the combustion of 0.1% sulphur fuel or lower, as described by the MARPOL Annex VI Regulation 14 on sulphur content in marine fuels used for operations in a SECA.

The report includes a brief description of the ship and its engines; the measurement process; raw data input; results; and findings and conclusions, in that order.

1.1 Stena Britannica

Stena Britannica is one of the largest RoPax ferries in the world. The ship is in service between Hoek van Holland in the Netherlands and Harwich in the UK. Details of the ship are presented in Table 1.

Table 1. Details of Stena Britannica

LR/IMO_Ship_No.	9419175
Name_of_Ship	STENA BRITANNICA
Built	2010
Ship type	Passenger/Ro-Ro Ship (Vehicles)
Ship type category	RoRo/Ferry
Deadweight	11600
GT	64039
TEU	n.a.
Total_kW_Main_Eng	33600
Engines_RPM	500
Propulsion type	n.a.
Aux._Engines _kW	1x1540 and 3x 1320
Length, m	240
Breadth, m	32
Draught, m	6.4

The ship has four main engines of two different models installed: two 8L MAN 48/60 CR and two 6L MAN 48/60 CR. The auxiliary engines are one 7L MAN 21/31 and three 6L MAN 21/31 engines. All the main engines have been fitted with scrubbers during 2017. The emission measurements are conducted on one of the main engines of type 8L 48/60, identified as engine no. 4.

The main engines are coupled in pairs to the two propeller shafts. Fuel is supplied to each pair of engines simultaneously. The fuel flow is measured by fuel mass flow meters of Coriolis type, employing one meter for each engine pair. The settings on fuel flow to each engine can be altered manually. During the emission measurements the engine coupled with engine no 4 was not in operation. Hence the recorded fuel flow meter readings only related to ME no 4.

The power trains are fitted with shaft generators that often replace electricity production from the auxiliary engines for operation at sea. The shaft generators are not used during the trials. Power readings are thus more representative for propulsion power from the crank shaft. However, all power readings are from after the gearbox. Approximately 3% power loss over the gearbox was estimated by the chief engineer, the interval being from 1-5% power loss per engine. No other losses of power are included in the result interpretations. The main engines also run various engine service pumps in addition to the propeller and, when in use, the shaft generators. Since these pumps provide services necessary for the engine to operate the associated power losses are taken to be simply a part of the overall engine parasitic losses which includes such aspects as bearing friction.

Other equipment on board that may have an influence on especially particulate matter concentration in the exhaust stream includes the economiser and the turbocharger, and their cleaning procedures.

The exhaust gas economiser is situated upstream of the measurement site. The economiser is not cleaned during measurements and has never been cleaned previously. The turbocharger is cleaned once a day with water and cleaning agents. Cleaning of the turbo charger was put on hold for the period of the emission measurement trials. The exhaust channel is not equipped with a smoke reader or smoke management system.

Back pressure from the exhaust system is not a registered parameter and thus the chief engineer cannot tell if it has changed due to the installations of the EGCS.

1.2 Test schedule

Consecutive tests with the same scope were planned for four different engine loads; 100%, 75%, 50%, and 25% of MCR. The actual case includes measurements close to these load points:

- 85%, 76%, 50%, and 34% of MCR, avoiding the extremes which were practically impossible to keep for a full journey for measurements in February on low sulphur fuel oil.
- 76%, 48%, and 41% of MCR for measurements in September on heavy fuel oil downstream the scrubber.
- 76%, 49%, and 32% of MCR for measurements in September on heavy fuel oil upstream the scrubber.

No idling conditions are included in the tests since main engines are not kept in idling mode for any significant period of time. As stated by the chief engineer, there are no specific engine devices that are manually adjusted as a result of load changes on the engine.

Concentrations of the following exhaust gas species SO_2, SO_3, NO, NO_2, CO_2, total HC, and CH_4, were determined as part of the measurement scheme. Furthermore, particulate matter emissions are determined by gravimetric sampling and characterized as PM_{tot}, and PM with a cutoff around 1.5 µm. Particle size distributions are determined for a limited number of trials in size distributions from 2.5 nm to >30 µm. Particle elemental contents are determined as well as contents of sulphate, black carbon, elemental carbon and organic carbon.

The instrumentation used is specified in Table 2. Gas analysers are calibrated, interference checked, zero and span checked and operated as per the NO_X Technical Code (International Maritime Organisation, 2008). Zero and span check gases are used on board.

Table 2. Specification of emissions to be measured and instrumentation used.

Species	Instrument	Comment	Instrument potential measurement range
Gaseous:			
SO_2	Horiba PG 350 E		0 - 500 ppm
SO_3	NaCl adsorbent tube – method for SO_3		
NO_x	Horiba PG 350 E		0 – 2500 ppm
NO	Horiba PG 350 E		
NO_2	Horiba PG 350 E		
CO_2	Horiba PG 350 E		0 - 30%
Total HC	FID: Graphite 52M		0-10 000 ppm
nonCH_4 hydrocarbons	FID: Graphite 52M	Diff: Total HC –CH_4	0-10 000 ppm
CH_4	FID: Graphite 52M		0-10 000 ppm
O_2	Horiba PG 350 E		0 - 25%
CO	Horiba PG 350 E		0 – 1 000 ppm
PAH (Total incl particle bound)	Absorbent Pur/XAD2	Analysis HPLC	
Particulate:			
PM_{tot}	Teflon Filter	Gravimetric analysis, analyses of elemental contents by ICP-MS, sulphate content	
$PM_{2.5}$	Teflon Filter + cyclone	Gravimetric analysis, analyses of elemental contents by ICP-MS sulphate content	
Particle number	EEPS	Electric charging of particles	32 channels; size distr. 5.6-560nm
Particle number	Grimm	Optical	15 channels; size distr. >0.30µm – 20 µm
Particle number	SMPS		Variable (1 nm to 1000 nm)
Black Carbon (BC)	AE33, Aethalometer	Continuous measurements of attenuation of transmitted light	
Elemental Carbon / Organic Carbon (EC/OC)	Quartz filter		

A schematic picture of the setup is presented in Figure 1.

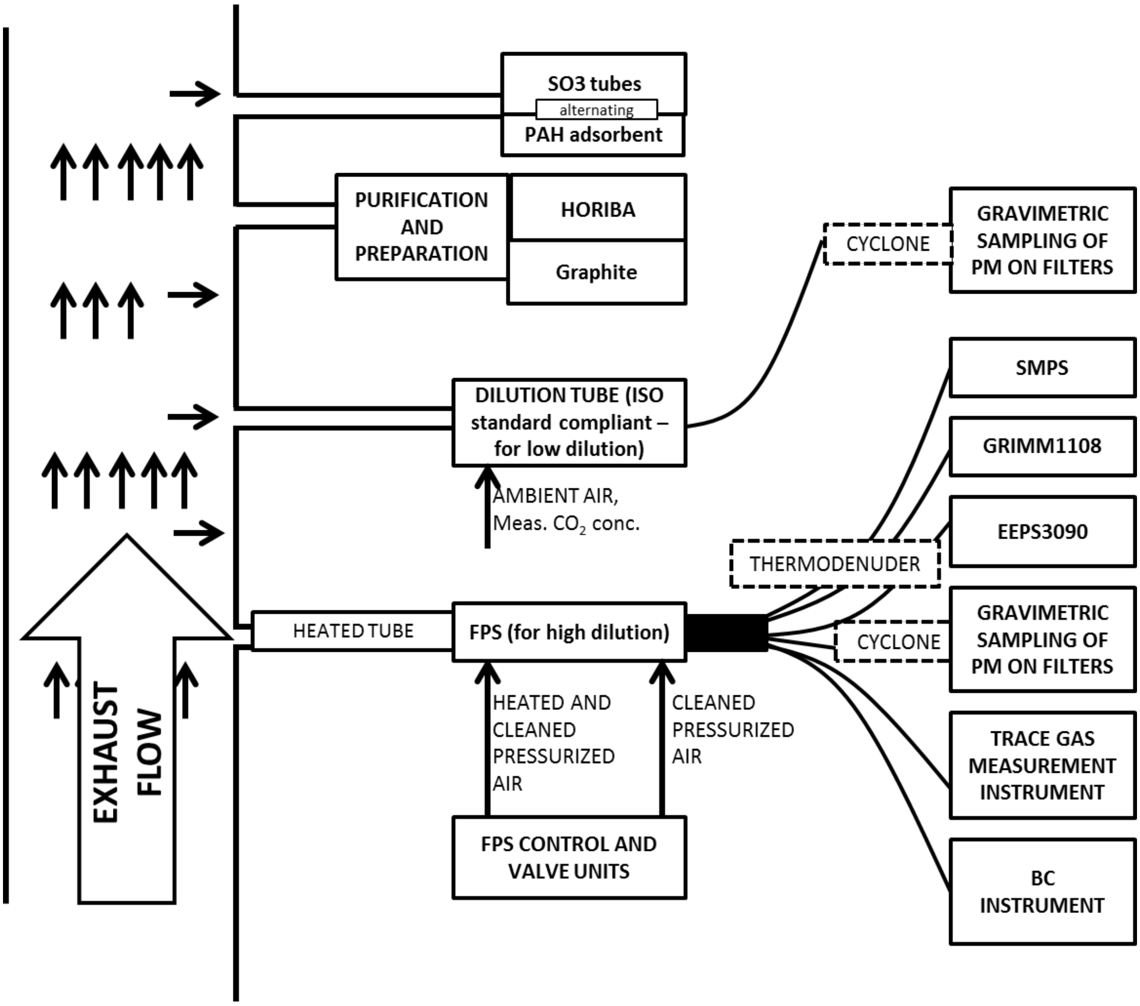

Figure 1. Schematic overview of the instrumentation setup

1.2.1 Exhaust Gas Measurement

Sampled exhaust gas is prepared prior to the measurements by conducting the raw gas through a heated tube with teflon lining via a ceramic filter to a preparation unit. The tube is heated to 190 °C. The gas preparation unit cools the gas to 4°C and removes particles by filtration; an Ankersmid sampling system APS303 is used to prepare the gas. The dry and particle free gas is used for continuous concentration measurements in the instruments with the interval 1 second.

The measurements follow the standard procedures set out in SJÖFS 2014:10, which are essentially those specified in ISO 8178-2, 2008 and IMO NOx Technical Code, 2008. Calibration and span gases with the following mixing ratios are used: NO_X 882±2 ppm, CO 452 ± 2 ppm, CO_2 15±2 vol%, O_2 20,95± vol%.

SO_3 is sampled in adsorbent glass tubes containing NaCl for analyses in the IVL laboratory in Gothenburg. The flow through the glass tube is determined using an Akai Tokei Denki AP25 gas flow measurement instrument.

PAHs are sampled by an adsorbent for later analyses in the IVL lab. XAD7-puffs are used. Contents of USEPA’s PAH-16 priority pollutants are analysed. These include naphtalene, acenaphtylene, acenaphtene, fluorene, phenantrene, anthracene, fluoranthene, pyrene, benz[a]anthracene, chrysene, benzo[b]fluoranthene, benzo[k]fluoranthene, benzo[a]pyrene, dibenz[a, h]anthracene, benzo[ghi]pyrelene, and indeno[1,2,3-cd]pyrene. The flow through the adsorbent is determined using an Akai Tokei Denki AP25 gas flow measurement instrument. PAH samples are kept in an electric cooling box at approximately 4°C. The samples are placed in the box approximately ten minutes after the exposure is ended and kept there until the measurement campaign is completed. During transport to the laboratory, the box was not cooled. The laboratory is not accredited for the analyses of naphtalene, acenaphtylene, acenaphtene, and fluorene. The same quality routines and control programs are followed for these and the PAHs for which the laboratory has accreditation for analyses. At the used laboratory, most PAH analyzes in air are carried out on particle samplers for which very large volumes of air have been drawn. In these, the most volatile PAHs do not get trapped in amounts that can be analyzed quantitatively. The sampling methods have led to such large variations that accreditation has not been relevant. We judge the results from not accredited PAH analyses as accurate as those from accredited, with regards to the stated measurement uncertainties for different compounds.

1.2.2 Measurements of particulate matter

Particles are sampled on filters with a partial flow dilution system, for subsequent gravimetric analysis. The exposed filters are also used for characterization of particle composition. From the dilution system, the sample gas was lead through a metal tubing before collection on filters. The quantity of sampled gas is determined by using an Akai Tokei Denki AP25 gas flow measurement instrument. The dilution system is described more closely below, see Exhaust gas dilution.

Particle mass is measured as PM_{tot} and $PM_{1.6}$. After dilution, the exhaust will be split to two separate filters, one for PM_{tot} and one for $PM_{1.6}$. Cyclones are used for the $PM_{1.6}$ sampling, assuring that large particles are removed from the sampling stream before the filter. The size cutoff at 1.6 µm is calculated from the flow through the system. The cyclones used are primarily intended for a cutoff at 2.5 µm. The flow through the cyclone was however set higher than it should have been causing a lower cutoff than intended. Teflon filters are used for PM measurements. The filters are weighed in a controlled environment before and after sampling.

Elemental Carbon and Organic Carbon (EC/OC) contents on particles are determined by sampling using impactors with double quartz filters. The analyses of filters are conducted by Laboratory of Aerosols Chemistry and Physics; Institute of Chemical Process Fundamentals, v.v.i. in Prague, Czech Republic. The analysis of EC/OC is done with a thermal/optical method on a filter section with a total area of 2.01 cm^2 that is cut out of the filter. Reported uncertainties by the laboratory for their analyses are 10% for OC and 20% for EC. An uncertainty relating to the sampling process is the distribution of particles over the filter surface. Since the EC/OC is analyzed for only a share of the total filter, the registered concentrations needs to be extrapolated to the full active/exposed area of the filter. Samples taken used two types of filter holders. Due to the setup of the filter holder the active filter area was different between the two. The reason relates to the use of two different dilution systems (see below). Filters holders in both systems gave an exposed filter area of 13.2 cm^2. A perforated disc was placed after the filters in both filter holder types, providing the filter with a flat supporting surface. This is customary for filter sampling. The difference between the discs used in the two different filter holders is the area of perforation. The disc in the holder in one of the systems was perforated equally over the whole surface, and the disc in the other holder type had perforations only in an area of 8.55 cm^2. Although the exposed area was 13.2 cm^2, it is assumed that the perforations caused uneven distribution of particles on the filter. The exposed area is assumed to be 8.55 cm^2, which gives underestimated results but is believed to be closer to the actual situation than the larger area.

Analyses of particle contents of sulphates and elemental composition are done for the teflon filters used for PM_{tot} and $PM_{1.6}$. Selected PM filters are thus used either for ICP-MS analysis, or the leaching process needed to determine sulphate content. For the analysis of metal content of filter, a set of filters were treated with HNO_3+H_2O_2 in high temperature and high pressure in a microwave oven according to IVL's method "A33-TM partiklar" causing particles to be dissolved for metal analysis. The samples are analysed for heavy metals with an ICP-MS[1] , which converts the test aliquot to an aerosol and conducts it to plasma of argon. In the plasma, the analytes are atomized and ionized. In a mass spectrometer the metal contents of the analyzed particles are determined. The analysis follows IVL method "A30 – Bestämning av metaller med ICP-MS", which is based on SS-EN ISO 17294-1:2006, SS-EN ISO 17294-2:2016, and SS-EN 15841:2009. This is another method than specified in the plan, but considered to produce equally reliable results.

Sulphate content of particles is analysed as SO_2 in gas, after dissolving particles in water and deducting and detecting gas phase SO_2.

For each load point of the engine the aim is to sample:

- 3 teflon filters for PM2.5 + characterisation
- 3 teflon filters for PMtot + characterisation
- 2 EC/OC

Apex source testing equipment sampling heads are used for $PM_{2.5}$ measurements and PM_{tot}.

Filters for the basic filter mass determination are handled in weighing facilities in the laboratory of IVL Swedish Environmental Research Institute, Gothenburg. The same laboratory pre-conditions and weighs blank filters. The filters will not be weighed within the wished for 80 hours due to the time schedule of measurement campaigns. The filters will be kept in a cold environment in Petri dishes until the laboratory can weigh them. Estimated exposure time for filters exceed 10 minutes in all instances.

Online measurements of nano-sized particles in diluted exhaust gas were planned but could not be performed for all trials. One instrument (SMPS) measuring number of particles between 2.5 nm and 1000 nm in diameters in 167size channels had electronic failure in the data logging function due to high ambient temperature. This problem was encountered during both campaigns and reliable results are not retrieved. A second instrument (EEPS) measuring number of particles between 5.6 nm and 560 nm in diameters in 32 size channels was not operational at measurements at LSFO operations after losing a part during routine cleaning of the instrument. Reliable results from measurement at HFO operations, upstream and downstream the scrubber are available from the EEPS.

An optical instrument, a GRIMM, measuring particles between 0.3 and >20 µm in diameters is used sporadically during measurements.

A black carbon instrument, Magee Scientific's Aethalomter AE33, was used with continuous measurement of the attenuation of transmitted light at eight wavelengths. Measurement of absorption at 880 nm is interpreted as concentration of Black Carbon. Any non-volatile fraction of

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[1] Inductively Couples Plasma Mass Spectrometry.

the BC measured at 880 nm was measured after use of a thermodenuder heated to 300° to vaporize volatile particles. Conductive tubing was used between the dilution system and the BC-instrument.

1.3 Location and arrangement of measurement holes

Four circular sampling holes with dimensions:

- 1 x 4”
- 2 x 2”
- 1 x 2½”

are cut in the exhaust pipe. One set of holes are made on deck 11 in the engine room, upstream the scrubber; and another set on deck 15, downstream the scrubber.

Due to spatial circumstances and requirements of the placement of the sampling holes, the cut holes will not allow isokinetic sampling of particles. Isokinetic sampling of the exhaust gas from diesel engines is not required by ISO 8178 since the particulate sizes are relatively small (as compared to, for example, coal fired boiler installations) and hence will have a greater tendency to be retained in any gas stream as sampled. The location of the holes is however considered to be adequately accessible, and spatially big enough to allow for the equipment. A reliable supply of electricity and pressurized gas was made available at the measurement location. The arrangement of the holes is shown in Figure 2.

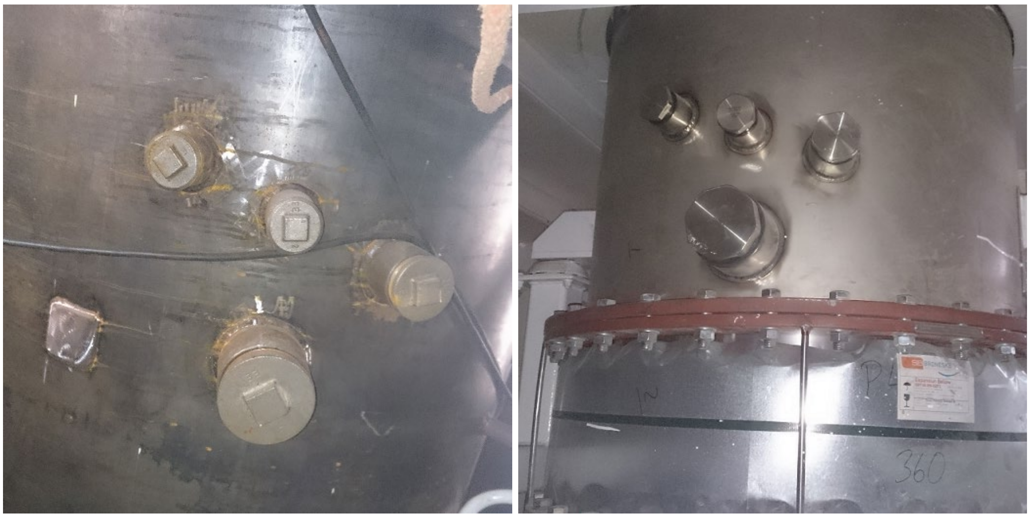

Figure 2. Arrangement of sampling holes at deck 11 and deck 15, respectively.

During the measurements at LSFO operations, the set of holes on deck 11 are used for sampling. However, gases are to a certain extent measured also at the upper deck in order to investigate the potential blend in of outside air. This location is approximately less than two meters from the end of the funnel. In ISO 8178 it is stated that in an exhaust channel of this dimension, the gaseous emissions sampling probes shall be fitted at three times the diameter of the exhaust pipe upstream of the exit of the exhaust gas system. The main reason for this, however, being to ensure an exhaust gas temperature of at least 70 °C at the probe.

1.4 Exhaust gas dilution

Two devices for exhaust gas dilution are used.

One system is designed to comply with ISO standard 8178:2/8178:1 for partial dilution systems, diluting raw exhaust up to 12 times, keeping temperatures steady and preferably between 42 and 52 °C, and with a dilution tunnel of 5 m length. The raw gas is led to the system in a heated tube with teflon lining. The dilution ratio is determined from the CO_2 concentration ratio of raw and diluted exhaust gas after having taken into account the ambient CO_2. This device is used for dilution prior to particle mass measurements on filters for measurements at LSFO operations and at HFO operations upstream the scrubber. Using only ambient air for dilution, this equipment is suitable and practical to use with the hot exhaust gases. The ambient air drawn through the dilution tunnel is filtered through a HEPA filter prior to use.

In parallel, a dilution device using pressurized and heated dilution air is used. The instrument is a Fine Particle Sampler (FPS) model 4000. The dilution ratio can be set to above 100:1, and the device is thus suitable for measurements of number of particles. The raw gas is led to the FPS from the probe via only metal tubing. This device is used to dilute the exhaust gas prior to the instruments EEPS, SMPS, Grimm; analysing the number and size distribution of particles, and prior to the BC-instrument. The concentration of a CO_2 is measured after the FPS in order to determine the dilution ratio after having taken into account the ambient CO_2. This is done using a CO_2/H_2O instrument in which the diluted gas and ambient gas alternatively is pumped through an optical path with an IR detection system from Li-cor. Also NO_X is used as a trace gas in order to determine dilution ratios. A heated probe, Dekati FPS stack heater connector FPS4230, was used at the measurement site prior to the scrubber.

All particle measurements at trials downstream the scrubber, are done using dilution by the FPS. The reason for this is positive experiences from previous tests with the FPS downstream a scrubber. Further, the physical circumstances in the funnel, and the many lifts involved in moving the large and heavy parts of the dilution tube to deck 15 made this option highly impractical and risky. The FPS system is also used during particle sampling for gravimetric analysis at the other trials in order to assure a fair comparison between the registered particle concentrations from the two dilution alternatives. Collection of particles on filters for gravimetric analyses is made after dilution with the FPS in addition to the standardized dilution setup. This is done to facilitate comparisons between the measurement campaigns of emissions of PM. Dilution settings are as similar as possible upstream and downstream the scrubber in order to facilitate the analyses of the abatement efficiency of the scrubber.

The dilution ratio is, as mentioned, determined from CO_2 concentrations and alternatively from NO_X concentrations. When CO_2 concentrations are used the ratio can be calculated as indicated in the formula:

$$DR = \frac{(C_{CO2\ raw\ gas})}{(C_{CO2\ diluted\ gas} - C_{CO2\ air})}$$

Where the DR is dilution ratio of the exhaust, $C_{CO2\ raw\ gas}$ is the CO_2 concentration in the undiluted exhaust gas, $C_{CO2\ diluted\ gas}$ is the CO_2 concentration in the diluted gas, and $C_{CO2\ air}$ is the CO_2 concentration in the ambient air.

NO_x concentrations in air are insignificant and the relation between the measured concentration in raw gas and diluted gas can be used directly.

The dilution in the dilution tunnel is determined by CO_2 levels only. A CO_2 sensor is fitted to the tunnel and directed to either the diluted gas or the raw gas. The levels are noted but not logged continuously. Variations over time or at specific instances are thus not registered and uncertainties are higher than if values are logged for a full trial.

1.5 Thermodenuder

A thermodenuder (TD) is used to remove the volatile fraction of particles. The use of a thermodenuder has been shown to also cause a loss of solid particles. Losses in the Dekati TD are reported to be:

- At flow of 5 L/min, T=275°C, particles with diameters of 20 nm a loss of 42.2% is reported by M. Fierz and H. Burtscher, Separation of solid and volatile fraction by thermodesorption and hot dilution, PMP report CH6
- Losses in the TD depend on particle diameter and can be calculated according to Dekati. At sizes between 10 and 50 nm, the loss is between 25% and 40%.
- Tests run on a test engine measured losses in the TD of sizes between 10 and 50 nm to between 37% and 61% (unpublished results from Chalmers University of Technology).
- In a study by VTT solid particle losses were 24.5% in a Dekati TD, (Timonen, Aakso-Saksa et al., 2017, Black carbon measurement validation onboard (SEAEFFECTS BC WP2)

Based on the different sources it will be difficult to determine the loss precisely. Loss depends on particle size, thermodenuder temperature, and velocity through the thermodenuder which in our tests are lower than the specification, favouring loss. The study by VTT specifies that the loss concerns solid particles, while the other studies are less clear. The estimates used further in the report are based on the loss ratio from VTT and the calculated values from Dekati. A loss of solid particles between 25% and 40% of black carbon concentrations is therefore considered probable.

2 Exhaust gas emission measurements at combustion of low sulphur fuel oil

This chapter describes measurements and results at combustion of low sulphur fuel oil (LSFO).

The environment in the funnel where the measurement took place was spacious enough to fit all the equipment and instruments. However, the temperature in the funnel was occasionally above 40°C causing sporadic problems for sensitive instruments.

Gas instruments are kept at deck 9, 2 decks below the measurement site, in order to keep them within their specified temperature range for accurate measurements. The same layout is not chosen for particle instruments since the long conductive tubing that this would have required is considered to cause significant impact on particle loss.

Further, during the measurement trials, welding work was conducted in the funnel. The air was contaminated by airborne residues from the welding work (undefined but noticeable in the work environment), possibly metal contamination. Since several people were moving around in the funnel and moving objects, the air was also very dusty. To protect instruments from welding sparks when they were not in use they were covered with blankets that were not as clean as would have been desirable.

2.1 Raw data and emission concentrations

Raw data from oil sample analyses, engine settings and gas and particle concentrations are presented in the following sections.

2.1.1 Oil analysis

The engine has run on low sulphur marine fuel oil (ISO 8217:2010) with <0.1% S, since beginning of January 2017, i.e. for a month's time before the first trials. Low sulphur fuel oils (LSFO), often referred to as 'hybrids' , differ significantly in composition from conventional distillates being specifically manufactured fuels to meet the 0.10% max sulphur limit. They are often products from vacuum gas oils and similar refinery streams and as such have, for example, much higher viscosity and density values than conventional distillates. The latest bunkering before the measurements was done on the 27th of January and one bunkering took place on the 3rd of February (during the campaign period). Both fuels were RMG380 (ISO 8217:2010). In order to make sure that the same fuel is used throughout the test period several fuel oil samples were collected for analysis. Bunker delivery notes for the bunkered fuels were received (included in APP_G). A sample of the lube oil was also collected for analysis. The same lube oil has been used for a long time.

Four oil samples, one taken each day of the trial, are sent for analysis of density, viscosity and sulphur content in order to establish that the same fuel is used throughout the campaign. For the four consecutive days sulphur contents are 0.10, 0.101, 0.100 and 0.100%; viscosities are 81.49, 82.19, 81.52, and 79.99 mm^2/s and densities were 908.5, 910.6, 908.9, and 909.0 kg/m^3 respectively. All samples are sent to the Saybolt Laboratory in Gothenburg who report measurement uncertainties in the analyses of 0.0004 for density, 0.014 for sulphur content and 3.783 for viscosity. The laboratory concludes that the fuel samples from the 2nd Feb and 4th Feb are from the same fuel, but that the sample from the 3rd of February deviates with respect to density. This sample is similar to the sample from the 1st Feb, which is sent for a full analysis. This suggests that the same fuel was in in use across the whole measurement period with marginal variation as are typically encountered.

The fuel analyses reports from Saybolt are appended (APP_D-APP_G) as is the lube oil analysis report (APP_H).

2.1.2 Fuel oil consumption

Information on fuel oil consumption at the time of the measurement is received from loggings of the ship's fuel flow meter. The engine room crew note fuel consumption during trials and log data for the fuel consumption during the full trials for main engine 3 and main engine 4. ME 3 and ME 4 are grouped and have a common fuel flow meter and delivers energy to the same propeller shaft. Only ME 4 is in use during the trials. The fuel consumption is noted at a few instances during a trial, in a protocol provided by IVL and represent readings from the monitor in the engine room. The values are presented in Appendix A, Table A1.

Data on fuel consumption for the full trial period are in addition received from the ship owner office in Gothenburg. Average fuel consumption at 85%, 75%, 50%, and 34% engine load are according to values from the ship owner office 1544, 1336, 981, and 805 kg/h respectively at periods of steady state load, see Appendix A, Table A2 and Figure 3.

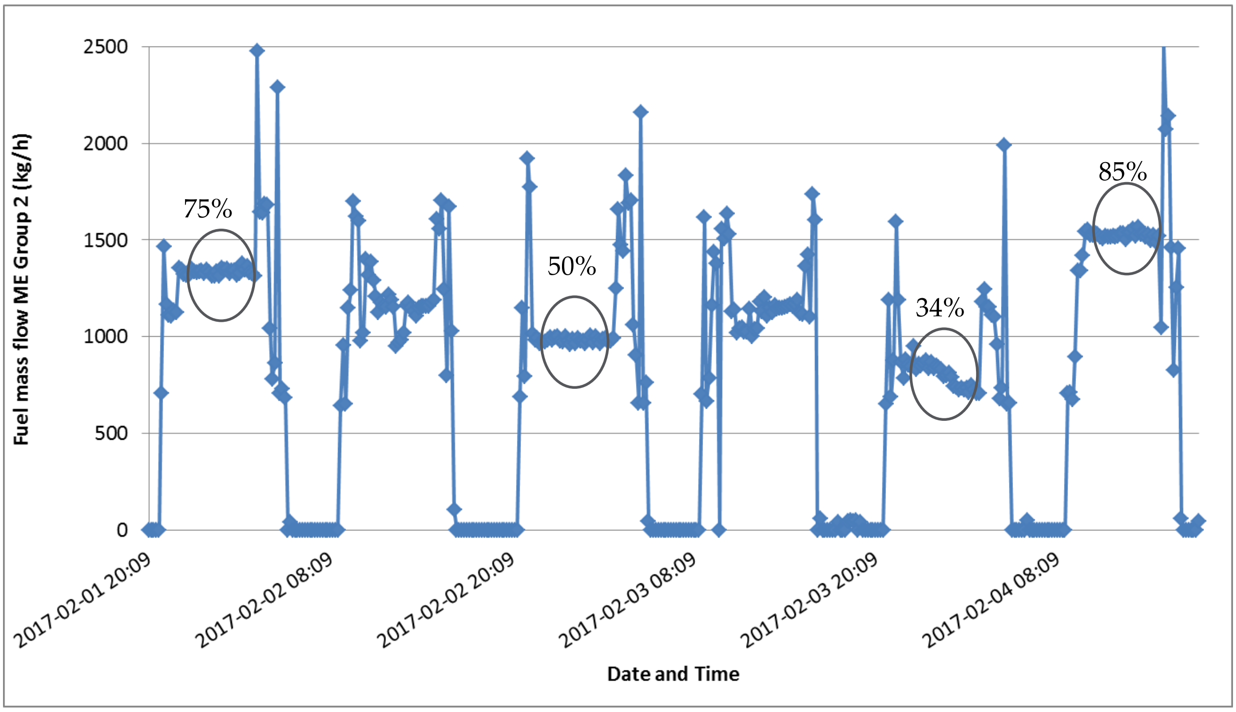

Figure 3. Fuel consumption during the trials. The periods for the four steady state engine load tests are indicated by red circles and the respective engine loads are given.

The values noted by the crew are higher on all occasions than the values from the ship owner's log.

The reason for the discrepancy is not known. It is however judged that the accuracy of measurements from the ship owner's office is higher than that of the readings from the displays in the control room. In a discussion with the chief engineer, it is concluded that the accuracy of meters is not known.

The first officer noted that the passing with 34% engine load was difficult to keep at a steady state. This is probably also the reason why fuel consumption varies for this trial period. Why there is such a clear decreasing trend of fuel consumption over time is however not fully explained.

Lube oil consumption does not differ between engine loads.

2.1.3 Engine settings and SFOC

The engine room crew notes engine parameters during the trials in a protocol provided by IVL. These are used to calculate emissions factors for the measured gases. Transcribed protocols on engine parameters from the trials are placed in Appendix A, Table A3.

The details on determining specific fuel oil consumption (SFOC) during the trials are presented in Appendix C. SFOC at the different loads in the trial was calculated to 181, 180, 198, and 239 g/kWh for 85%, 75%, 50% and 34% respectively.

2.1.4 Gas concentrations

Averages of gas concentrations for each gas, over a set period of time, is used in the calculation of specific emission rates. A time period when signals are stable is then chosen. A stable signal free from disturbances and fluctuations are considered to represent a stable engine load and smooth combustion. Gas concentrations of NO_x, CO, CO_2, O_2, and SO_2 over time for the engine loads, 85%, 75%, 50% and 34% are presented in Appendix A, Figures A1 to A4. The time periods for which concentration averages are calculated are indicated in the captions of Figures A1 to A4 (Appendix A).

The concentration of CO_2 is between 5% and 6% for all engine loads. The SO_2 levels however differ significantly between the engine loads, a situation that is not possible when combusting the same fuel. Both CO_2 and SO_2 concentrations are linearly correlated with the carbon content and the S content, respectively, of the fuel combusted. This might suggest that the instrument is tuned to an irrelevant span for the SO_2 or that SO_2 somehow is affected by the transport line from the exhaust pipe to the signal logging. For calculation of emission rates of SO_2, the S-content of fuel presents a more reliable value and is therefore used.

The measured average values at the different trials that are used for further calculations are presented in Table 3.

Table 3. Concentration averages (dry basis) for CO_2, CO, NO_x, O_2, and SO_2 for the four engine loads on which tests were conducted.

Engine load	CO_2 (%)	CO (ppm)	NO_x (ppm)	O_2 (%)	SO_2 (ppm)
85%	5.42	59.7	1 223	13.3	15.6
75%	5.35	74.2	962	13.6	13.4
50%	5.52	115	1 087	13.3	15.6
34%	5.66	108	1 259	13.1	18.7

The measured concentration of gaseous hydrocarbon emissions (total hydrocarbons=THC, non-methane hydrocarbons=nmHC, and methane=CH4) are presented for three engine load trials in Appendix A, Figures A5-A7. Unfortunately the results from tests on 75% engine load were not logged.

The average values at periods of steady state engine loads that are used for further analysis are presented in Table 4.

Table 4. Average concentrations of total hydrocarbons (THC), non-methane hydrocarbons (nmHC), and methane (CH_4) at steady state engine loads at tests on LSFO. Concentrations given as ppm C_1.

Engine load	THC (ppm)	nmHC (ppm)	CH_4 (ppm)
85%	65.1	64.6	0.50
75%	No data	No data	No data
50%	77.0	76.4	0.58
34%	98.5	97.7	0.77

At 85% engine load there is a clear decreasing tendency with time for THC and nmHC. Such trends are not seen during tests on 50% and 34% engine load. The reason for this is not known. THC and nmHC levels are stable around 80 ppm at the test at 50% engine load, and varying, but without a clear trend, at 34% engine load.

Methane levels contain peaks with short durations but are in general fairly stable. At 85% engine load there is an increasing trend over time. Methane levels are considerably lower than nmHC levels at all engine loads.

2.1.4.1 SO_3 concentration

Measurements of gas concentrations of SO_3 indicated low levels in the exhaust gas. For all tested engine loads, the concentrations were below detection limit. The detection limit for the analysis is 0.003 mg S/L, corresponding to 0.0075 mg SO_3/L. Important to note is however that a longer exposure time of the NaCl column to the exhaust gas would have resulted in a quantification of the SO_3 concentration.

2.1.5 Particle concentrations

Two dilution systems were used for determining particle concentrations. For online measurements with the BC instrument, the SMPS/CPC, and the GRIMM, the FPS system was used. Particle sampling on filters for gravimetric analysis were made after two different dilution systems; the FPS system and the dilution tunnel.

2.1.5.1 Gravimetric analysis

Sampling of particles is made using teflon filters[2]. In total 16 filters are sampled after the dilution tunnel (DT). At each engine load, 2 filters are used for PM_{tot} sampling, and 2 are used for $PM_{2.5}$ sampling. Temperatures at the filter were between 29°C and 33°C, which is lower than prescribed by the latest version of ISO-8178. Dilution ratios were between 15.9 and 23.8.

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[2] Gravimetric analyses were also made on quartz filters used. These were however mainly used for analysis of content of elemental and organic carbon of the particles sampled.

PM_{tot} and $PM_{2.5}$ are often sampled in parallel, using a metal Y-split to diverge the gas in two separate streams to the filter holders. A cyclone is used prior to $PM_{2.5}$ sample filter to cut off particles with diameters over 2.5 µm. The flow through the cyclone was over-dimensioned by mistake causing the cut off to be around 1.6 µm rather than 2.5 µm. The term $PM_{2.5}$ is therefore misleading and will not be used in the following. It is clear though, that differences in concentrations between PM_{tot} and "$PM_{1.6}$" are small. This suggests that the main part of particle mass is from combustion particles with less than 1.6 µm diameter. A discussion on this will follow in the result section.

The FPS dilution system is used to dilute sample gas for five filters. Dilution ratios are between 40 and 92.

An overview of the sampling details for all filters including one blank and two sampled without exposure to exhaust is presented in Appendix A, Table A4. All filters are listed and numbered from 1-24.

2.1.5.1.1 Dilution at gravimetric sampling, LSFO trials

The dilution factor is determined by CO_2 levels. A CO_2 sensor is fitted to the tunnel and directed to either the diluted gas or the raw gas. The levels are noted but not logged continuously.

For the particle sampling after the FPS dilutor, both NO_X and CO_2 were used as trace gases.

At all instances the registered concentrations of trace gases have a wavelike fluctuation. The reason for this is not known, but can be assumed to be related to the ratio control dynamics of the dilution system since a corresponding fluctuation is not seen for the gas measurements. It is believed to be of little significance to the results since sampling is done for longer periods of time and calculations use average values.

2.1.5.2 Thermal optical analyses of Elemental carbon and Organic carbon (EC/OC)

Twenty quartz filters are exposed to diluted exhaust gas for sampling of particles for thermal/optical determination of contents of elemental- and organic carbon. The filters are placed in pairs in the filter holders with one filter for the exposure (Primary filter) and the other for determining condensate content at measurement conditions (Secondary filter). The mass of the condensate is subtracted from the mass of particles on the primary filter in each pair.

Details on the filters are given including for each filter sampling conditions, sampling times and volumes, concentrations of total carbon (TC), OC, and EC, and total mass from the gravimetric analysis in Appendix A (TableA5).

2.1.5.2.1 Dilution at quartz filter sampling, LSFO combustion

The exhaust gas is diluted in the dilution tunnel in most cases. The dilution is then determined by CO_2 levels. The logged values from the CO_2 instrument during sampling after FPS dilution are presented in Appendix A, Figures A13 and A14.

2.1.5.3 Contents of metals and sulphur in particles

Sulphur content of particles are analysed for five filters; one filter for each load condition of the engine, and one for sampling of surrounding air. The samples indicate low sulphur contents of particles, from 0.12% S to 0.76% S. The two highest engine loads result in higher sulphur content in particles than the two lowest loads. The analysed concentrations of S, and the calculated share in particles are presented in Appendix A Table A6.

Two exposed filters and one filter only exposed to surrounding air are analyzed for elemental content, focusing metal content, according to the previously described method.

One of the filters is exposed at 75% engine load and one at 34% engine load. The filter used at 75% sampled total particle mass while the filter at 34% sampled after a cyclone with a cutoff of around 1.6 µm.

Total element concentrations in the sample taken at 34% engine load are close to background levels. The result from this sample should be considered as uncertain. At 75% engine load, the five most abundant elements are Cd, Ni, Cu, Fe, and Zn in decreasing order. The surrounding air holds high concentrations of several of the analysed metals which may indicate influence of the welding activities in the funnel during measurements. In Appendix A, Table A7, the analysed concentrations of elements in particles are presented.

2.1.5.4 On-line measurements

On-line measurements are made for concentrations of black carbon (BC). Due to malfunction of the instrumentation for measuring concentration of particle number, data are only available from the SMPS instrument for 50% engine load. Data from the Grimm instrument are also analysed.

2.1.5.4.1 Black carbon concentrations

Black carbon concentrations were measured after dilution at all four engine loads. At 85% and 34% engine loads, the BC instrument was run twice in order to have duplicate series both with and without thermodenuder. In Table 5 the BC concentrations from the measurement series, times for tests, and dilution ratios are presented.

Table 5. Results from on-line measurements of BC concentrations with the Aethalometer (AE33).

	85%	85%	85%	85%	*75%*	50%	34%	34%	34%	34%
Date/ Time Start	02-04 11:00	02-04 11:55	02-04 14:00	02-04 14:14	*02-02 22:34*	02-03 00:29	02-03 22:51	02-03 23:29	02-04 02:50	02-04 02:25
Date/ Time Stop	02-04 11:45	02-04 12:10	02-04 14:12	02-04 14:22	*02:02 22:54*	02-03 01:20	02-03 23:22	02-03 23:45	02-04 03:09	02-04 02:45
Average BC conc after dilution µg/m3	12.2*	5.24	5.28	11.0	*3.16*	29.0***	32.5	14.2	9.03	2.7
Standard deviation BC conc (% of average conc)	7.3%	4.7%	3.7%	5.1%	*35%*	6.0%	5.6%	3.1%	6.0%	4.5%
Average dilution	90	84	84	85	*204*	55	46	46	74	68
Trace gas used for determining dilution	CO_2	CO_2	CO_2	CO_2	*See comment***	NO_x	NO_x	NO_x	CO_2	CO2
Thermodenuder ON / OFF	OFF	ON	ON	OFF	*OFF*	OFF	OFF	ON	ON	OFF
Assumed loss in thermodenuder****	n.a.	25% - 40%	25% - 40%	n.a.	*n.a.*	n.a.	n.a.	25% - 40%	25% - 40%	n.a.
Calculated average concentration before dilution and compensated for loss in TD (mg/Nm3)	1 100	576 - 724	588 - 739	935	*644*	1 590	1490	865 – 1090	884 – 1110	1 542

* Increasing trend in concentration over time

*** DR is calculated based on that the same valves in the dilutor is open during this period of time as 02:49 - 04:19, the results have a relatively high uncertainty and are therefore written in italics.*

*** Increasing trend in concentration over time

2.1.6 PAH concentrations

PAH concentrations are sampled for analyses both as gas phase PAHs and particle bound PAHs. The sums of gas phase and particle bound PAHs are presented in Table 7, for the four engine loads. Results are given as mass per sample and exhaust gas concentrations. Further, the particles sampled for PAH analyses are weighed before and after exposure, masses of particles are also given in Table 7.

Table 6. Mass per sample and concentration per sample of 16 PAHs, and total particle mass per filter, for the four-engine load test.

Engine load	85%	75%	50%	34%	filter blank**	Measurement uncertainty in method (±%)
	ng/sample	ng/sample	ng/sample	ng/sample	ng/sample	
naphtalene *	21 000	18 000	27 000	28 000	13	40
acenaphtylene *	1 400	1 200	2 400	3 400	<15	40
acenaphtene *	750	930	1 300	1 400	14	40
fluorene *	2 300	2 600	3 100	3 200	<1.0	40
phenantrene	7 600	8 000	9 900	12 000	5.9	30
anthracene	750	600	740	1 200	<0.1	40
fluoranthene	980	1 200	1 500	2 200	2.7	20
pyrene	2 300	2 600	3 100	3 900	<1.3	20
benz[a]anthracene	***	***	***	***	<0.60	40
chrysene	3 400	3 900	4 200	5 200	1.9	30
benzo[b]fluoranthene	530	550	600	860	<0.7	30
benzo[k]fluoranthene	52	59	76	120	<0.4	20
Benso(a)pyren	120	110	78	300	<0.5	20
dibenz[a, h]anthracene	83	89	120	170	<0.5	30
benzo[ghi]pyrelene	260	230	320	540	<1.0	40
indeno[1,2,3-cd]pyrene	53	<41	76	130	<2.0	20
SUM	42 000	40 000	55 000	63 000	38	
Mass of particles on filter (g)*	**0.046**	**0.043**	**0.031**	**0.030**	**0.0036**	
Sample volumes (Nm3)	0.552	0.569	0.502	0.535		
Sampling time	10:00-11:00	23:15-00:20	23:35-00:35	23:05-00:05		
PAH concentrations (µg/m3)	85%	75%	50%	34%		
naphtalene *	38	32	54	52		
acenaphtylene *	2.5	2.1	4.8	6.4		
acenaphtene *	1.4	1.6	2.6	2.6		
fluorene *	4.2	4.6	6.2	6.0		
phenantrene	14	14	20	22		
anthracene	1.4	1.1	1.5	2.2		
fluoranthene	1.8	2.1	3.0	4.1		
pyrene	4.2	4.6	6.2	7.3		
benz[a]anthracene	***	***	***	***		
chrysene	6.2	6.9	8.4	10		
benzo[b]fluoranthene	0.96	0.97	1.2	1.6		
benzo[k]fluoranthene	0.09	0.10	0.15	0.22		
Benso(a)pyren	0.22	0.19	0.16	0.56		
dibenz[a, h]anthracene	0.15	0.16	0.24	0.32		
benzo[ghi]pyrelene	0.47	0.40	0.64	1.0		
indeno[1,2,3-cd]pyrene	0.10		0.15	0.24		
SUM	76	70	110	120		

2.2 Output – specific emission rates at LSFO operations

Specific emission rates for gases and particles were calculated using the carbon balance method[3]. For calculation procedure we refer to ISO 8178-2:2008, ISO 8178-1:2017. The ingoing parameters and constants are presented in detail in Appendix A, Table A8. The calculated specific emissions are given in Table 8.

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[3] The method follows emission calculation for marine diesels, based on ISO 8178-1:2017 and 8178-4:2017

Table 7. Specific emission rates at tests on LSFO. Values in brackets indicate filter reference number, see App. A, Table A4.

Date/Test	170204	170201-170202	170202-170203	170203-170204
MCR (100 % load), MCR of engine (brake kW) =	9 600	9 600	9 600	9 600
Load, Brake Load during test (%) =	85%	75%	50%	34%
P, Brake Power during test (kW) =	8 160	7 200	4 800	3 264
Calculated specific emission rates:				
CO2 Specific emission (g/kWh) =	601	598	659	793
O2 Specific emission (g/kWh) =	1 078	1 106	1 157	1 339
CO Specific emission (g/kWh) =	0.42	0.53	0.88	0.96
NOx Specific emission (g/kWh) =	12.96	10.46	12.68	16.84
NOx Specific emission (g/kWh) (corrected) =	11.84	9.73	11.85	15.38
SO2 Specific emission measured (g/kWh) =	0.26	0.22	0.28	0.39
SO2 Specific emission calculated (g/kWh)	0.36	0.36	0.40	0.48
SO3 Specific emission (g/kWh) =	b.d-l.	b.d-l.	b.d-l.	b.d-l.
THC Specific emission (g/kWh) =	0.24	n.d.	0.30	0.45
nmHC Specific emission (g/kWh)=	0.24	n.d.	0.30	0.45
CH4 Specific emission (g/kWh)=	0.0018	n.d.	0.0023	0.0035
PMtot Specific emission, Dilution = DT (g/kWh)	0.16 (15)	0.11 (2)	0.17 (5)	0.13 (10)
PMtot Specific emission, Dilution = DT (g/kWh)	0.12 (18)	0.13 (4)	0.15 (8)	0.18 (14)
PMtot Spec. emission, Dilution = FPS (g/kWh)	0.20 (23)		0.20 (21)	0.37 (22)
PMtot Spec. emission, Dilution = FPS (g/kWh)=	0.19 (24)			
PM + cyclone spec. emission, Dilution = DT (g/kWh)	0.17 (16)	0.11 (1)	0.16 (6)	0.13 (9)
PM + cyclone Spec. emission, Dilution = DT (g/kWh)	0.13 (17)	0.12 (4)	0.15 (7)	0.17 (13)
PM + cyclone Spec. emission, Dilution = FPS (g/kWh)			0.21 (20)	
TC Specific emission, Dilution with tunnel (g/kWh)	0.116	0.093	0.106	0.186
TC Spec. emission, Dilution with FPS (g/kWh)	0.100	n.a.	n.a.	0.342
TC spec. emission (size cutoff with cyclone), Dilution with tunnel (g/kWh)	0.090	0.081	0.087	0.162
OC Specific emission, Dilution in tunnel (g/kWh)	0.111	0.088	0.101	0.179
OC Spec. emission, Dilution with FPS (g/kWh)	0.079	n.a.	n.a.	0.332
OC spec. emission (size cutoff with cyclone), Dilution in tunnel (g/kWh)	0.104	0.067	0.082	0.156
EC Specific emission, Dilution in tunnel (g/KWh)	0.0047	0.0046	0.0044	0.0065
EC Spec. emission, Dilution in FPS (g/kWh)	0.0038	n.a.	n.a.	0.0096
EC spec. emission (size cutoff with cyclone), Dilution in tunnel (g/kWh)	0.0051	0.0141	0.0042	0.0062
BC Spec emission (g/kWh)	0.006	0.004	0.010	0.012
BC Spec emission using thermodenuder (g/kWh)	0.0037-0.0047			0.0071-0.0089
PAH Spec emission (mg/kWh)	0.248	0.238	0.350	0.471

2.3 Discussion of results

2.3.1 Gaseous emissions

The specific emission rates for most measured gases show a decreasing trend with increasing engine load. Exceptions are CO_2, for which a minor increase between 75% and 85% engine load is determined with increasing engine load, and NO_x. NO_x emission rates vary significantly with engine load with a minimum value of the four tested loads of 9.73 g/kWh at 75% of MCR. The emission factors for CO, HC, NO_x, CO_2 and O_2, at different engine loads are presented in Figure 6.

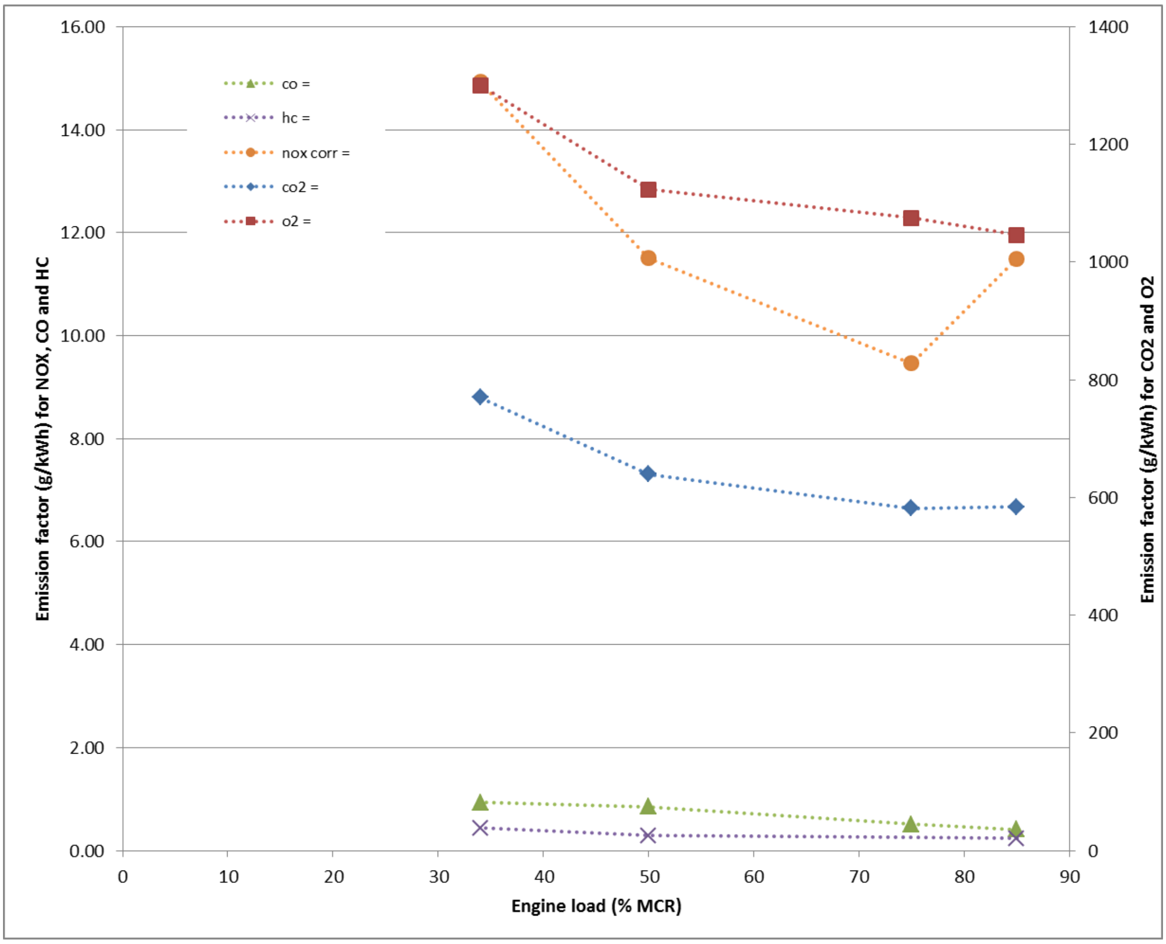

Figure 4. Specific emission rates for CO, HC, NO_x, CO_2 and O_2, at different engine loads. Tests on LSFO.

The test engine is a Tier I engine according to IMO MARPOL Annex VI NOx emission limits. It is rated at 500 rpm and the maximum allowed weighted NO_x emission value is calculated as 45*n^-0.2, where "n" is the rated engine speed in rpm. Maximum allowed NO_x Emissions Values, weighted over the test cycle, is thus 13.0 g/kWh. Only the emissions at the lowest tested engine load exceeds the limit. No attempt to weigh the emissions from these trials has been made.

Typical emission factors for CO and HC from medium speed diesel engines on marine distillates at high engine loads (assumed around 80%) are reported to be 1.1 g/kWh and 0.2 g/kWh, respectively (Cooper and Gustavsson 2004). The same report estimates emissions at reduced speeds to be twice those. CO measurements during these trials are lower than the typical values on all tested loads, while the hydrocarbons are slightly higher. This indicates that the engine does not cause incomplete combustion at low loads. The emission test report for the engine specifies emission rates for NO_x and hydrocarbons at 100% engine loads to be 10.85 and 0.458 respectively. The NO_x emission rate is thus 1 g/kWh lower at the 100% engine load at the engine test than at the measurements on board at 85% engine load, on the 10 year old engine.

Emissions of SO_2 are calculated from fuel sulphur content as well as measured. There is a discrepancy between the two values for all engine loads, see Table 9. Calculated values suggest higher emissions than what is registered by the Horiba, from 19% to 38% higher. Tests were conducted in laboratory conditions after the on-board trial to see if the instrument or gas treatment system possibly scrubbed SO_2. The lab tests indicated a high scrubbing effect at low concentrations but less visible effect at high concentrations. The measured concentration in the exhaust was between 13 and 19 ppm. Examples of the scrubbing effect of the gas treatment system at different concentrations are presented in Table 10.

Table 8. Specific emission for SO_2, calculated from sulphur content in fuel and measured

	85%	75%	50%	34%
SO_2 Calculated from fuel S content - Specific emission (g/kWh) =	0.36	0.36	0.40	0.48
SO_2 Measured and calculated from - Specific emission (g/kWh) =	0.26	0.22	0.28	0.39

Table 9. Reduction of SO2 in gas treatment system

Concentration in test gas	Concentration after gas treatment system	Reduction in treatment system
500 ppb	5-10 ppb	98-99%
244 ppm	227 ppm	7%
109 ppm	102 ppm	6%

These tests are not all inclusive. The test gas used is a dry gas, whereas the exhaust gases have a significant water fraction and potentially quite different result would be obtained. Further, in order to make comparisons and conclusions on whether there is a loss of SO_2 during trials the concentrations during our control tests should preferably have been in a range of 20-30 ppm. What can be concluded is thus that there seem to be a certain loss but more tests are needed in order to determine the magnitude of the loss. A full explanation for the discrepancy has not been found.

The concentrations of sulphur trioxide (SO_3) in the exhaust were below detection limit in the samples taken, suggesting very low concentrations in the exhausts. Measurements of gas concentrations of SO_3 indicated low levels in the exhaust gas. A longer exposure time of the NaCl column to the exhaust gas would have resulted in a quantification of the SO_3 concentration.

The gas emissions from Stena Britannica are well in line with literature data on measurement results from similar engines.

2.3.2 Particle emissions at LSFO combustion

The filters measured as PM_{tot}, return median values for specific particle emissions of 0.14, 0.13, 0.15, and 0.18 g/kWh at 85%, 75%, 50%, and 34% engine load respectively when using a partial flow dilution system for sampling in close accordance with ISO 8178-2. It should however be noted that the measurements deviate from the standard in certain aspects. One important issue being the low temperature at the filters.

It seems that despite the error in flow through the cyclone for $PM_{2.5}$, the sampling after use of cyclone ($PM_{1.6}$) give mass concentrations in the same range as for PM_{tot}. It is therefore likely that only combustion particles, with diameters <1.6, are sampled also at PM_{tot} sampling. Further, PM sampling after dilution with the FPS system (filters 23, 24, 21, 22, and 20) returns higher emission rates than the sampling after the dilution tunnel. There are larger uncertainties in determining dilution ratio after the FPS than after the dilution tunnel. Further, the lower temperatures in the diluted gas after the FPS dilution might have favored condensation of particles increasing total particle mass.

In order to avoid a high influence of extreme emission rates, median values are more representative than average values. Median emission rates for the four engine loads are presented in Table 11 and Figure 7. Emission rates for PM_{tot} and ~$PM_{1.6}$ are overlapping (see Table 11), although median values indicate less particle mass for particles with diameters <1.6 µm, than when also larger particles are included.

The difference between engine loads is small. Only emissions at 75% engine load are significantly different from emissions at the other engine loads. At 75% engine load there were no tests using FPS dilution. The higher emission rates calculated from sampling after the FPS dilution do not explain the low median specific emission at 75% engine load.

Table 10. Median values for PM specific emissions for the four engine loads.

	85%	75%	50%	34%
Median PM_{tot} (g/kWh)	0.18	0.12	0.17	0.18
Median PM + cyclone (g/kWh)	0.15	0.12	0.16	0.15
Median PM all (g/kWh)	**0.17**	**0.12**	**0.17**	**0.17**
Median PM_{tot} Dilution tunnel(g/kWh)	0.14	0.13	0.15	0.18
Median PM + cyclone, Dilution tunnel (g/kWh)	0.15	0.12	0.16	0.15
Median PM all, Dilution tunnel (g/kWh)	0.15	0.12	0.16	0.15

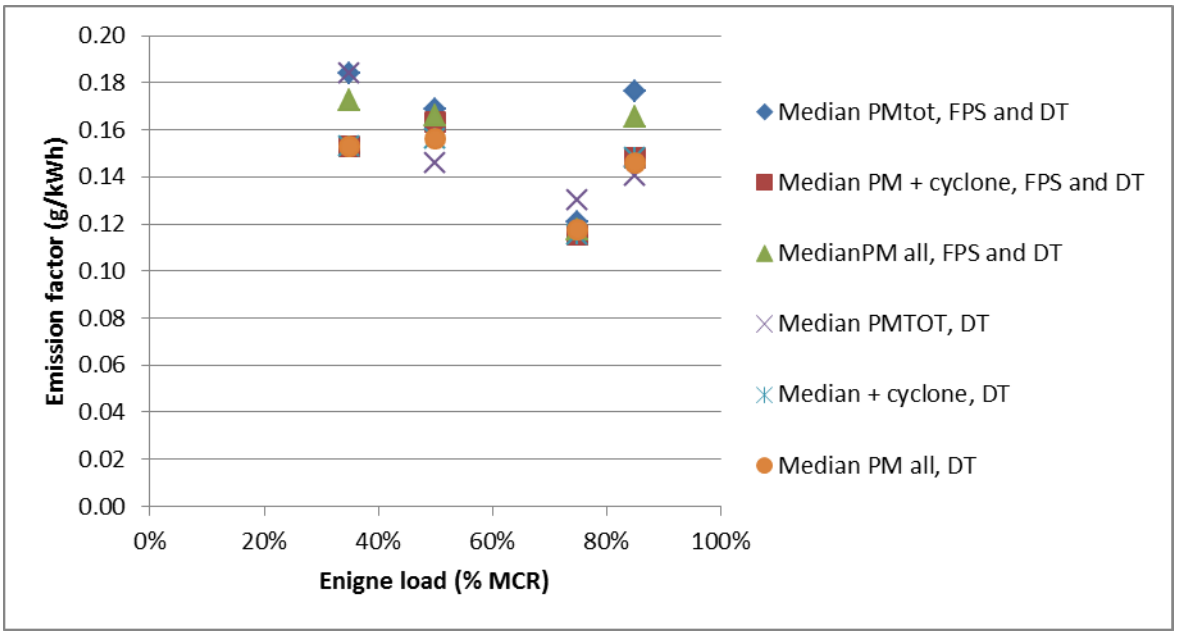

Figure 5. Median values for PM specific emissions for the four engine loads. Cyclone cutoff at 1.6µm, DT = Dilution tunnel.

Filters 2, 9, and 16 were noted to contain grease by laboratory personnel. This occurs if the filters are accidently touched by hands during handling. These are however not extreme values and are kept in the analyses.

Compared to previous studies on particle emissions from low sulphur fuels the values measured at these trials are in the lower end. PM emissions increase with sulphur content of fuel due to sulphate content of particles. However, the correlation between particle emissions and S content in fuel is weak for low-sulfur fuels (FSC <0.5%). It should be noted that there are a limited number of on board measurements trials for particle emissions using low sulfur fuels, with only 13 data points for PM_{10} and 18 for $PM_{2.5}$, many of which are from the same ships. Emission factors derived for the interval 0-0.5% FSC gives a mean value for the PM_{tot} emission factor of 0.2 g/kWh. Emission factors for PM_{10} and $PM_{2.5}$ are not relevant to sort out from the data set used since $PM_{2.5}$ average values sometimes exceed emission factors for the particles with larger cutoff diameters. Differences between engines and measurement setups have a much higher effect on the established emission factors. (ICCT, 2016; Winnes Fridell, 2009; Agrawal, 2008; Cooper, 2003; Cooper, 2001; Winnes, 2016; Zetterdahl et al., 2016; Moldanova et al., 2013; Kasper et al., 2007; Fridell et al., 2008).

The analysis of EC/OC is done with a thermal/optical method on a filter section with a total area of 2.01 cm^2 that is cut out of the filter. Our analysis has resulted in specific emissions rates of total carbon content (EC+OC) of many samples that are higher than the specific emission rates for total particle mass. Reported uncertainties by the laboratory for their analyses are 10% for OC and 20% for EC. An uncertainty relating to the sampling process is how even the particles are distributed over the filter. Since the EC/OC is analyzed for only a share of the total filter, the registered concentrations needs to be extrapolated to the full active/exposed area of the filter.

For samples taken after the FPS-dilutor we use different types of filter holders than samples from after the dilution tunnel. Due to the setup of the filter holder the active area differ between the two dilution systems; filter holders used after FPS systems give an exposed filter area of 13.2 cm^2, while the filter holders after the dilution tunnel had a different design. A perforated disc was placed after the filter, providing the filter with a flat supporting surface. This is customary for filter sampling, and a similar disc was used for the filter holder after the FPS dilution system. The difference between the discs is the area of perforation. While the disc in the holder after the FPS were perforated equally over the whole surface the disc in the holder after the dilution tunnel had perforations only in an area of 8.55 cm^2. Although the exposed area was 13.2 cm^2, it is assumed that the perforations caused uneven distribution of particles on the filter. Another indication of this is that the total calculated concentrations of carbon (TC) extrapolated from the analyzed filter stance, exceeds concentrations of particles in total (PM) if the assumed exposed area is 13.2 cm^2. The two filters from filter holders after the FPS system has an average carbon content of particles corresponding to 66% of the total particle mass concentration in the exhaust. Assuming the exposed area to be 8.55 cm^2 results in levels very close to this, indicating that this is close to the actual situation.

The online analysis with the aethalometer gives concentrations of BC that can be compared to the concentrations from analysis of EC on filters. There is a fairly good agreement between the calculated specific emissions for EC and BC when the smaller exposed filter (8.55 cm^2) area is used in the calculations, see Figure 8. If a larger exposed filter area is assumed (13.2 cm^2) the specific emission for EC is lower than, or the same as, the specific emission for BC measured without the use of a thermodenuder, and higher than specific emissions for BC measured after a thermodenuder, see Figure 9. Comparisons are made between specific emissions for similar loads, see values in Table 12.

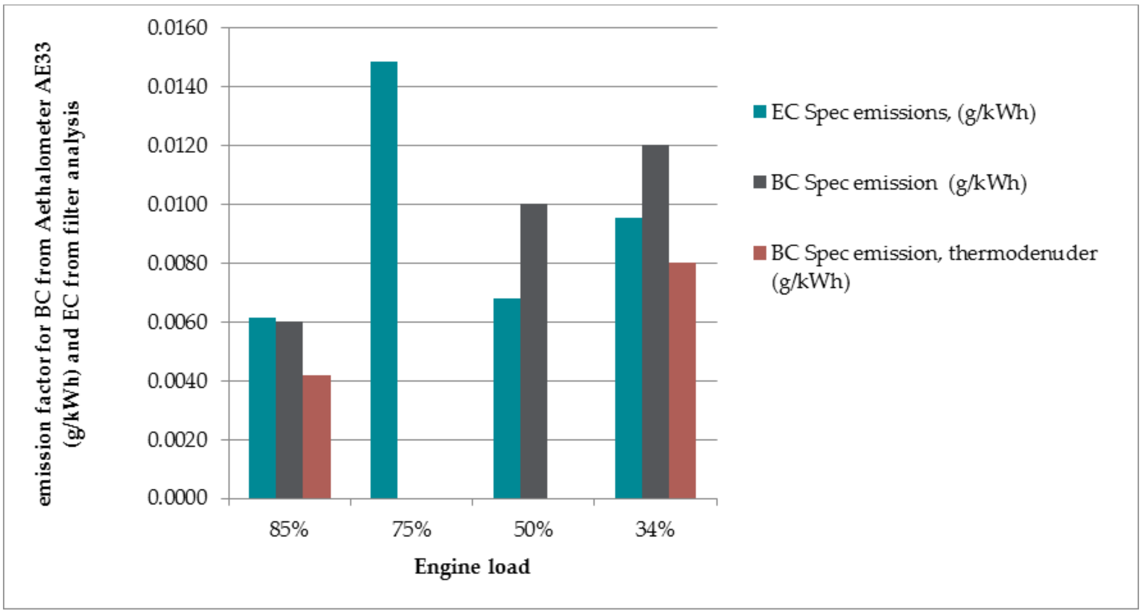

Figure 6. Specific emissions for BC from online measurements with EF from filter analysis of EC. Values in this figure is caclulated from an exposed area of the filter of 8.55 cm². Tests at LSFO.

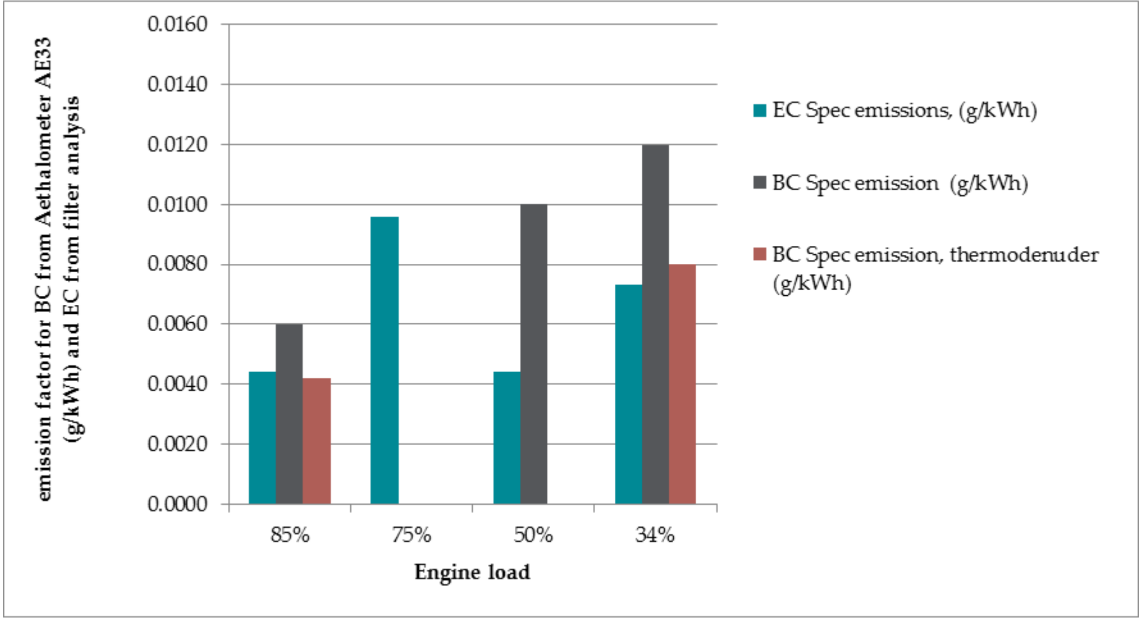

Figure 7. Specific emissions for BC from online measurements with EF from filter analysis of EC. Values in this figure is caclulated from an exposed area of the filter of 13.2 cm². Tests at LSFO.

Table 11. Specific emissions for BC and EC. The exposed filter area is assumed to be 8.55 cm². The loss in the thermodenuder is assumed to be a central value between the two extremes; 25% and 40% loss.

Engine load	85%	75%	50%	34%
BC Spec emission, (g/kWh)	0.006	n.d.	0.010	0.012
BC Spec emission thermodenuder, (g/kWh)	0.004	n.d.	n.d.	0.007
EC Spec emissions, (g/kWh)	0.004	n.d.	0.004	0.007

The metal content of the particles differs significantly between the two analysed filters. One of the filters is used for analysis of total PM while the other is used for mass of smaller particles (cutoff around 1.6 µm). Neither the engine load nor the particle size cutoff is however considered to have a theoretically significant impact on the metal content of particles. The amount of fuel combusted per volume unit of exhaust gas is slightly less at 34% load but not to an extent that can account for the differences discussed here. Particles larger than 1.6 µm are not primary combustion particles but most likely reentrained particles from the linings of the chimney and the exhaust system. The concentrations of particles from the two filter samples were very similar 21 mg/Nm^3 and 26 mg/Nm^3 at 34% and 75% engine load, respectively.

For many elements, the concentration at the sample from 75% engine load is up to two times higher the concentrations at the sample from 34% engine load. An extreme difference is registered for concentration of Cadmium (Cd). High concentrations of certain elements were registered for the filter exposed only to surrounding air, conducted through the dilution tube. The element concentrations that were relatively high in the reference sample in a comparison with the exposed filters, and as absolute concentrations, were Fe, Al, Zn, Cr, Cd, and Cu.

The content of elements in the fuel and lube oil can be compared to the concentrations determined by the particle analysis. With an assumption of a lube oil consumption of 1 g/kWh, a simple calculation based on the contents in fuel and lube can derive a maximum yield of concentration of elements in the exhaust gas. Such a calculation gives that the analysed concentrations of Cd, and Cu collected on filter samples cannot be accounted for by contents in fuel and lube. Also Zn is slightly higher in the filter analysis than what can be accounted for from fuel and lube. All these were present in the reference filter for surrounding air suggesting that they may have passed through the filter to the dilution air and contaminated the samples. The welding activities in the funnel can have caused elevated levels of metals in the ambient air. It can also be expected that the concentrations in the surrounding air fluctuated depending on the activities by welders. Other element concentrations that were relatively high in the reference sample in a comparison with the exposed filters, and as absolute concentrations, were Fe, Al, and Cr.

Three elements that were present in the fuel and lube to relatively high extents were not found on the filters to a corresponding degree. These were Ni, Fe, and P, and their absence on the filters is not explained.

The sulphate content of particles is low compared to previous reported studies. The highest sulphur content from these tests is 0.8% S in particles at 85 % engine load. The corresponding total sulphate content in particles and associated H_2O are thus around 2% at most in our trials. In IMOs 2nd GHG report, particles from combustion of fuel with 0.1% sulphur content are reported to contain 19% sulphates (IMO, 2009). Also in Moldanová et al., significantly more particle mass is constituted by sulphur (Moldanová et al., 2013) In combination with the results on gaseous SO_3, it seems reasonable to suggest that the equilibrium between O_2, S, and H_2O in the exhaust favor the formation of SO and SO2 before SO_3 and H_2SO_4. "To which degree the sulfur is oxidised or converted into H_2SO_4 depends on both thermodynamics and reaction kinetics. [...] According to the principle of Le Chatelier this implies that the higher the temperature the less degree of oxidation i.e. SO is favored and vice versa at lower temperatures SO_3/H_2SO_4 is favored. Also pressure is important; the higher the pressure, the higher degree of oxidation." (Andreasen and Mayer, 2010)

Concentrations of particle numbers (PN) are in the lower end of previous measurement studies on marine diesel engines. The number concentration is quite dependent on the dilution conditions. Since only one series of data were gathered from the measurement campaign, due to instrument failure during a majority of the trials, these results should be considered uncertain.

2.3.3 PAH

PAH content in the exhaust was consisting of naphthalene to around 50%, and the profile of constituent species are similar for all loads, see Figure 10. The two- and three ring PAHS (naphtalene, acenaphtylene, acenaphtene, fluorene, phenantrene, and anthracene constitute between 78 and 81% of total PAHs, which is close to the 76% concluded as a typical value for diesel engine exhausts reported by Khalili et al., 1995.

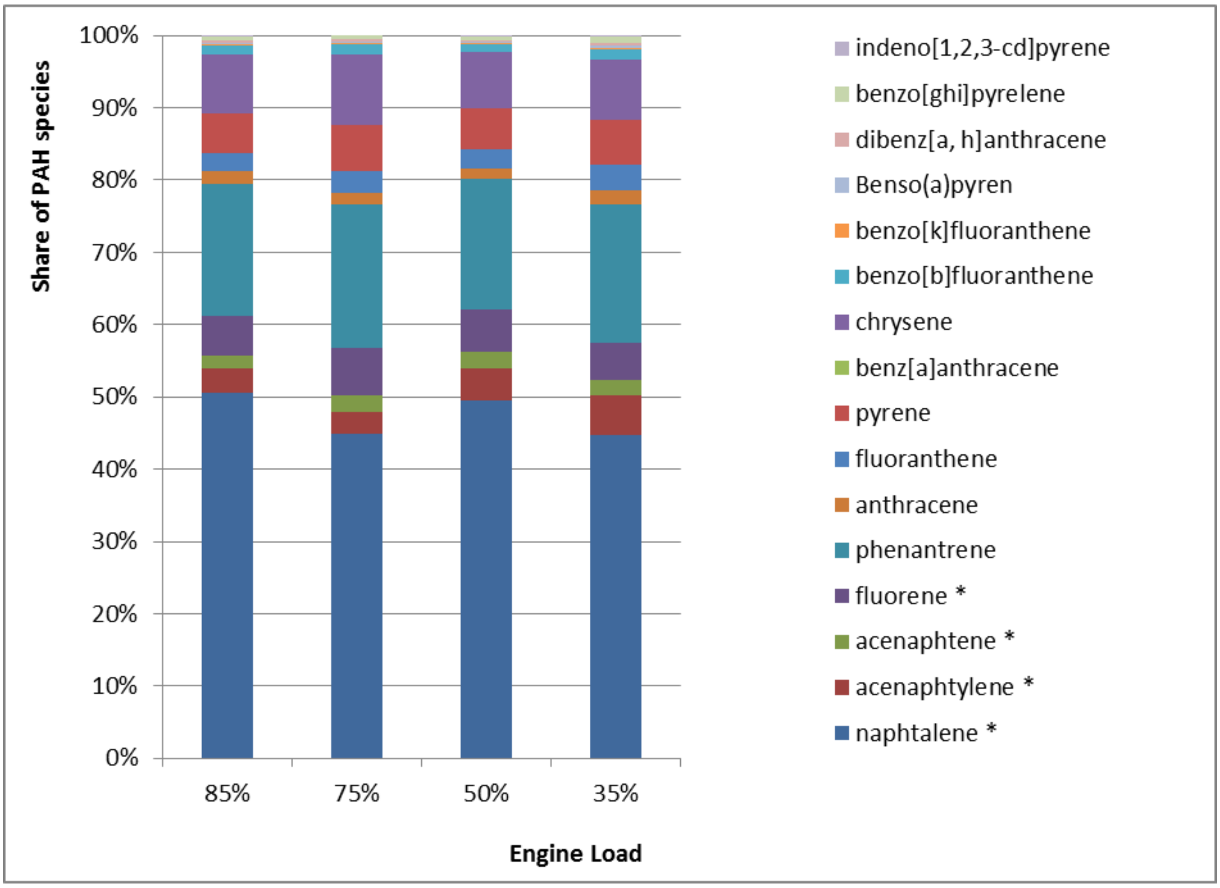

Figure 8. Shares of different PAH species at different engine loads.

The resulting specific emissions for different species are 0.45, 0.42, 0.70, and 0.88 mg/kWh for engine loads 85%, 75%, 50% and 34%, respectively. This indicates higher emissions of PAH at lower engine loads.

These specific emissions are well in line with previously reported ranges for PAH emission factors for marine engines (see eg Cooper 2003). PAH emissions depend to some extent on the PAH content of the fuel but are also formed during combustion. Total aromatic content of the tested fuel was 15.5%, also including monocyclic aromatic hydrocarbons (benzene and derivatives).

3 Exhaust gas emission measurements at combustion of HFO, upstream and downstream the scrubber, Sep 2017

In September 2017, emission measurements were conducted at combustion of heavy fuel oil upstream and downstream the scrubber.

The exhaust gas scrubber was commissioned in August 2017, and was in operation for approximately one month prior to the trials. Reports from the crew indicate that operations encountered minor problems during this time period. Major issues were mentioned to be related to unexpected work with cleaning the scrubber towers and the weather deck due to salty precipitation. Further, ambient temperatures in the funnel casing had risen after installations, and were during the measurement campaign exceeding 50°C at several occasions at the measurement sites. At these measurements the ambient temperature, and is 10°C or more above those experienced at measurements in February.

In order to protect instruments and measurement personnel from the high temperatures in the funnel, plastic tents were setup adjacent to the measurement holes at deck 11 and deck 15. Sensitive instruments were arranged in these tents, where temperatures were kept around 25°C with the aid of ventilation fans and air condition units. Gas measurement instruments were kept at deck 9 close to the funnel exit to weather deck, where temperatures were below the indicated limit for instrument operations.

The tent arrangement on deck 15 could fit all instruments that needed temperature protection and provided a specious environment for arrangement and handling of measurement probes. All filters for particle sampling were handled on the decks of the measurement site. Managing the filters in a cleaner environment would have been preferable but implied transporting filter holders and filters six decks down and up, including risks of dropping and damaging equipment and filters. Measurements on deck 15, downstream the exhaust gas cleaning device, were conducted on the 19th to the 21st of September.

The tent arrangement on deck 11 was less suited for the purpose since holes were needed to be cut in the plastic tent wall for handling of the probes. This caused warm air leaking into the tent and exposure to exhaust gases when probes were changed. All sensitive instrumentation was fitted in the tent. Filters and filter holders were managed in the tent. All work was conducted using masks. Measurements on deck 11, upstream the exhaust gas cleaning device, were conducted on the 22nd to the 24th of September.

Conditions were kept as similar as possible to the trials in February. Differences included that the main engine 3, that is coupled in pair with the main engine 4, was started on occasions. Main engine 4 is the engine on which the exhaust gas measurements were conducted, As far as we are informed this only occurred during measurements before the scrubber. At the measurements on the day of the 24th of September, i.e. at 76% engine load before the scrubber, we experienced electricity blackouts which caused these measurements to cover a shorter time period than the other.

3.1 Raw data and emission concentrations

Raw data from oil sample analyses, scrubber settings and function, engine settings and gas and particle concentrations are presented in the following.

3.1.1 Oil analysis

The engine is run on a heavy fuel oil (420 cSt) with 2.77% S. According to the bunker delivery note 350 tonnes of the fuel was bunkered on the 15th of September. The BDN specifies the S content to 2.55%. The chief engineer estimates that a new fuel reaches the engine from three days after bunkering. The next bunkering was performed on Friday 22nd. One fuel oil sample from the bunkering on the 15th is sent for analysis. A second sample is taken on the 26th of Sep, but judged unlikely to represent fuel oil combusted during trials and therefore not analysed. The fuel bunkered on the 22nd has a sulphur content over 3%, and no indications of corresponding elevations of sulphur emissions in the measurements are noticed. The oil analysis results are presented in APP_I, together with the BDN. A sample of the lube oil was also collected for analysis, results are given in APP_J. The same lube oil has been used for a long time. Lube oil consumption does not differ between engine loads.

All analyses are made by Saybolt Laboratory in Gothenburg.

3.1.2 Exhaust gas cleaning system – system parameters log

For the tests conducted downstream the scrubber, on the 19th to the 21st of September, the performance of the system was in compliance to regulations according to the log[4].

The scrubber log for the 19th to the 20th at measurements at 41% engine load, indicates non-compliance of the scrubber with regard to the ratio SO_2/CO_2 at start-up of the engine. Normal scrubber operations are noted from approximately 21:30 and onward. Whether this is related to malfunction of the system or the continuous emission measurement system (CEMS) device is not known. From the CO_2 and SO_2 measurements it is difficult to draw conclusion on this. CO_2 and SO_2 levels are stabilized at approximately 21:45. This points towards potential problems with the CEMS. However, both the CEMS and the HORIBA give fluctuating levels until 21:45, which could be a sign of trouble with the engine or scrubber. Further, concentration readings from the HORIBA instrument indicate higher CO_2 levels than those from the CEMS. SO_2 concentrations as given by the CEMS are in a similar range as values from the HORIBA, although fluctuations are not necessarily according to the same pattern. Exhaust gas measurement trials are conducted after 21:45 when levels are stabilized.

Measurements at 48% engine load were conducted on the night between the 20th and the 21st of September. The scrubber log indicates compliance from approximately 20:00 on the 20th and onwards the full journey. Values from the CEMS are in good correspondence with the HORIBA,

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[4] An hourly log of scrubber parameters for the tested engine loads 41%, 48%, and 76%, have been provided to the project and can for project internal purposes be found as appendixes to this report. APP_K, APP_L, and APP_M, respectively.

although CO_2 levels as measured by the HORIBA are consistently slightly higher those from the CEMS.

The logged values from the scrubber at 76% engine load from the tests on the 21st of September show a more fluctuating pattern than that seen at the two lower engine loads. Peaks in the ratio between SO2 and CO_2 are seen with two hour intervals. The HORIBA reveals this is due to changes in the SO_2 concentration while the CO_2 levels are stable. The scrubber was running in compliance the full journey.

3.1.3 Fuel consumption

Fuel flow meters for the main engine on which the emission measurements were conducted are partly out of function during the period of the measurements. A definite malfunction is registered on the two last trials at 49% and 76% engine load upstream the scrubber, as no data on fuel consumption is logged this period. For trials at 41% and 48% engine load downstream the scrubber, the fuel consumption seems to rise dramatically half way through the measurements. The data from the fuel consumption log from the ship owner's office are given in Appendix B, Table B1 and Figure B1. The chief engineer mentioned that the main engine 3 (which is coupled in pair with main engine 4 on which all tests are conducted) was by necessity used periodically during the trials. This would explain a registered increase in fuel consumption as there is only one fuel flow meter per engine pair. According to the chief engineer this happened at the trials upstream the scrubber and not downstream.

It is not possible to conclude the registered variations are due to actual fluctuations of malfunction of the flow meters. However, due to the close contact with the engine room and bridge reassuring constant loads were kept, we neglect the fuel consumption data registered during these trials and use fuel consumption data from the February measurements as the best available values. The values are adjusted for minor differences in engine loads and for heating value of the fuels. Fuel flows were not noted by engine room crew during these trials. The fuels are different in several aspects that affect combustion characteristics. Due to the described malfunction of the fuel flow registration and difficulties in keeping main engine 3 out of operation such differences has not been possible to take into account.

3.1.4 Engine settings

Engine room crew notes engine parameters during the trials. The protocol values are used to calculate specific emission rates for the measured gases. Notes on engine parameters from trials at HFO combustion are presented in Appendix B, Table B2 (downstream) and Table B3 (upstream).

3.1.5 SFOC and relevance of values on fuel consumption and engine loads

The engine loads at the trials downstream the scrubber were noted to be 76%, 48%, and 41%. Tests upstream the scrubber were performed at engine loads 76%, 49%, and 32%. Assumptions are that the tests on e.g. the lowest engine loads in the three trials (32%, 41%, and 34% from tests on LSFO) are comparable despite potential differences in combustion efficiency. We sometimes refer to 76% engine load as "high", 48% and 49% as "medium", and 41% and 32% as "low" engine loads in order to facilitate for the reader. For the calculation of fuel consumption and specific emission rates at the different loads the actual loads, as noted by engine room crew, are used. Linear increase/decrease between fuel consumption at different engine loads is assumed. Similarly, linear increase/decrease in sfoc is assumed.

Since the fuel flow meter was not working satisfactorily during the trials, we assume the same SFOC as during combustion of LSFO but corrected for the lower heating value of the HFO. Figure 11 presents the SFOC in relation to engine load for HFO and LSFO.

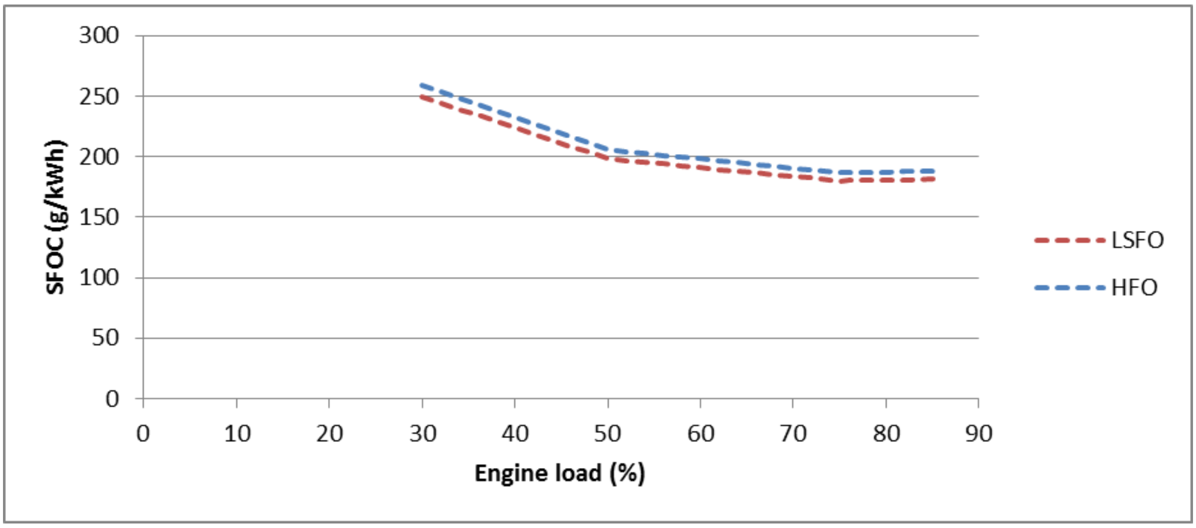

Figure 9. SFOC as a function of engine loads, at combustion of HFO and LSFO

Comparisons of fuel consumption data from the ship owner's log and our calculated values from periods of seemingly stable engine loads have been done. For the engine loads requested for each test the values we use in our calculations are in general lower than the logged values, see Table 13:

Table 12. Comparison of logged and calculated fuel consumption data

Engine load	Average fuel consumption in ship owner's log (kg/h)	Calculated value (kg/h)
76% MCR	1 420	1 405
48% MCR	1 020	995
41% MCR	930	915
32% MCR	850	812

An energy loss of 3% over the gearbox is assumed.

3.1.6 Gas concentrations

Gas concentrations of NO_X, CO, CO_2, O_2, and SO_2 over time for the tested engine loads at measurements upstream and downstream the scrubber are given in Appendix B, Figure B2 to B7. Averages of gas concentrations for each gas, over a set period of time, is used in the calculation of specific emission rates. The time period is chosen where signals are stable. A stable signal free from disturbances and fluctuations is considered to represent a stable engine load and smooth combustion. The time periods for which concentration averages are calculated are indicated in the captions of appended figures (Figure B2 to B7, Appendix B).

The concentration of CO_2 is close to 6% for all engine loads. The lowest average concentrations (appr. 5.7%) are noted at high engine load (76%), the mid average concentrations (5.9% and 6.0%)

are noted at medium engine loads (48% and 49%), and the highest average concentrations (6.0% and 6.2%) are noted at the low engine loads (41% and 32%). The readings were taken a few days apart. The ratio between SO_2 and CO_2 upstream the scrubber is 108, 109, and 108 at high, medium and low engine load, respectively. Average values of gas concentrations of CO_2, CO, NO_X, O_2, and SO_2 used for further calculations are presented in Table 14.

Table 13. Concentration averages for CO_2, CO, NO_X, O_2, and SO_2 at the three engine loads on which tests were conducted when the scrubber was in use.

	CO_2 (%)		CO (ppm)		NO_X (ppm)		O_2 (%)		SO_2 (ppm)	
Engine load	Up-stream scrubber	Down-stream scrubber	Up-stream scrubber	Down-stream scrubber	Up-stream scrubber	Down-stream scrubber	Up-stream scrubber	Down-stream scrubber	Up-stream scrubber	Down-stream scrubber
High	5.69	5.65	134	114	974	1 019	13.4	13.6	615	3.69
Medium	5.98	5.86	235	187	1 124	1 056	13.1	13.4	650	1.53
Low	6.02	6.17	209	197	1 202	1 265	13.1	12.9	649	1.26

The measured concentration of gaseous hydrocarbon emissions (total hydrocarbons=THC, non-methane hydrocarbons=nmHC, and methane=CH_4) are presented for three engine load trials in Appendix B, Figures B8 to B12. Tests on hydrocarbon concentrations were run at all trials except at the 41% engine load downstream the scrubber due to a miss in data logging procedure.

Average values at periods of steady state engine loads that are used for further analysis are presented in Table 15.

Table 14. Average concentrations of total hydrocarbons (THC), non-methane hydrocarbons (nmHC), and methane (CH_4) at steady state engine loads at tests upstream and downstream the scrubber. Concentrations are given as ppm C_1.

	THC (ppm)		nmHC (ppm)		CH_4 (ppm)	
Engine load	Upstream scrubber	Downstream scrubber	Upstream scrubber	Downstream scrubber	Upstream scrubber	Downstream scrubber
High	53.7	45.4	52.8	44.2	0.82	1.14
Medium	87.9	63.4	87.0	62.8	0.97	0.56
Low	82.9	n.a.	81.8	n.a.	1.10	n.a.

At the tests upstream the scrubber at 76% engine load the concentrations fluctuate significantly. The reason for this is not known. For two tests; one on 48% engine load (Appendix B, Figure B11) and one on 32% engine load (Appendix B, Figure B12) it takes some time for values to stabilise.

Average levels of THC and nmHC are higher at medium engine loads than at the other tested loads, while concentrations of methane are highest at low engine load. The average concentrations of total hydrocarbons are reduced over the scrubber. For methane in particular no such pattern was noted.

3.1.6.1 SO_3 concentration

Measurements of gas concentrations of SO_3 indicate a reduction over the scrubber. Concentrations are higher upstream the scrubber at all instances. Highest concentrations are noted at high engine loads, while concentrations at medium and low are very similar upstream and downstream the scrubber. The concentration of SO_3 in exhaust at different tests is presented in Table 16.

Table 15. Gaseous SO_3 in exhaust, mg/Nm^3

	SO_3 (mg/Nm^3)	
Engine load	Upstream scrubber	Downstream scrubber
High	64	14
Medium	21	8
Low	21	9

3.1.7 Particle concentrations

3.1.7.1 Dilution

For the measurements at HFO combustion, upstream and downstream the scrubber, CO_2 was used as trace gas. The CO_2 level in the ambient air was determined to 420 ppm. Details on the dilution ratios are presented in Appendix B, Figures B13 to B18. The dilution ratios that are used in the calculations of emissions in the following are listed in Appendix B, Table B4.

3.1.7.2 Gravimetric analysis

Sampling of particles on filters is made on teflon filters[5]. From tests upstream the scrubber, 6 filters are sampled after the dilution tunnel (DT). Temperatures at the filter are close to 40 °C throughout the trials. Dilution ratios are between 14 and 16. The FPS dilution system is used to dilute sample gas for eleven filters at tests upstream the scrubber. Dilution ratios are between 150 and 250.

At tests downstream the scrubber, 16 filters are exposed after exhaust gas dilutions between 53 and 350.

The same cyclone and flow is used during tests as in the exhaust gas measurements at LSFO, and using the same setup. Thus, also this time the flow through the cyclone is over-dimensioned causing the cut off to be around 1.6 µm rather than 2.5 µm.

An overview of the sampling details for all filters is presented in Appendix B, Table B5 (tests downstream the scrubber) and Table B6(tests upstream the scrubber).

3.1.7.3 Thermal optical analyses of Elemental carbon and Organic carbon (EC/OC)

Twenty-two quartz filters are exposed to diluted exhaust gas for sampling of particles for thermal/optical determination of contents of elemental- and organic carbon. Ten filters are used in tests downstream the scrubber and twelve filters are used in tests upstream the scrubber.

In Appendix b, Table B7, details on the filters are listed, including for each filter sampling conditions, sampling times and volumes, concentrations of total carbon (TC), OC, and EC, and total mass from the gravimetric analysis. Dilution ratios for each filter are presented, as are results before dilution (calculated) and after dilution (measured). Calculated values are only given for one filter per pair, condensate is subtracted and results are multiplied with the dilution factor.

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[5] Gravimetric analyses were also made on quartz filters used. These were however used for analysis of content of elemental and organic carbon of the particles sampled.

All quartz filters are sampled after dilution with the FPS dilution system and dilution ratios are determined from CO_2 measurements in diluted and undiluted sample gas.

3.1.7.4 Contents of metals and sulphur on particles

A selection of the teflon filters are further analysed for contents of metals and sulphur in particles.

The metal content are analysed on five filters; two from measurements downstream the scrubber, and three from measurements upstream the scrubber. All filters are from high and low engine loads. The concentration of particle bound metals compares well in all but one instance - one of the filters from 76% engine load upstream the scrubber. This filter has low concentrations of the otherwise most abundant metals. Further, this filter is diluted with the dilution tunnel, while the remaining filters are diluted with the FPS system.

If the filter with exceptionally low values is excluded from the analysis, the total concentration as analysed from the remaining four filters does not indicate any reduction over the scrubber system. The average concentrations are lower on the filters exposed at high engine loads, compared to the average concentrations on filters exposed at low engine loads. These tests does thus not indicate any significant wash out of the ash fractions, which represent the exit state of these metals

The four elements Vanadium, Nickel, Iron, and Aluminum constitute between 98% and 99% of the metal content in all samples.

In Appendix B, Table B9, the analysed concentrations of elements in particles are listed.

Sulphur content of particles are analysed on five filters; two filters downstream the scrubber and three upstream. Similar to the elemental analysis, filters from tests at high and low engine loads are analysed. The samples do not indicate a loss of particle bound sulphur in the scrubber. Sulphur content of particles are calculated to be between 2.9 and 9% of total particle mass. The results from the particulate sulphur analysis are presented in Appendix B, Table B8.

3.1.7.5 On-line measurements of particles

On-line measurements are made for concentrations of Black Carbon (BC), and number of particles. Instrumentation for measuring concentration of particle number was not running 100% of the time and there are therefore some gaps in the results.

3.1.7.5.1 Black carbon concentrations

Black carbon concentrations are measured after dilution at three engine loads upstream and downstream the scrubber.

At all loads tests with and without a thermodenuder are made. The values are adjusted for an assumed loss of solid particles in the thermodenuder of 25% to 40%. At tests downstream the scrubber, the tests using thermodenuder result in slightly higher or comparable BC concentrations than those tests conducted without a thermodenuder. The tests upstream the scrubber indicate that BC concentrations are similar in with and without a thermodenuder. The tests made at 49% engine load upstream the scrubber are less certain than the rest since it is expected but not confirmed that the instrument was malfunctioning during these measurements.

The reduction in BC level over the scrubber increases with decreasing load.

In Table 17 the BC concentrations from the measurement series, times for tests, dilution ratios are presented.

Table 16. Results from on-line measurements of BC concentrations with the Aethalometer (AE33), at tests on HFO downstream and upstream the scrubber.

	76%	76%	48%	48%	41%	41%	76%	76%	*49%*	*49%*	32%	32%
	Downstream	Downstream	Downstream	Downstream	Downstream	Downstream	Upstream	Upstream	*Upstream*	*Upstream*	Upstream	Upstream
Date/ Time Start	2017-09-21 10:27	2017-09-21 11:03	2017-09-20 22:18	2017-09-20 23:35	2017-09-19 23:25	2017-09-20 00:30	2017-09-24 11:30	2017-09-24 12:04	*2017-09-23 22:23*	*2017-09-23 22:58*	2017-09-22 23:20	2017-09-22 23:37
Date/ Time Stop	2017-09-21 10:40	2017-09-21 11:15	2017-09-20 22:30	2017-09-20 23:45	2017-09-19 23:50	2017-09-20 00:47	2017-09-24 11:50	2017-09-24 12:14	*2017-09-23 22:40*	*2017-09-23 23:10*	2017-09-22 23:30	2017-09-22 23:43
Average BC conc after dilution µg/m3	0.0107	0.00740	0.0210	0.0170	0.0337	0.0238	0.0260	0.0177	*0.0224*	*0.0113*	0.0339	0.0240
Standard deviation BC conc (% of average conc)	5.1%	6.6%	3.4%	3.7%	5.3%	4.1%	4.9%	2.7%	*8.5%*	*8.3%*	4.9%	5.3%
Average dilution	358	434	165	165	131	131	149	149	*252*	*212*	251	251
Trace gas used for determining dilution	CO_2	CO_2	CO_2	CO_2	CO_2	CO_2	CO_2	CO_2	CO_2	CO_2	CO_2	CO_2
Thermodenuder ON / OFF	Off	On	Off	On	Off	On	Off	On	*Off*	*On*	Off	On
Assumed loss in thermodenuder	n.a.	25% - 40%	n.a.	25% - 40%	n.a.	25% - 40%	n.a.	25% - 40%	*n.a.*	*25% - 40%*	n.a.	25% - 40%
Calculated average concentration before dilution and compensated for loss in TD (mg/Nm3)	3820	4280 - 5350	3470	3730 - 4660	4410	4150 - 5190	3870	3510 - 4390	*5640*	*3190 - 3990*	8510	6780 – 8470

3.1.7.5.2 Number concentration of particles

The total concentration of number of particles is measured with the EEPS at three engine loads upstream and downstream the scrubber. Tests cover both volatile particles and non-volatile particles, i.e. tests with and without a thermodenuder.

Size dependent loss of particles in the thermodenuder is calculated for the whole size range. This is a simplification as the smaller particles are lost to a larger extent than the larger particles. A loss of 40% is unlikely since this would cause the total concentrations at two tests with a thermodenuder (i.e. the non-volatile particles) to exceed the concentrations without thermodenuder (i.e. both volatile and non-volatile particles).

Number concentrations of particles are at all tests significantly higher upstream the scrubber than downstream when no thermodenuder is used. When the thermodenuder is used, the tests downstream the scrubber resulted in higher concentrations than at tests at corresponding engine loads upstream the scrubber for both high and low engine loads. At medium engine loads the concentration is the same at tests upstream and downstream the scrubber. The total concentrations are presented in Table 18 and Figure 12. It can be worth remembering that the engine loads were not exactly at equal levels during tests upstream and downstream the scrubber.

Table 17. Total number concentrations of particles in the exhaust gas at different engine loads.

Test	DR used	Total PN in tests without TD (#/cm3)	Total PN in tests with TD, Calculated size dependent loss in TD (#/cm3)
76 %, Upstream scrubber, without TD	213	9.6E+08	
76 %, Upstream scrubber, with TD	163		1.7E+08
49 %, Upstream scrubber, without TD	257	7.9E+08	
49 %, Upstream scrubber, with TD	190		1.5E+08
32 %, Upstream scrubber, without TD	206	6.6E+08	
32 %, Upstream scrubber, with TD	246		1.2E+08
76 %, Downstream scrubber, without TD	192	2.0E+08	
76 %, Downstream scrubber, with TD	406		2.2E+08
48 %, Downstream scrubber, without TD	157	1.4E+08	
48 %, Downstream scrubber, with TD	167		1.5E+08
41 %, Downstream scrubber, without TD	131	3.1E+08	
41 %, Downstream scrubber, with TD	131		1.4E+08

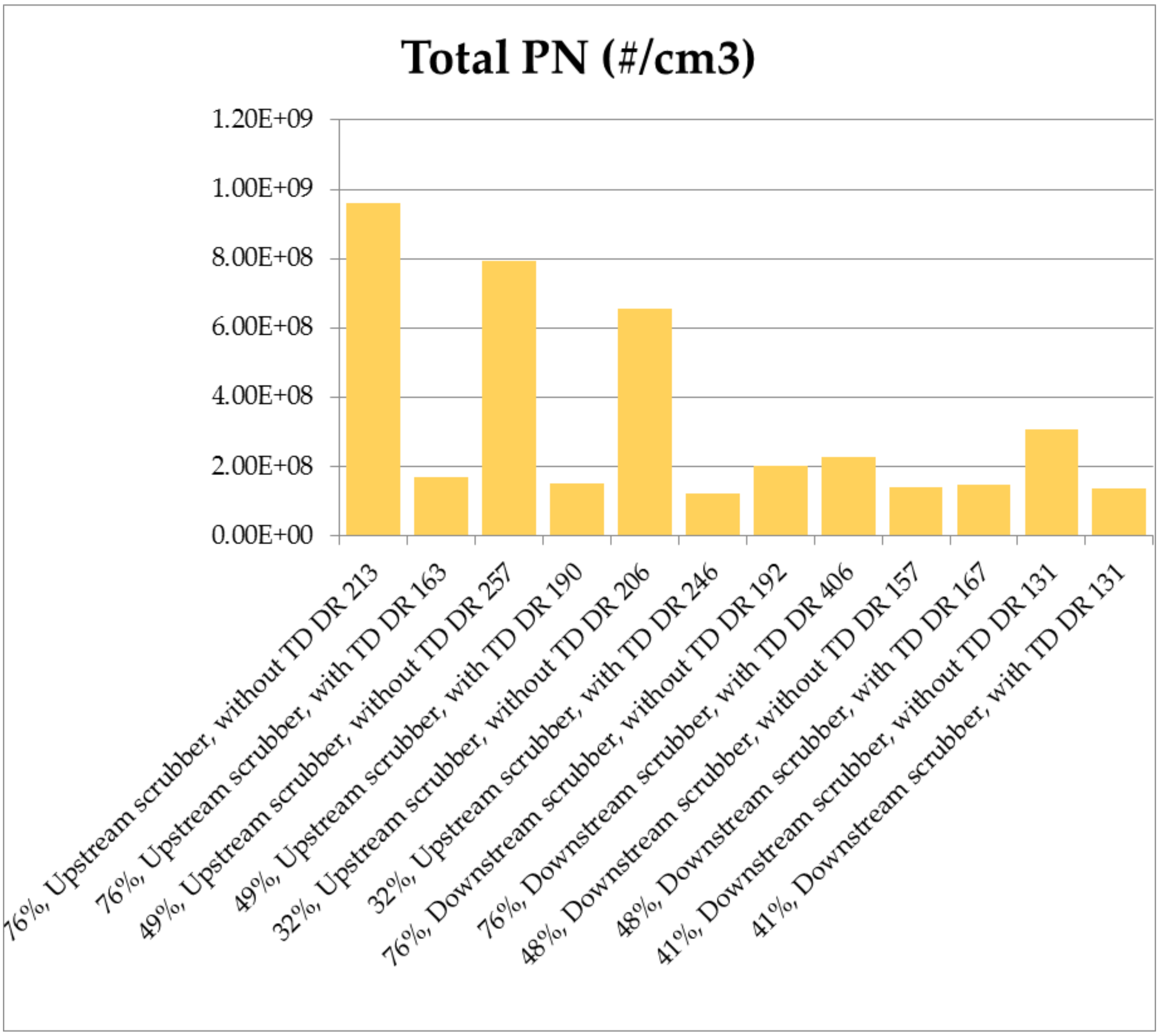


Figure 10. Total number concentrations of particles in the exhaust gas at different engine loads.

For all tests, particle size distributions are considered. For all engine loads at tests without the thermodenuder, a mode below 20 nm is dominant upstream the scrubber. At 32% engine load, there might be a potential mode at particle diameters below the instrument detection limit at 6.04 nm.

The tests upstream the scrubber are all demonstrating a bimodal particle size distribution both at tests with and without the thermodenuder. At use of thermodenuder the modes are at approximately 8-9 nm and at 40-45 nm. At tests without the thermodenuder, the modes are at approximately 15-20 nm and 60-70 nm, with more explicit modes at tests at 32% and 49% engine loads, than at 76% engine load.

At tests downstream the scrubber the distribution is less clear in shape. One mode at around 30-35 nm is measured at all tests.

The particle size distributions at high, medium and low engine loads are presented in Figure 13, Figure 14, and Figure 15 respectively.

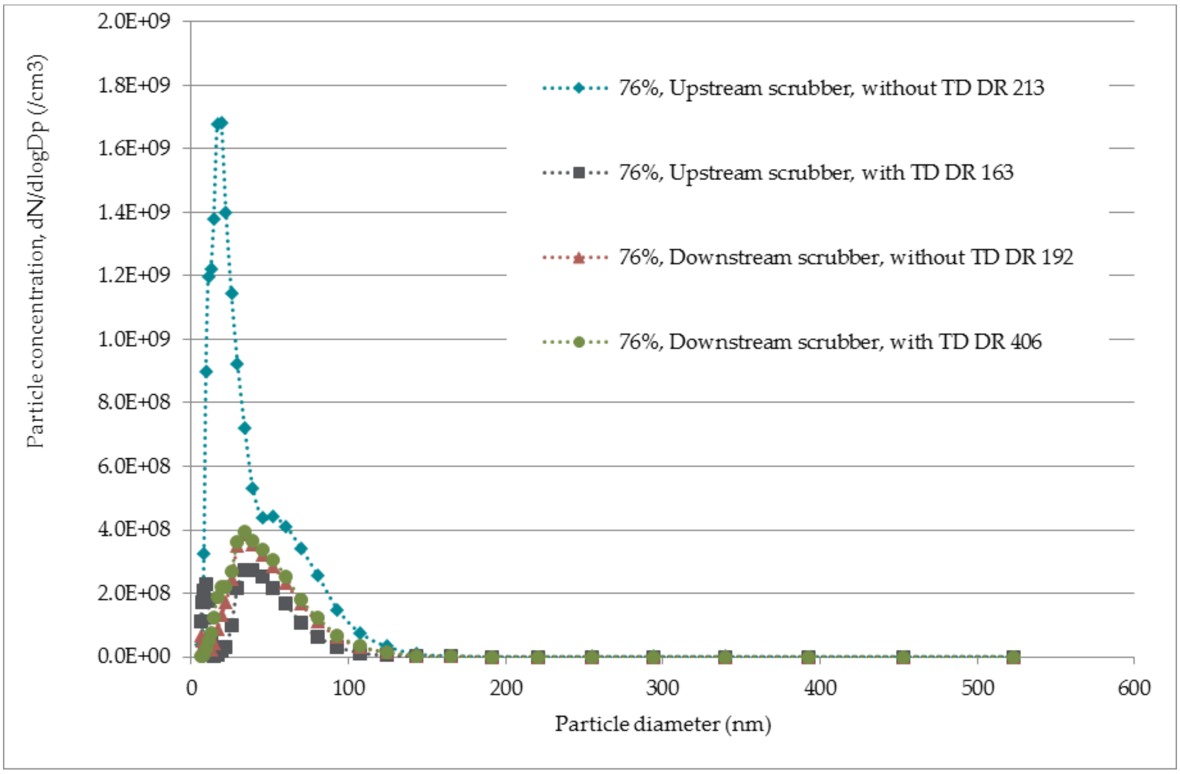


Figure 11. Particle size distributions from EEPS data, from different tests on 76% engine load.

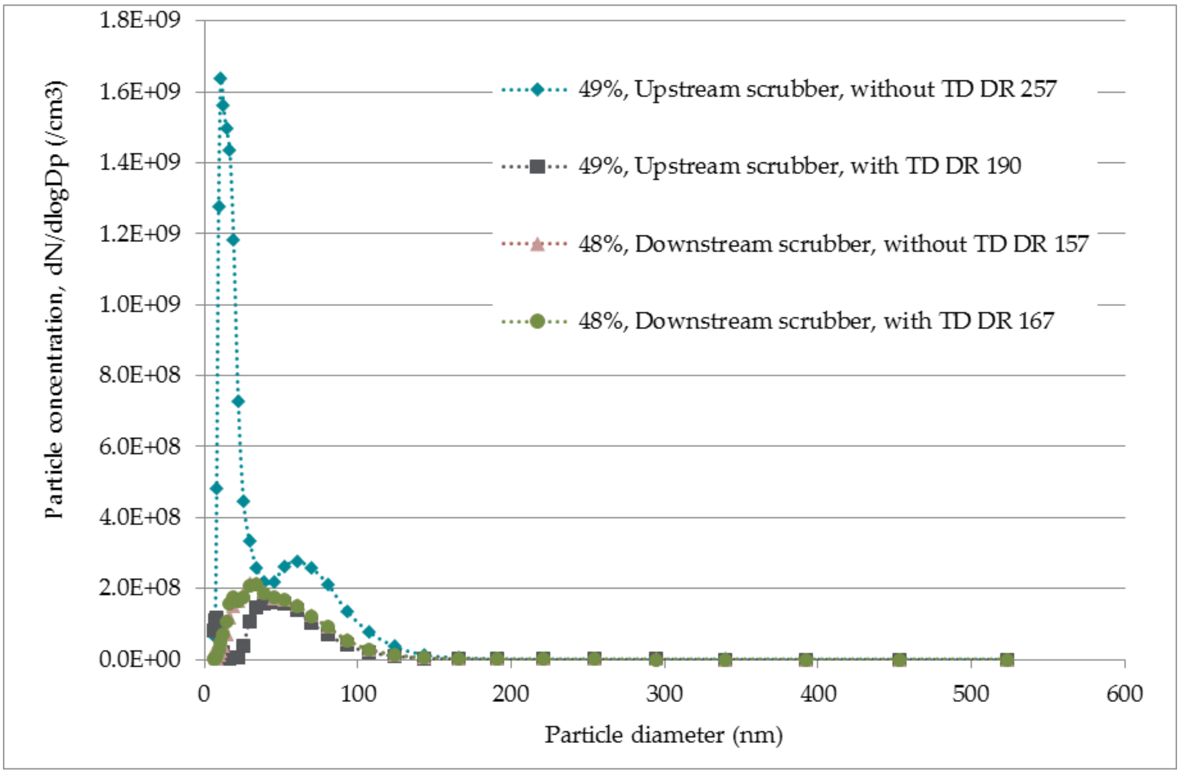


Figure 12. Particle size distributions from EEPS data, from different tests on 48% (downstream) and 49% (upstream) engine load.

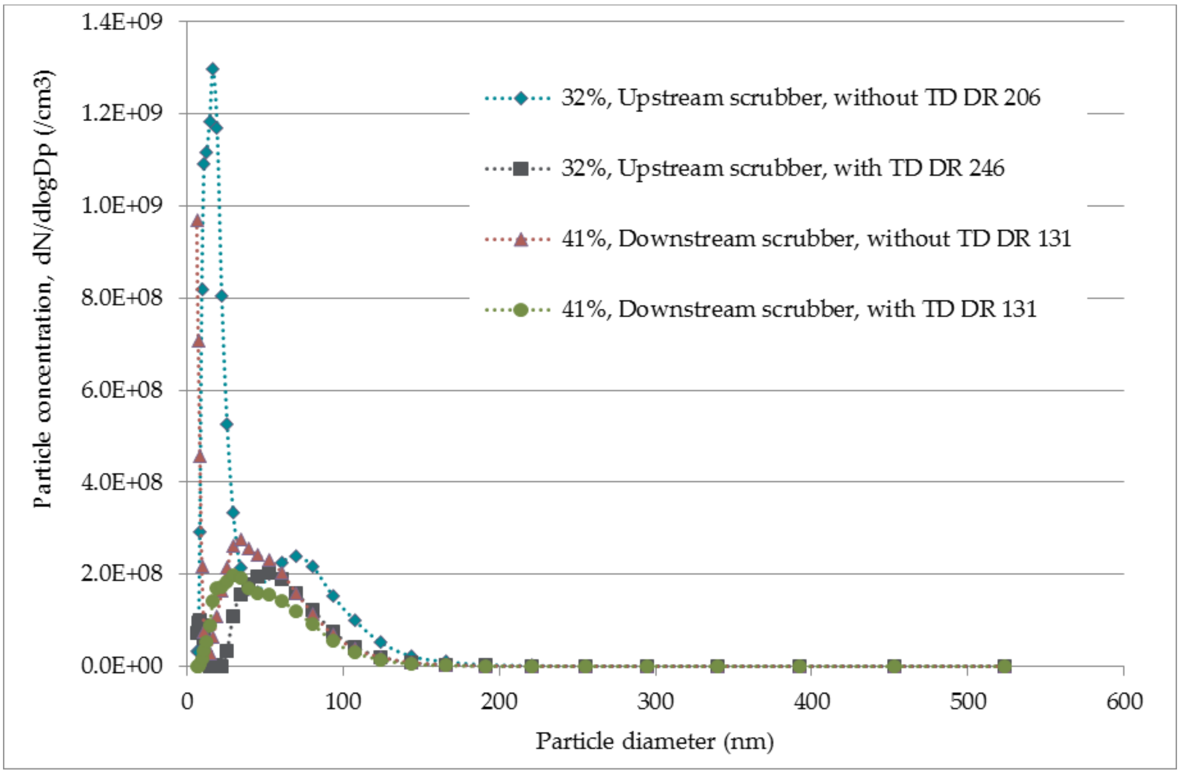


Figure 13. Particle size distributions from EEPS data, from different tests on 41% (downstream) and 32% (upstream) engine load.

Measurements with the SMPS/CPC are done at 48% and 76% engine load downstream the scrubber. Due to problems with the instrument, possibly relating to the temperature during tests, no data series from other engine loads can be considered reliable. The measurements indicate total number concentrations in fair agreement to those measured with the EEPS, considering the different measurement principles used and the different size ranges covered, see Table 19.

Table 18. Total number concentrations of particles at 76% and 48% engine load at tests downstream the scrubber.

	76% downstream scrubber		48% downstream scrubber	
	Without TD	With TD (calculated loss 25% / 40%)	Without TD	With TD (calculated loss 25% / 40%)
PN (#/cm3)	$1.7 \cdot 10^8$	$1.6 \cdot 10^8$ / *$2.0 \cdot 10^8$*	$1.3 \cdot 10^8$	$9.7 \cdot 10^7$ / *$1.2 \cdot 10^8$*

3.1.8 PAH concentrations

PAH concentrations are sampled for analyses both as gas phase PAHs and particle bound PAHs. The sums of gas phase and particle bound PAHs from tests at HFO combustion are presented in Table 20, for the three engine loads and upstream and downstream the scrubber. Results are given as mass per sample and exhaust gas concentrations. Further, the particles sampled for PAH analyses are weighed before and after exposure, masses of particles are also given in Table 20.

Table 19. Mass per sample and concentration per sample of 16 PAHs, and total particle mass per filter, for the three engine load tests upstream and downstream the scrubber.

Engine load	Upstream Scrubber			Downstream scrubber			filter blank	Measurement uncertainty in method (±%)
	76%	49%	32%	76%	48%	41%		
	ng/ sample	ng/ sample	ng/ sample	ng/ sample	ng/ sample	ng/ sample	ng/sample	
naphtalene *	82 000	67 000	82 000	63 000	92 000	75 000	14	40
acenaphtylene *	5 200	5 700	5 300	5 500	6 900	4 500	9	40
acenaphtene *								40
fluorene *	7 000	7 600	7 800	8 100	9 500	5 700	<10	40
phenantrene	35 000	28 000	29 000	23 000	27 000	19 000	<20	30
anthracene	2 100	2 000	2 300	450	660	270	<0.1	40
fluoranthene	3 400	1 600	1 400	1 700	2 100	1 400	1.3	20
pyrene	10 000	5 800	5 100	5 200	6 000	4 400	<1.3	20
benz[a]anthracene	3 100	2 400	1 300	1 500	2 100	1 100	<0.60	40
chrysene	8 100	3 700	770	2 600	3 700	2 500	1.7	30
benzo[b]fluoranthene	1 500	970	82	330	750	620	<0.7	30
benzo[k]fluoranthene	230	140	<15	<15	52	52	<0.4	20
Benso(a)pyren	170	270	41	<18	36	57	<0.5	20
dibenz[a, h]anthracene	130	30	<19	34	100	100	<0.5	30
benzo[ghi]pyrelene	740	44	62	43	110	77	<1.0	40
indeno[1,2,3-cd]pyrene	210	38	<77	<74	110	110	<2.0	20
SUM	**160 000**	**130 000**	**140 000**	**110 000**	**150 000**	**120 000**		
Mass of particles on filter (g)*	0.19	0.14	0.14	0.11	0.097	0.098		
*not part of accredited analysis								
Sample volumes (Nm3)	0.667	0.526	0.538	0.822	0.847	0.83		
Sampling time	11:00-12:00	21:15-22:05	22:55-23:45	09:35-10:45	21:45-23:00	22:45-00:15		
PAH concentrations (µg/m3)	76%	49%	32%	76%	48%	41%		
naphtalene *	123	127	152	77	109	90		
acenaphtylene *	8	11	10	7	8	5		
acenaphtene *	0	0	0	0	0	0		
fluorene *	10	14	14	10	11	7		
phenantrene	52	53	54	28	32	23		
anthracene	3	4	4	1	1	0		
fluoranthene	5	3	3	2	2	2		
pyrene	15	11	9	6	7	5		
benz[a]anthracene	5	5	2	2	2	1		
chrysene	12	7	1	3	4	3		
benzo[b]fluoranthene	2	2	0	0	1	1		
benzo[k]fluoranthene	0	0	n.a	n.a	0	0		
Benso(a)pyren	0	1	0	n.a	0	0		
dibenz[a, h]anthracene	0	0	n.a	0	0	0		
benzo[ghi]pyrelene	1	0	0	0	0	0		
indeno[1,2,3-cd]pyrene	0	0	n.a	n.a	0	0		
SUM	**240**	**247**	**260**	**134**	**177**	**145**		

3.2 Output – calculation of exhaust gas flow and specific emission rates at HFO combustion

Specific emission rates for gases and particles measured upstream the scrubber are calculated using the carbon balance method[6]. For the calculation procedure we refer to ISO 8178-1:2017 and 8178-4:2017.

For the emissions downstream the scrubber there is no standard available for these calculations. Carbon in the fuel can be expected to be measured as CO_2 in the exhaust gases to a dominant extent. However, a minor amount of CO_2 can be washed out in the scrubber system. We evaluated the following options:

- **the carbon balance method (ISO 8178-1:2017 and 8178-4:2017).** This method is based on the mass flow of exhaust gases. It is based on that a known amount of the elements C, H, O and N are combusted per time unit. The method considers the humidity and temperature of the inlet air. The actual effect of the addition of water and chemicals in the scrubber to the exhaust gas flow is unknown but assumed to be small. The addition of water to the exhaust gases in the scrubber should have little effect on the volume flow through the exhaust channel once corrected for temperature. Uncertainties in this approach concern the potential removal of CO_2 in the scrubber system. This is by necessity neglected, since the carbon dioxide level in the exhaust is used in the mass balance calculations.
- **flow measurements with a Pitot tube.** The flow is estimated from pressure differences in the Pitot tube, indicating the velocity of the exhaust gas within the tube. There is a standardized way of conducting these measurements, which was not possible to fully comply with at the tests. A transect of the exhaust gas velocity across the pipe including six, seven, and nine points of measurement at 41%, 48%, and 76% engine load, respectively, were studied. Uncertainties relate to differences in flow in different areas of the exhaust pipe. Other uncertainties are the alignment of the Pitot tube relative to the flow direction.
- **a simplified approach to volume flow calculation.** This method is not standardised but assumes that all carbon in the fuel can be detected as carbon dioxide in the exhaust pipe. This is a simplified approach that does not consider any influence of other elements in the fuel than carbon and neglects impact of humidity. The calculation includes the following:

$$F = \frac{FC \times \frac{FCC}{100} \times \frac{mw_{CO2}}{mw_C}}{\frac{C_{CO2}}{100} \times \rho_{CO2}}$$

---

[6] The method follows emission calculation for marine diesels based on ISO 8178-1:2017 and 8178-4:2017

where F is Exhaust gas flow in m^3, FC is fuel consumption in kg/h, FCC is fuel carbon content in %, mw_{CO_2} is the molar weight of carbon dioxide (44 g/mol) and mw_C is the molar weight of carbon (12 g/mol), C_{CO_2} is the measured concentration in the exhaust gases in %, and ρ_{CO_2} is the density of CO_2 in room temperature in (kg/m^3). A carbon dioxide density of 1.963 kg/m^3 is used.

In order to compare the methods, the volume flow (in Nm3/h) at different engine loads is analysed. The results from the different methods are presented in Table 21.

Table 20. Exhaust gas volume flow downstream the scrubber calculated by different methods.

	Exhaust gas volume flow (Nm^3/h), 76%	Exhaust gas volume flow (Nm^3/h), 48%	Exhaust gas volume flow (Nm^3/h), 41%
Carbon balance	42 013	28 741	25 151
Pitot tube	35 907	24 956	24 771
Simplified approach Volume flow calculation	39 666	27 072	24 898

There is a good agreement between the approaches at the lowest engine load test but differences increase with engine load. The Pitot tube measurements are considered too uncertain to use in further calculations. Should there have been a removal of CO_2 in the scrubber, these values are however reasonable. Details of the Pitot tube measurements and related calculations are presented in APP_N. The difference between the results from the carbon balance method and the simplified approach is 6% at both 76% and 48% engine load.

In the following, all specific emissions are calculated using the carbon balance method. This approach might cause an overestimation of the specific emission rates.

Ingoing parameters, constants, and specific emission at measurements upstream and downstream the scrubber are listed in Appendix B, table B10 and the calculated specific emission rates are presented in Table 22.

Table 21. Specific emission rates calculated from trials on HFO. Values in brackets indicate filter number, see Table B10 in Appendix B.

Date/Test	**170921**	**170920-170921**	**170919-170920**	**170924**	**170923-170924**	**170922-170923**
Sulphur content of fuel (%)	2.77	2.77	2.77	2.77	2.77	2.77
	Downstream scrubber			**Upstream scrubber**		
MCR (100 % load), MCR of engine (brake kW) =	9 600	9 600	9 600	9 600	9 600	9 600
Load, Brake Load during test (%) =	76%	48%	41%	76%	49%	32%
P, Brake Power during test (kW) =	7 296	4 640	3 968	7 296	4 672	3 072
Calculated specific emission rates:						
CO2 Specific emission (g/kWh) =	617	687	739	618	690	847
O2 Specific emission (g/kWh) =	1 080	1 143	1 122	1 063	1 101	1 336
CO Specific emission (g/kWh/kWh) =	0.79	1.40	1.50	0.93	1.72	1.87
NOx Specific emission (g/kWh) =	11.28	12.68	15.22	11.06	13.06	16.97
NOx Specific emission (g/kWh) (corrected) =	10.9	12.4	14.6	11.0	12.6	16.3
SO2 Specific emission measured (g/kWh) =	0.06	0.03	0.02	9.90	11.11	13.51
SO2 Specific emission calculated (g/kWh)	n.a.	n.a.	n.a.	10.36	11.55	14.06
THC Specific emission (g/kWh) =	0.162	0.243	No data	0.360	0.332	0.382
nmHC Specific emission (g/kWh)=	0.158	0.241	No data	0.36	0.3	0.4
CH4 Specific emission (g/kWh)=	0.004	0.002	No data	0.001	0.004	0.005
PMtot Specific emission (g/kWh)	0.54 (35)	0.28 (29)	0.23 (25)	0.68 (53)	**0.45 (47)**	**0.63 (43)**
PMtot Specific emission (g/kWh)	0.27 (38)	0.19 (31)	0.27 (28)	**0.37 (55)**	**0.38 (48)**	0.35 (45)
PMtot Specific emission (g/kWh)	0.27 (40)	0.16 (33)		0.44 (56)	0.23 (49)	**0.41 (46)**
PMtot Specific emission (g/kWh)				**0.48 (57)**	0.21 (51)	
PM + cyclone spec. emission (g/kWh)	0.27 (36)	0.25 (32)	0.22 (26)	0.28 (54)	0.36 (50	0.75 (42)
PM + cyclone spec. emission (g/kWh)	0.24 (37)	0.25 (30)	0.26 (27)	0.36 (58)	0.36 (52)	0.44 (44)
PM + cyclone spec. emission (g/kWh)	0.22 (39)	0.21 (34)				
TC Specific emission (g/kWh)	0.11	0.13	0.050	*0.130*	0.165	0.351
TC spec. emission (size cutoff with cyclone) (g/kWh)	0.09	0.11	No data	0.106	0.205	*0.360*
OC Specific emission (g/kWh)	**0.096**	**0.116**	**0.041**	***0.070***	**0.115**	**0.253**
OC spec. emission (size cutoff with cyclone) (g/kWh)	**0.073**	**0.099**		**0.084**	**0.151**	***0.264***
EC Specific emission (g/kWh)	**0.016**	**0.018**	***0.009****	***0.060****	**0.050**	**0.0985**
EC spec. emission (size cutoff with cyclone) (g/kWh)	**0.013**	**0.016**		**0.022**	**0.054**	***0.0965****
BC Spec emission (g/kWh)	**0.022**	**0.022**	**0.028**	**0.022**	**0.035**	**0.065**
BC Spec emission using thermodenuder (g/kWh)	**0.023**	**0.022**	**0.029**	**0.020**	**0.020**	**0.061**
PN Spec emission (#/kWh)	**1E+15**	**8E+14**	**No data**	**No data**	**No data**	**2E+15**

PN Spec emission, thermodenuder (#/kWh)	9E+14	6E+14	No data	No data	No data	6E+14
PN Spec emission (#/kWh)	1E+15	9E+14	2E+15	6E+15	5E+15	7E+15
PN Spec emission, thermodenuder (#/kWh)	1E+15	9E+14	8E+14	9E+14	2E+15	9E+14
SO_3 Spec emission (g/kWh)	0.08	0.05	0.06	0.37	0.13	0.16
PAH Spec emission (mg/kWh)	0.77	1.1	0.92	1.4	1.5	1.9

*Not used in further analysis due to suspected handling errors during sampling

3.3 Discussion of results from measurements on HFO, upstream and downstream scrubber

3.3.1 Gaseous emissions

Emission factors for gases in general show a decreasing trend with engine load. Exceptions are O_2, at tests downstream the scrubber, for which an increase between 41% end 48% engine load is measured. The specific emission rates for CO, HC, NO_x, CO_2 and O_2, at different engine loads are presented in Figure 16 and Figure 17. The high specific emission of NO_x at low engine loads is possibly due to the electric control of the cylinder valves that allows for efficient high temperature combustion also at low engine loads (MAN, 2018).

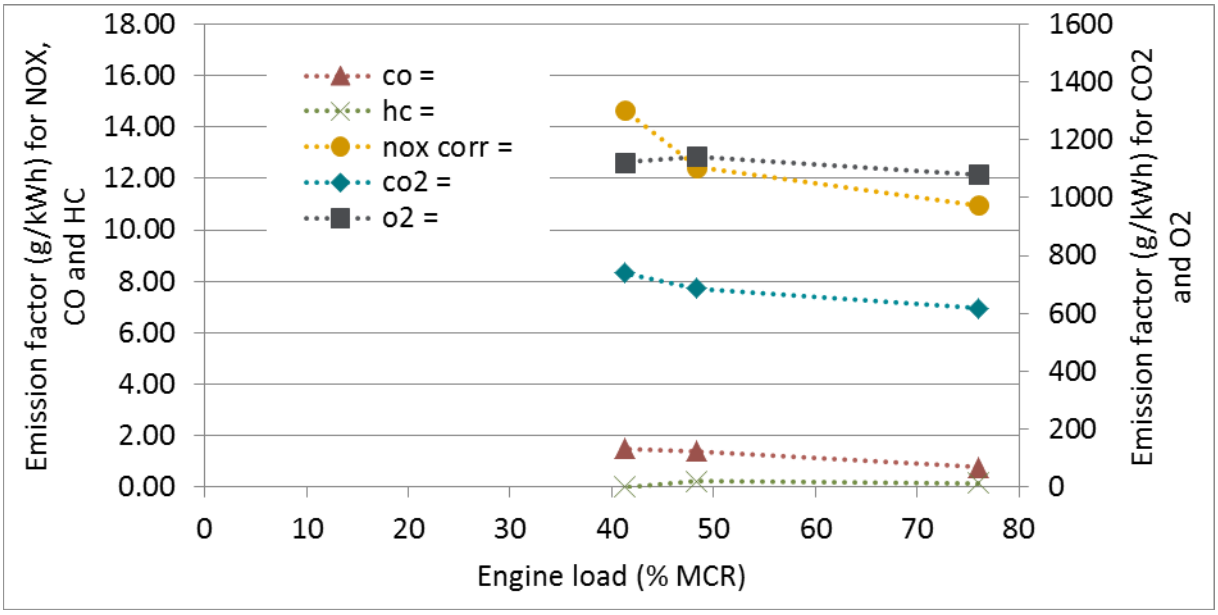


Figure 14. Specific emission rates for CO, HC, NO_x, CO_2 and O_2, at different engine loads. Tests on HFO downstream the scrubber.

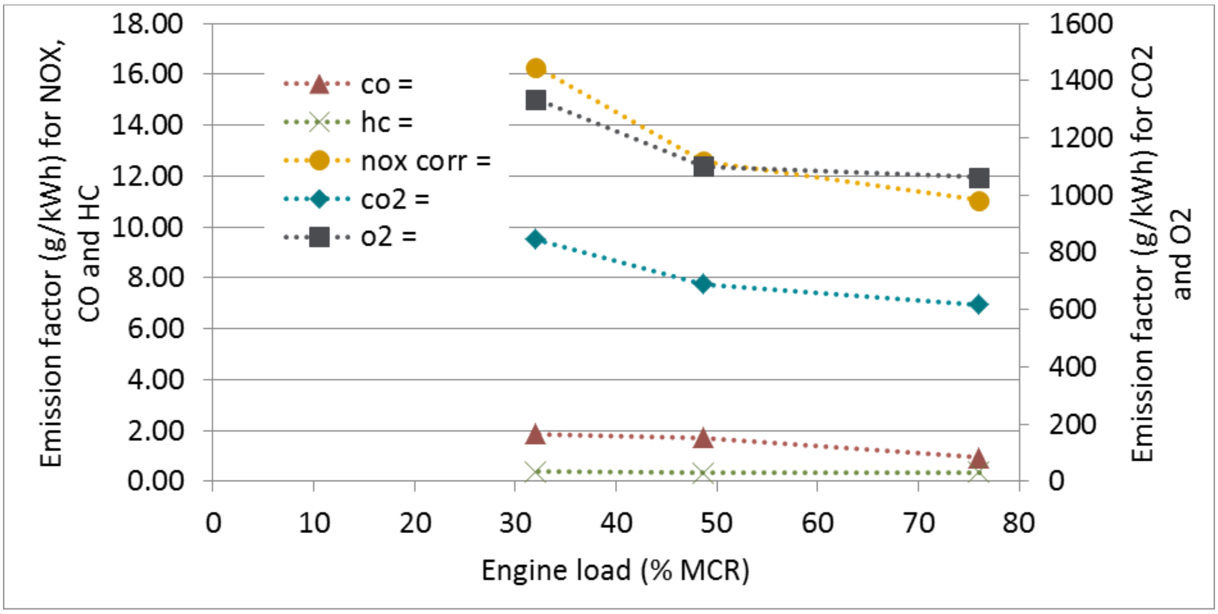


Figure 15. Specific emission rates for CO, HC, NOx, CO_2 and O_2, at different engine loads. Tests on HFO upstream the scrubber.

As previously pointed out, the test engine is a Tier I engine according to IMO MARPOL Annex VI NOx emission limits. It is rated at 500 rpm and the maximum allowed weighted NOx emission value is calculated as 45*n^-0.2, where "n" is the rated engine speed in rpm. Maximum allowed NOx Emissions Value, weighted over the test cycle, is thus 13.0 g/kWh. Only the emissions at the lowest tested engine load exceeds the limit.

Typical specific emission factors for CO and HC from medium speed diesel engines on residual oil at high engine loads (assumed around 80%) are reported to be 1.1 g/kWh and 0.2 g/kWh, respectively (Cooper and Gustavsson 2004). The same report estimates emissions at reduced speeds to be twice those. CO measurements during these trials give slightly lower values than this on tests downstream the scrubber. The CO specific emissions are below these values also at test upstream the scrubber. However, HC emissions are close to or exceeding the literature values. This gives no specific indication of incomplete combustion in the engine at low loads. Specific emission rates of HC and CO are both lower downstream the scrubber than upstream. A reduction of CO emissions between 15 and 20% over the scrubber is measured. The indicated reduction of HC over the scrubber is higher; 27% reduction at medium engine loads and 55% reduction at high engine loads.

The scrubber removes about 1% of NOx. At low engine load tests the NOx emissions are 10% less in the tests downstream the scrubber than in the one upstream. This is probably a reflection of the factual engine load differences during tests upstream and downstream (32% at tests upstream the scrubber compared to 41% at tests downstream the scrubber).

SO_2 emissions are reduced by over 99% at all engine loads. For tests upstream the scrubber, the emissions of SO_2 are calculated from fuel sulphur content as well as measured. There is 4% discrepancy between the two values for all engine loads, see Table 23, where the measured value is lower than the calculated value. The suspected effect of "scrubbing" in the instrument indicated by the measurements on LSFO was thus not noticed. It might however be that "instrument scrubbing" occurred at tests downstream the scrubber, where comparisons of measured values with calculated values are not possible. Previous tests of the instrument indicated higher removal of SO_2 at low concentrations.

Table 22. Specific emissions for SO_2 at tests on HFO upstream the scrubber calculated from sulphur content in fuel and measured.

	76%	49%	32%
SO_2 Calculated Specific emission (g/kWh) =	10.36	11.55	14.06
SO_2 Measured Specific emission (g/kWh) =	9.90	11.11	13.51

From the measurements it is suggested that over 99% of the SO_2 is removed in the scrubber.

The concentrations of sulphur trioxide (SO_3) in the exhaust are significantly reduced in tests downstream the scrubber. At 76% engine load there is a removal of 78% of the SO_3. At the two lower engine loads the reduction is lower 61-63%. Removal of SO_3 in scrubbers does not reach 100%. Sub-micron H_2SO_4 particles are formed and partly removed by mass transfer mechanisms in Brownian diffusion (Srivastava et al., 2004). As a removal mechanism, it is not efficient enough to remove all H_2SO_4 from the exhaust gas (Srivastava et al., 2004).

The scrubber is still less efficient in removing SO_3 than in removing SO_2. The measured SO_3 concentrations are higher than the SO_2 concentrations in the tests downstream the scrubber.

3.3.2 Particulate emissions

Filters sampled with a dilution tunnel, measured as PM_{tot} and using sampling methods following ISO 8178, could only be performed upstream the scrubber due to spatial constraints of taking the dilution tunnel to the higher measurement site. The specific emission median values during these measurements were 0.41, 0.41, and 0.52 g/kWh at 76%, 49%, and 32% engine load respectively.

It seems that specific emission rates are little affected by the choice of dilution method. Further, is seems that the cyclone cutoff used ($PM_{1.6}$) results in specific emissions similar to PM_{tot} specific emissions. In fact, the median values from filters sampled after the cyclone are higher than that from those sampled without a cyclone. It is therefore likely that only combustion particles with diameters <1.6µm are sampled also at PM_{tot} sampling. Specific emission rates at the lowest engine load are in general higher than specific emission rates at tests at higher engine loads.

Median values for specific emissions at tests upstream the scrubber is presented in Table 24 and Figure 18. In order to avoid a high influence of extreme values on specific emissions, median values that are more representative than the average values are presented.

The difference between engine loads is small.

Table 23. Median values for PM specific emissions for the three engine loads at tests upstream the scrubber.

Engine load:	76%	49%	32%
Median PMtot, FPS and DT	0.46	0.30	0.41
Median PM + cyclone, FPS	0.32	0.36	0.60
Median PM all, FPS and DT	0.41	0.36	0.44
Median PMTOT DT	0.41	0.41	0.52

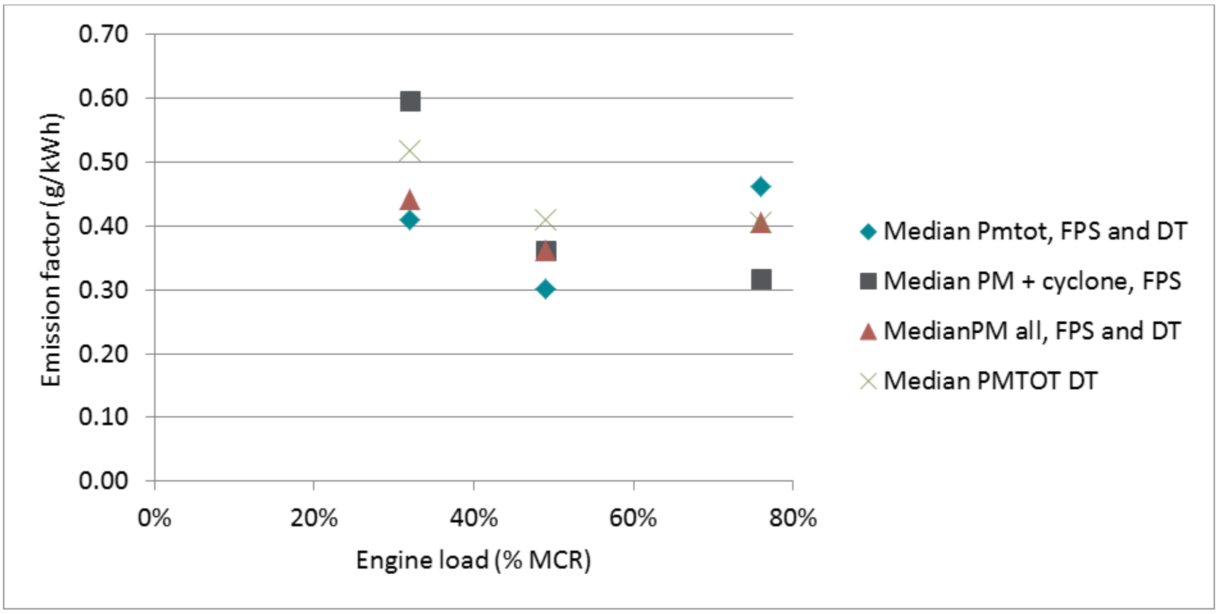


Figure 16. PM specific emissions at tests on HFO, upstream scrubber. Median values for specific emissions for the three engine loads. Cyclone cutoff at 1.6µm, DT = Dilution tunnel.

At tests downstream the scrubber, the PM specific emissions are all through lower than at tests upstream the scrubber. No significant impact of engine load is seen. Nor is any effect from the cyclone noted. Median values for specific emissions at tests upstream the scrubber are presented in Table 25 and Figure 19. The reduction of particles over the scrubber is estimated to 34%, 44% and 52% at engine loads of approximately high, medium, and low engine loads, respectively.

Table 24. Median values for PM specific emission for the three engine loads at tests downstream the scrubber.

Engine load:	76%	48%	41%
Median PMtot, FPS	0.27	0.19	0.25
Median PM + cyclone, FPS	0.24	0.25	0.24
Median PM, all, FPS	0.27	0.23	0.25

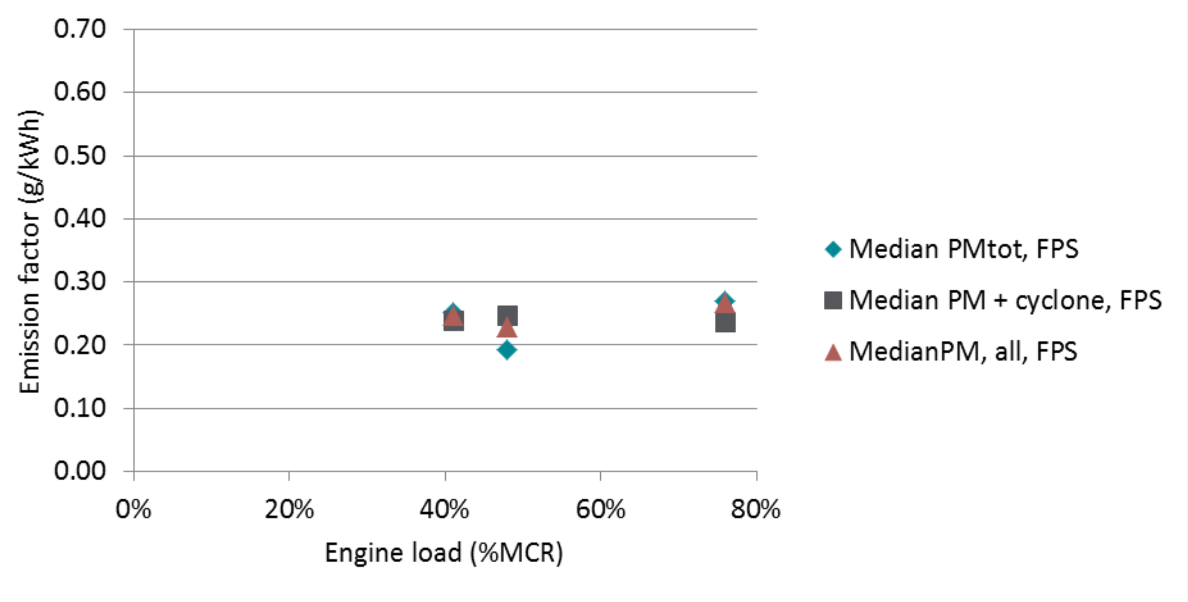


Figure 17. PM specific emissions at tests on HFO, downstream scrubber. Median values for specific emission factors for the three engine loads. Cyclone cutoff at 1.6µm, DT = Dilution tunnel.

The unabated PM emissions from the engine are low compared to literature values.

A share of the particles can be expected to be washed out with the scrubber water. Further, particle formation can be expected to be affected by the change in exhaust gas temperature, as well as by the changed composition of the exhaust gas with increased humidity and reduction of sulphur in gas form. Volatile particles are expected to be more affected by this than the solid particles. Previous studies on particle emissions from measurements downstream scrubber systems do not provide a unified picture of the effect of the scrubber on particles. This could be due to difficulties in measuring at equal conditions upstream and downstream the scrubber system. Another reason that is pointed out by Hansen (2012) is the design of the scrubber system. Some studies indicate an increase of particle mass emissions after a scrubber (ICCT, 2017). This could happen if salt water is used in which case salt particles may form during dilution and be collected in the filter. Salts including sulfates could also be formed and contribute to particle mass. Other studies report reductions up to 75% (Fridell and Salo, 2012). There is a lack of well described published values. Many reported reduction ratios refer to scrubber manufacturers own measurements. It is difficult to draw conclusions on effects on particle emissions from the published studies; some studies point at no reduction while others indicate up to 75% reduction(ICCT, 2017; Fridell and Salo, 2012; DTI, 2012; Hansen J-P, 2012; Køcks et al., 2012; Wärtsilä, 2010). The discrepancies can be attributed both to the challenges with using filter sampling for the exhaust after the scrubber but also to that different scrubber designs may have different abatement efficiencies for PM. An estimated central value is a 40% reduction.

Total carbon content is reduced over the scrubber. Both OC and EC contribute to this reduction. Contrary to expected, the relative reduction of EC is greater than that of OC:

Estimated contributions of OC to total particle mass at the tests downstream the scrubber are between 31% and 40%, EC contribution is between 5% and 6%, at different engine loads. At the tests upstream the scrubber, the estimated contribution of OC to total particle mass is 21% to 62% and the estimated contribution of EC is between 5% and 24%.

The online analysis with the aethalometer gives concentrations of BC that can be compared with the concentrations from analysis of EC on filters. The agreement between the calculated emission factors for EC and BC at the tests downstream the scrubber is lower at 41% engine load than at the higher engine loads. At the measurements upstream the scrubber, only measurements at 76% engine load shows a good agreement between EC and BC. At the two lower engine loads tested, the EC values analysed from the filters constituted 13% and 24% of the total particle mass, which is rather high and could indicate an analytical mistake. BC values from tests at 49% engine load upstream the scrubber are uncertain, as previously pointed out. However, BC values at 32% loads are expected to be correct. At tests downstream the scrubber, EC emission factors are lower than BC emission factors, while the situation is reversed upstream the scrubber. An overview is presented in Figure 20. BC and EC cannot be directly compared since BC is an optically measured and EC is a physical characteristic that is measured thermally. It seems unlikely though that any elemental carbon is not detected as black carbon. Rather, the black carbon measure should comprise the EC. The analysis of EC is more sensitive to incidents during sampling and handling than BC measurements with the continuous on-line instrument, and the BC measurements could therefore possibly be considered as more robust.

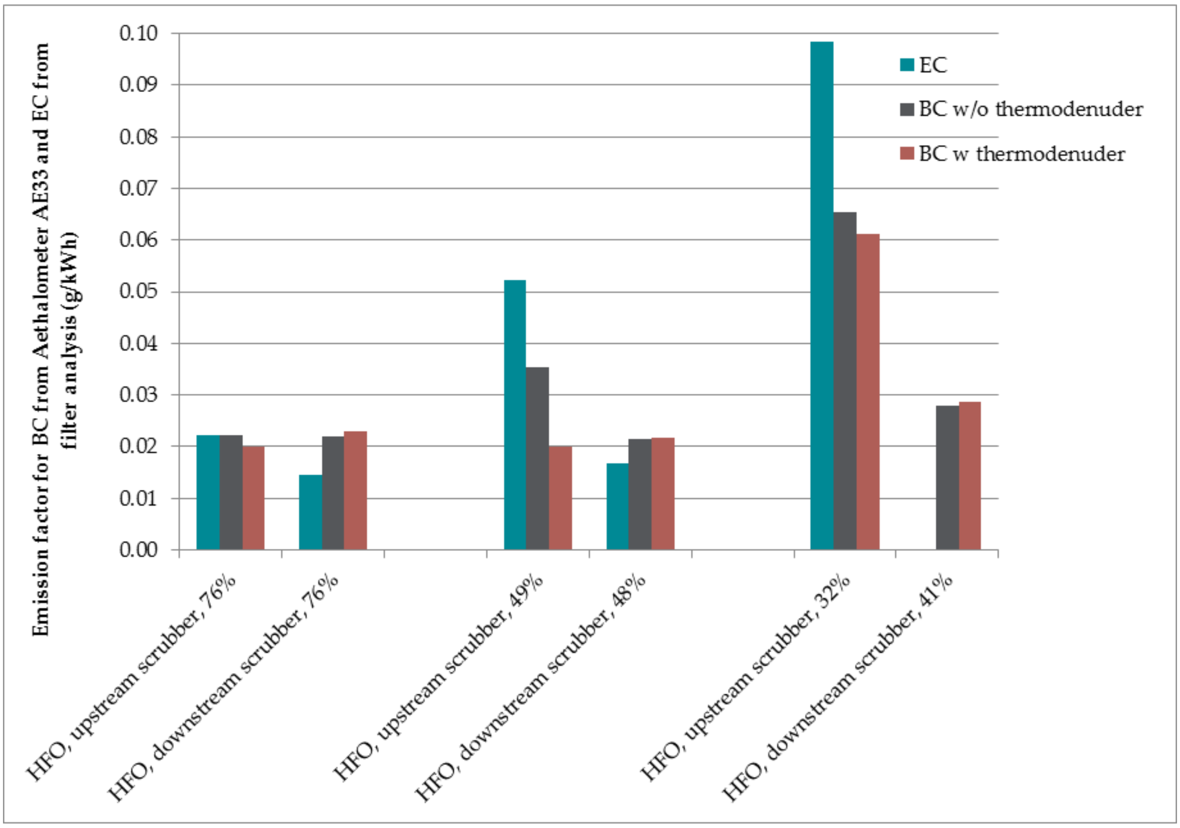


Figure 18. Correlations of emission factors for BC from online measurements with EF from filter analysis of EC. Values from tests at HFO downstream and upstream the scrubber

Metal contents are analysed on five filters of which one differed significantly from the rest. No general reduction of metal content over the scrubber is noted. Instead the relative share of metal content of total particle mass increases somewhat suggesting that the metal containing particles are rather unaffected by the scrubbing of exhaust gases.

The filter that deviated from the rest is sampled after dilution in the dilution tunnel while other filters are sampled after the FPS dilution system. It has not been tested if the difference in metal content if particles in any way relates to the sampling setup.

The content of elements in the fuel and lube oil is compared to the concentrations determined from the analysis of elements in particles. Similar to the analysis of LSFO samples, we assume a lube oil consumption of 1g/kWh. It is possible to compare the concentration of Vanadium, Nickel, and Iron. Other elemental concentrations are either too low to be detected in the fuel or lube analysis, or is not detected in the particle metal analysis, or both. Vanadium, Nickel, and Iron are all lower in concentration in the particle samples than if exhaust gas concentrations are calculated from contents in the fuel and lube oil; 52-66% of the Fe, 11-31% of the Ni, and 18-39% of the V in fuel and lube, is unaccounted for.

The sulphur content of particles is comparable upstream and downstream the scrubber. It is assumed that this particulate sulphur is predominantly in a sulphate form SO_4^{2-} with water molecules attached.

The measurements of number of particles clearly shows that the mode of volatile particles with diameters <20nm observed at measurements upstream the scrubber disappears before measurements downstream the scrubber. Since the mode is non-existing in measurements with the thermodenuder, it is a fair assumption that it is the volatile particles that are removed. Volatile particles can be of organic particles or sulphate. No analysis of the mass of the number of volatile particles is made. Particles of these small sizes will generally not contribute to the particle mass emissions to a great extent.

Thus, volatile particles appear to be efficiently removed in the scrubber.

3.3.3 PAH

PAH content in the exhaust is to more than 50% consisting of naphthalene, and the profile of constituent species are similar for all loads, see Figure 21. The two- and three ring PAHs (naphtalene, acenaphtylene, acenaphtene, fluorene, phenantrene, and anthracene constitute between 82 and 91% of total PAHs, which is close but higher than the 76% concluded as a typical value for diesel engine exhausts reported by Khalili et al., 1995.

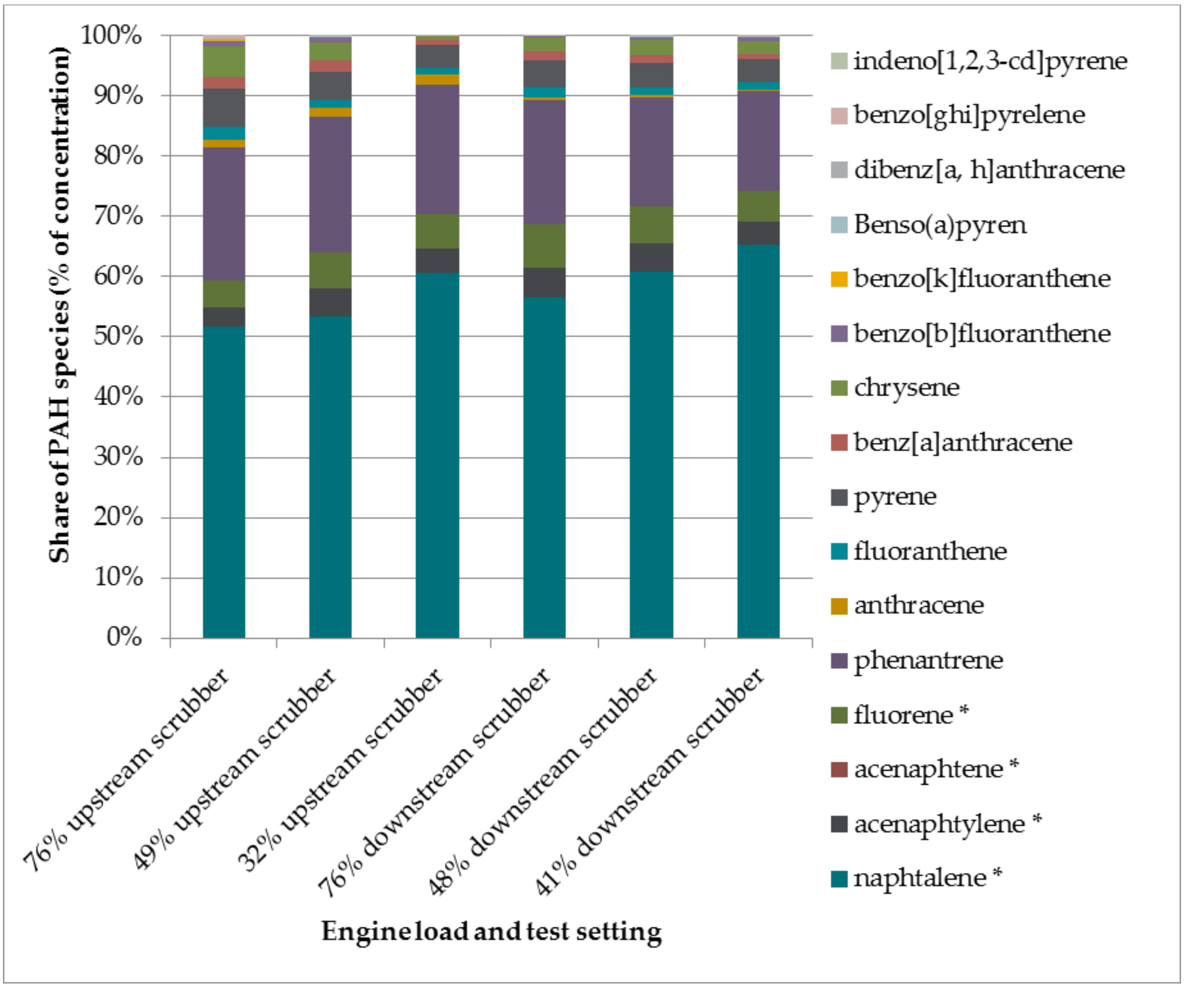


Figure 19. Shares of different PAH species at different engine loads.

The emission factors for total emissions upstream the scrubber are 1.4, 1.5, and 1.9 mg/kWh for engine loads 76%, 49% and 32%, respectively. At tests downstream the scrubber, the emission factors are 0.77, 1.1, and 0.92 mg/kWh at 76%, 48% and 41% engine load. There is thus a reduction of PAH in the scrubber at all engine loads. There are also indications of higher emissions of PAH at lower engine loads. At tests downstream the scrubber, the two lowest engine loads were in reality rather similar (48% and 41%), which may be an explanation to the rather similar emission factors at these loads.

These emission factors are well in line with previously reported ranges for PAH emission factors for marine engines (see eg Cooper 2003). PAH emissions further depend to some extent on the PAH content of the fuel but are also formed during combustion. Total aromatic content of the tested fuel was 23.5%, also including monocyclic aromatic hydrocarbons (benzene and derivatives).

4 Concluding analysis of the measurements on LSFO, upstream, and downstream the scrubber

The scrubber on Stena Britannica efficiently reduces emissions of sulphur dioxide in the exhaust gases. Reductions result in lower emissions than what is the case with LSFO combustion. Further, significant differences in emissions between the use of scrubber with HFO and the use of LSFO are observed for a number of species:

- CO; Emissions are lower for LSFO combustion than HFO combustion both upstream and downstream the scrubber. There is also a reduction of the CO concentration over the scrubber. At lower engine loads this is more pronounced.
- NO_X; Emissions are lower for LSFO combustion compared to downstream the scrubber. The difference in the emissions observed for low engine loads upstream and downstream the scrubber are probably more related to the different actually obtained engine loads than to scrubbing of NO_X. The engine load is around 32% upstream the scrubber and 41% downstream the scrubber.
- SO_2; There is significant reduction of the SO_2 emissions in the scrubber. The emission factor is reduced >99% at all engine load. The emission of SO2 downstream the scrubber is 17%, 8%, and 4% of corresponding factors at LSFO combustion at high, medium, and low engine loads, respectively.
- THC; There is significant reduction of the THC concentration in the scrubber. Specific emissions downstream the scrubber is lower than specific emissions at LSFO combustion for all engine loads tested.

In addition changes in concentration of several exhaust components are also observed when varying the engine load. For O_2 and CO_2 changes observed can be attributed to changes in combustion for different loads.

Figure 22 through Figure 26 present the calculated specific emission rates for the different gases.

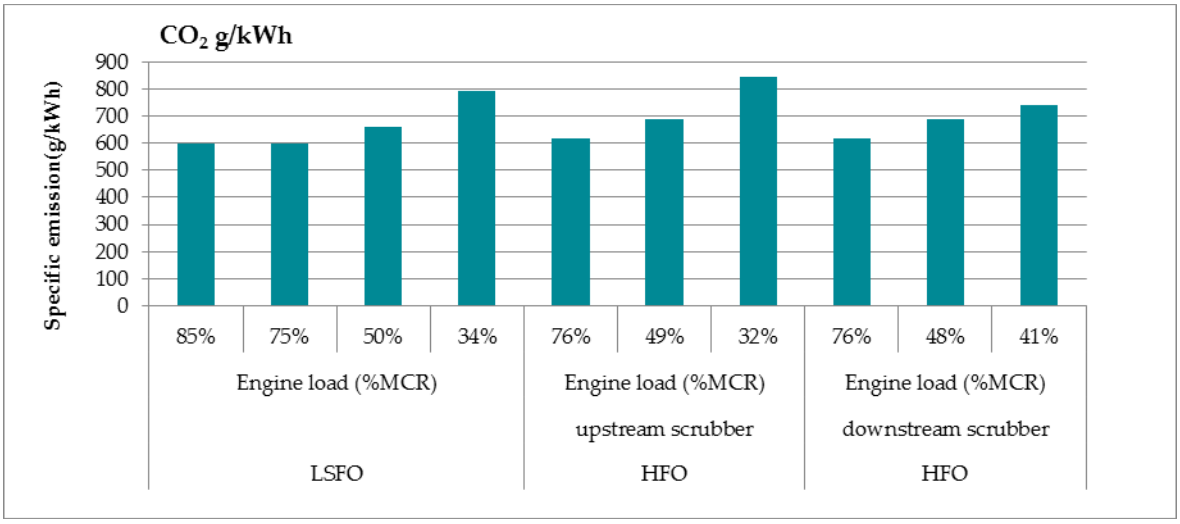


Figure 20. Comparison of CO₂ specific emission rates from all trials.

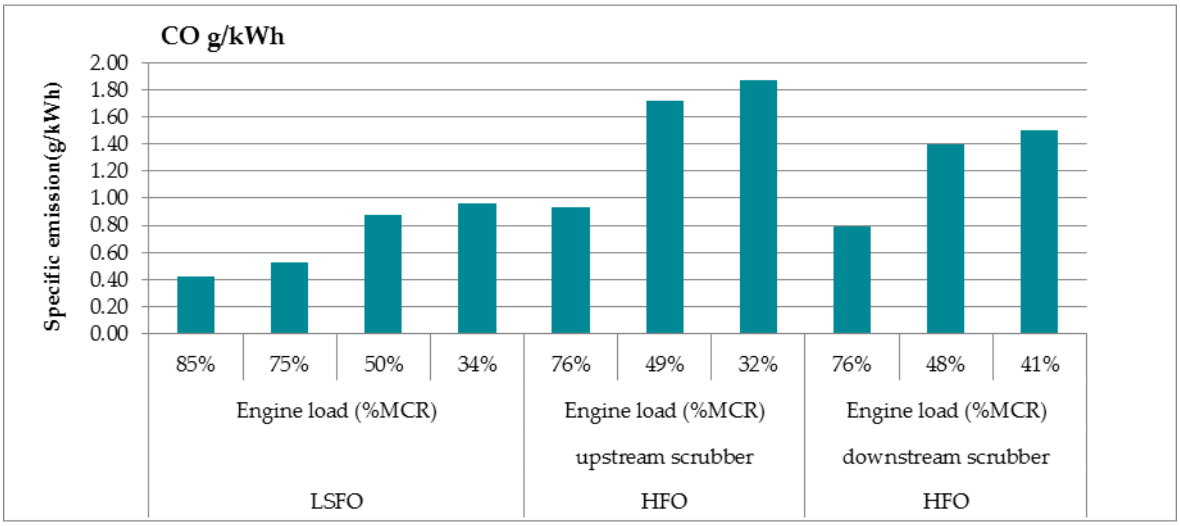


Figure 21. Comparison of CO specific emission rates from all trials.

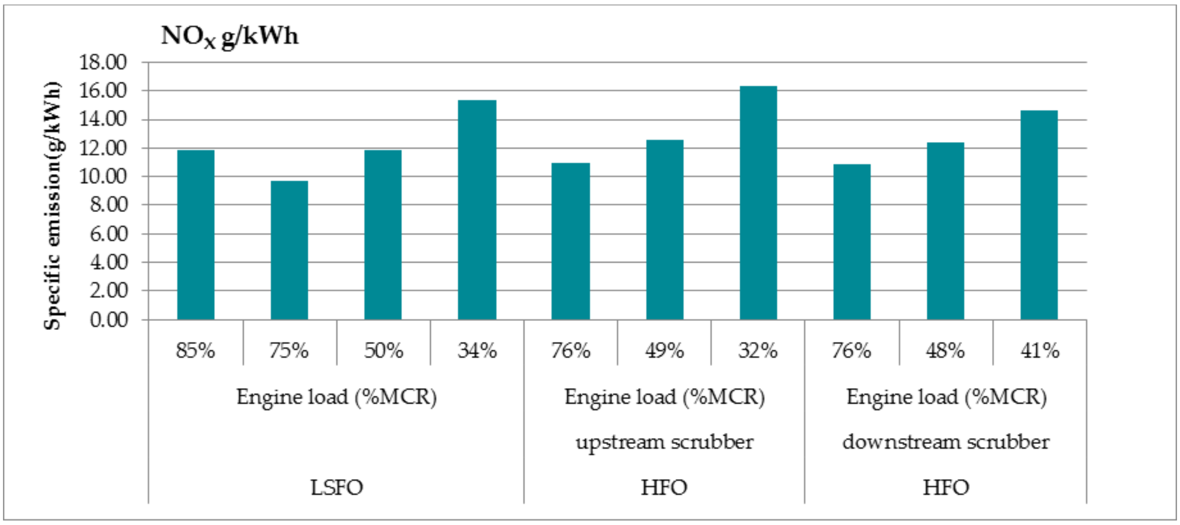


Figure 22. Comparison of NO_X specific emission rates from all trials.

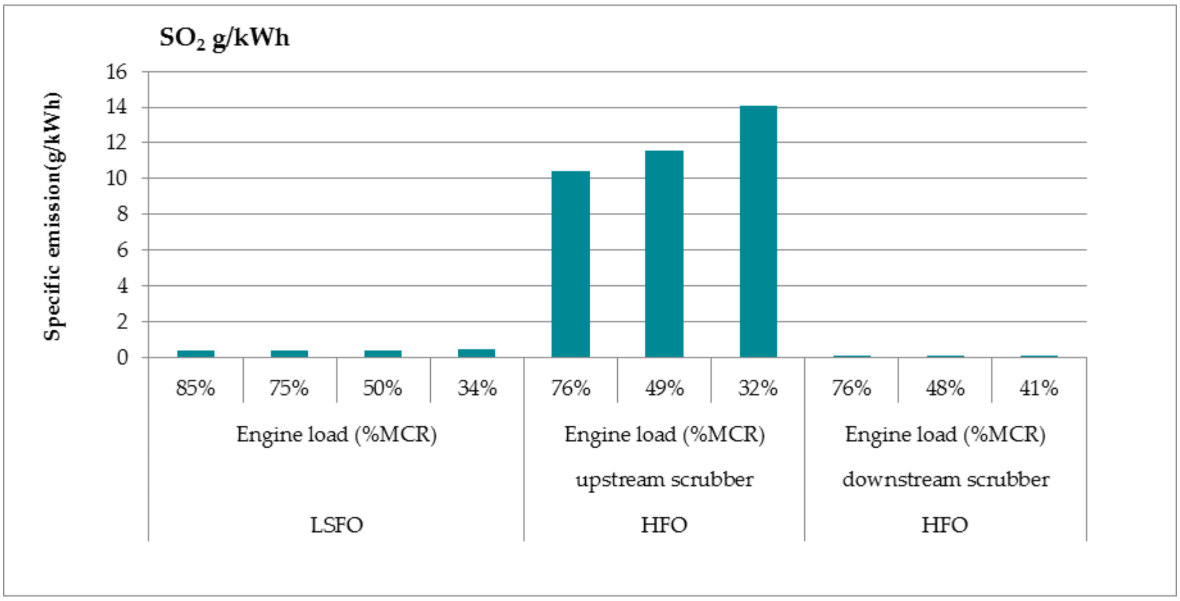


Figure 23. Comparison of SO_2 specific emission rates from all trials.

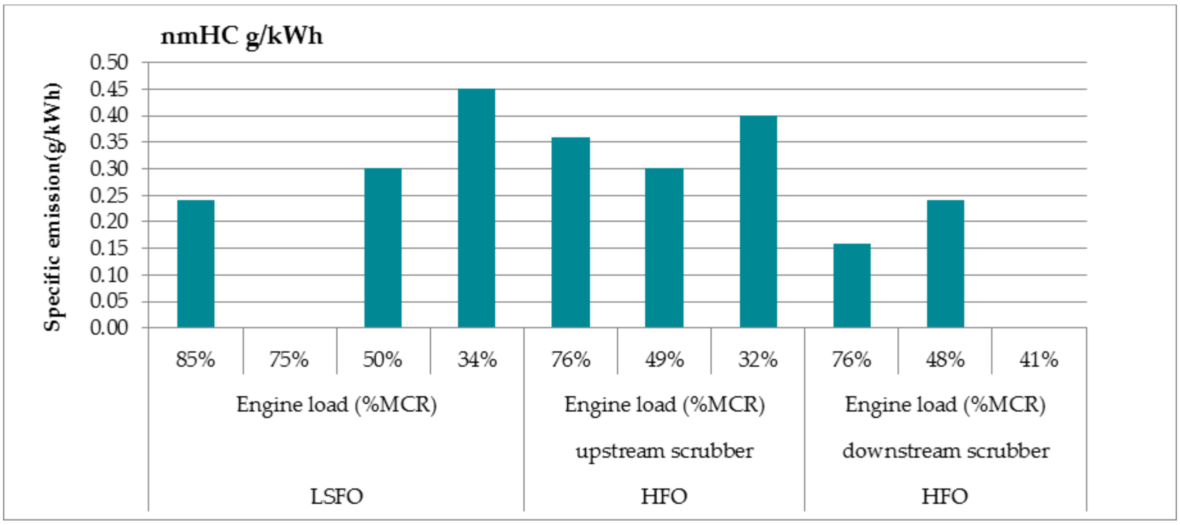


Figure 24. Comparison of nmHC specific emission rates from all trials.

The concentrations of gas phase sulphur trioxide (SO_3) in the exhaust are significantly reduced in tests downstream the scrubber. At high engine loads there is a removal of 78% of the SO_3. At the two lower engine loads the reduction is lower 61-63%. The scrubber is still less efficient in removing SO_3 than in removing SO_2. The measured SO_3 concentrations are higher than the SO_2 concentrations in the tests downstream the scrubber. In the tests on LSFO no gas phase SO_3 was measured.

PM emissions (mass) are reduced over the scrubber with 34%, 42% and 52% at high, medium, and low engine loads respectively. PM emissions at combustion of LSFO with 0.1% sulphur are still lower than PM emissions downstream the scrubber.

The particles consist of metals (elemental contents of V, Ni, Fe, Al, Co, Ba, Mn, Zn, Cr, Sr, Cd, Cu, As, Se, Pb, Mo, P, S, Li were analysed), sulphates, and organic and elemental carbon. The average concentration of particles in the exhaust is taken from filters at each studied engine load and trial setup (LSFO, HFO upstream scrubber, or HFO downstream scrubber). Different filters are used for analysis of metal analysis and analysis of sulphate. Yet other filters are used for EC/OC analysis. The analysis gives an approximation of reductions of different materials over the scrubber and compares emissions from combustion of LSFO with emissions downstream a scrubber. For several cases the results are not consistent for mass balance of various species which likely is associated with the uncertainties in the analyses.

Results for metals and sulphates are available from tests high and low engine loads. In Figure 27 and Figure 28 the approximate division between particulate contents of EC, OC, sulphates, and metals at high and low engine loads, respectively, are presented.

At high engine loads there are for all trial setups (LSFO, HFO upstream scrubber, or HFO downstream scrubber) a relatively large share of the particle mass that is not accounted for by the analyses. Organic carbon is abundant in all setups, and sulphate with associated water (calculated) are contributing significantly only in tests with HFO combustion. The scrubber seems to reduce the concentration of all analysed parameters in the particle mass with the exception of metals. It is not likely that the increase in metal mass downstream the scrubber is real, but is rather due to the analyses of materials on different filters described above. Emissions of particle bound metals, sulphates and EC are all lower at LSFO combustion than from measurements downstream the scrubber.

At the low engine loads the organic carbon content dominates particle mass upstream the scrubber and for LSFO combustion. The scrubber seems to reduce both OC and EC significantly. Sulphate content are higher downstream the scrubber compared to upstream the scrubber, which could possibly be due to formation of sulphate from SO_2 in the exhausts when temperatures are lowered. The mass analyses of particle contents at LSFO combustion and HFO upstream the scrubber sum up to higher masses than the gravimetric analysis. The mass of contents from tests at LSFO and upstream the scrubber is 7% and 15% higher, respectively, than the gravimetric analyses of filters give. This is within the uncertainties related to measurements and analysis methods.

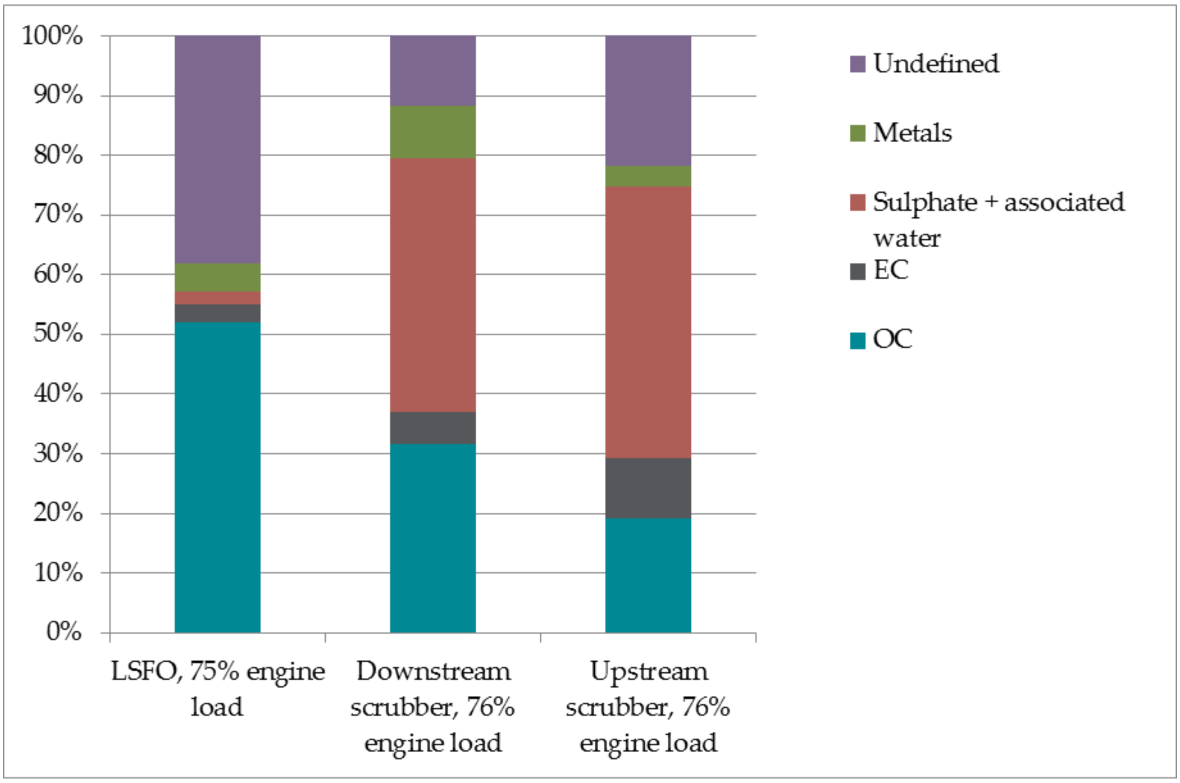


Figure 25. Particle mass divided between constituents at high engine loads.

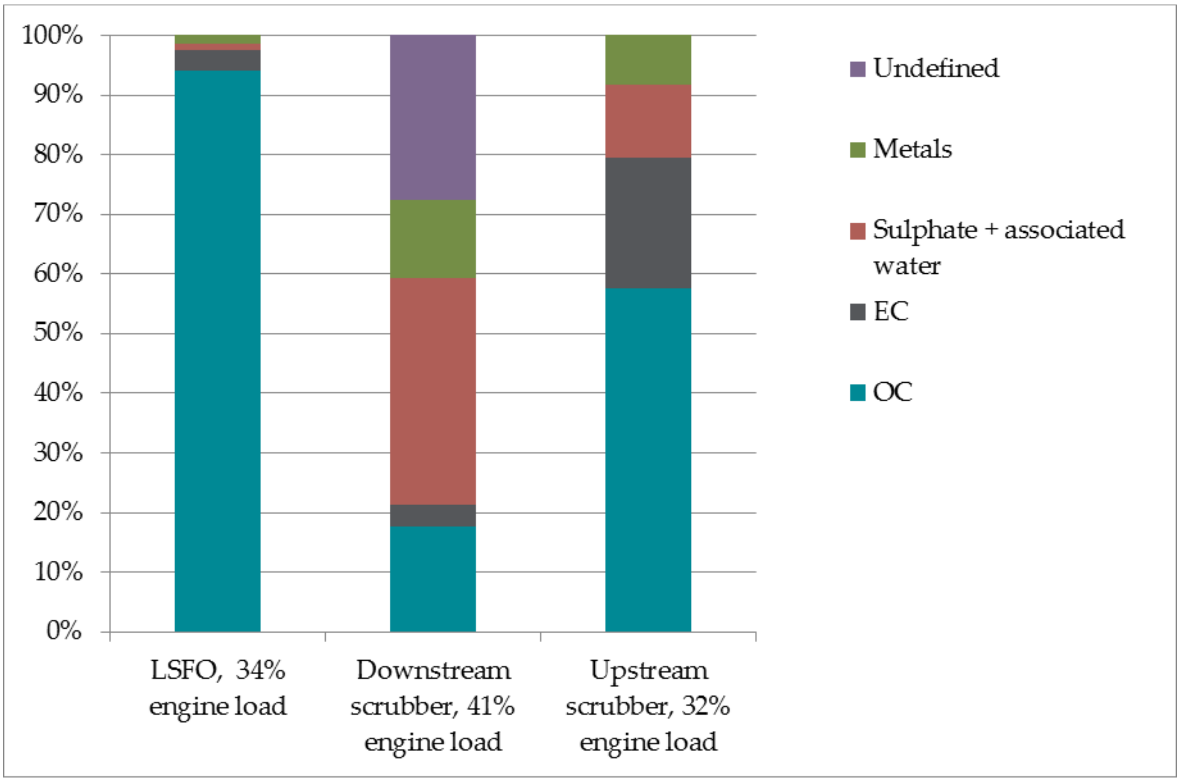


Figure 26. Particle mass divided between constituents at low engine loads.

The PAH emissions are lower from LSFO combustion than tests at HFO combustion, both upstream and downstream the scrubber. All tests with LFSO show lower PAH concentrations than any of the other tests. Engine loads have little effect on the concentration of PAHs in the exhaust gas. A comparison of PAH specific emissions at different tests are presented in Figure 29.

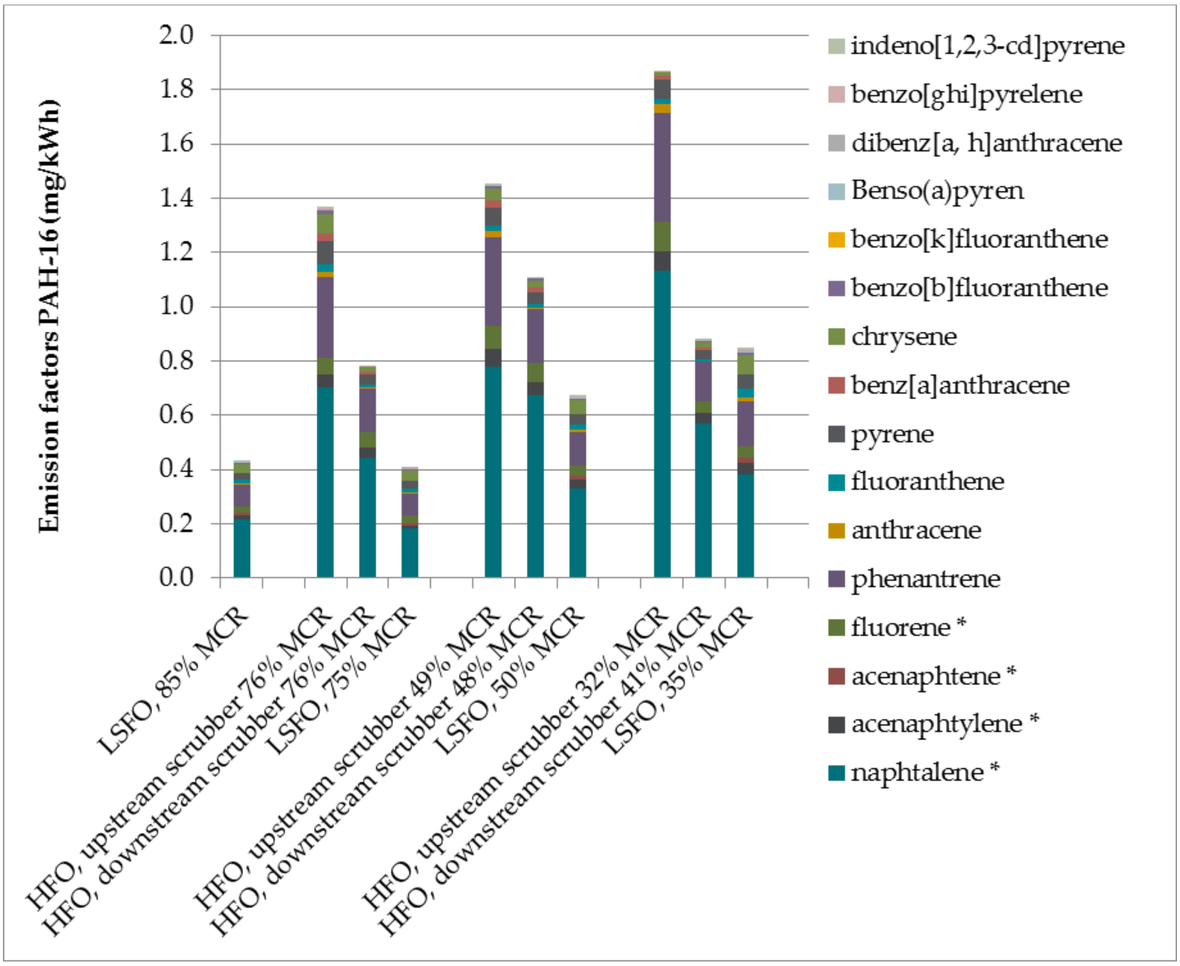


Figure 27. PAH concentrations in the exhaust at the different tests.

5 References:

Agrawal H., Welch A., Miller J. W., Cocker R. D., 2008. Emission Measurements from a Crude Oil Tanker at Sea. Environmental Science & Technology, 42(19), p. 7098–7103.

Andreasen A. and Mayer S., 2010, Modelling of the oxidation of fuel sulfur in low speed two-stroke diesel engines, CIMAC conference paper No.39

Cooper, D., 2001. Exhaust emissions from high speed passenger ferries. Atmospheric Environment, Volume 35, p. 4189–4200.

Cooper, D., 2003. Exhaust emissions from ships at berth. Atmospheric Environment, Volume 37, p. 3817–3830.

Cooper D. and Gustafsson, T. 2004. Methodology for calculating emissions from ships - 1. Update of emission factors, SMED report 4.2004.

DTI, FORCE, Univ. of Copenhagen, Alfa Laval Aalborg A/S, 2012, Characterization of the effect of the scrubber system installed on Ficaria Seaways Results from 2nd measurement campaign

Fridell, Erik. Salo. Kent, 2008. Primary particles in ship emissions. Atmospheric Environment, Volume 42, p. 1160–1168.

Hansen J-P. Alfa-Laval for Miljöstyrelsen DK, 2012, Exhaust Gas Scrubber Installed Onboard MV Ficaria Seaways

ICCT, 2016. Black Carbon Measurement Methods and Emission Factors from Ships, s.l.: s.n.

IMO, 2008, NO_X Technical Code 2008

IMO, 2009, Second IMO GHG Study, Buhaug, Ø., Corbett, J.J., Endresen, Ø., Eyring, V., Faber, J., Hanayama, S., Lee, D.S., Lee, D., Lindstad, H., Markowska, A.Z., Mjelde, A., Nelissen, D., Nilsen, J., Pålsson, C., Winebrake, J.J., Wu, W., Yoshida, K., London, UK

ISO 8217:2010, petroleum products – Fuels (Class F) – Specifications of marine fuels, fourth edition 2010-06-15

Kasper A., Aufdenblatten S.,Forss. A.,Mohr, M. & Burtscher H., 2007. Particulate Emissions from a Low-Speed Marine Diesel Engine. Aerosol Science and Technology, 41(1), pp. 24-32.

Khalili N. R., Scheff P. A., and Holsen T. M., 1995, PAH source fingerprints for coke ovens, diesel and, gasoline engines, highway tunnels, and wood combustion emissions, Atmospheric Environment, Volume 29, Issue 4, Pages 533-542

Køcks, M., A.G. Hemmersam, K. Fuglsang, T. Rosenørn, J.B. Markussen, J.P. Hansen, K.I. Lieke and M. Bilde, 2012, Shipboard characterization of a wet scrubber system: Influence on particle number concentration, particle size distribution

Lahtinen J., 2016, Closed-loop Exhaust Gas Scrubber Onboard a Merchant Ship – Technical, Economical, Environmental and Operational Viewpoints, Acta Wasaensia 342

MAN, 2018, MAN 48/60CR Project Guide – Marine; Four-stroke diesel engine compliant with IMO Tier II, MAN Energy Solutions

Moldanová J., Fridell E., Winnes H., Holmin-Fridell., Boman J., Jedynska A., Tishkova V., Demirdijan B., Joulie S., Bladt H., Ivleva N. P., Niessner R., 2013. Physical and chemical characterisation of PM emissions from two ships operating in European Emission Control Areas. Atmospheric Measurement Techniques, Volume 6, p. 3577–3596.

Srivastava R.K., Miller C.A., Erickson C., and Jambhekar R., 2004, Emissions of Sulfur Trioxide from Coal-Fired Power Plants, Journal of Air and Waste Management Association, 54, 750-762

Winnes H., Fridell E., 2009. Particle Emissions from Ships: Dependence on Fuel Type. Journal of the Air & Waste Management Association, Volume 59, p. 1391–1398.

Winnes H., Moldanová J., Anderson M., Fridell E., 2016. On-board measurements of particle. Journal of Engineering for the Maritime Environment, 230(1), p. 45–54.

Zetterdahl, M., 2016. Particle Emissions from Ships, s.l.: s.n.

Wärtsilä, 2010, EXHAUST GAS SCRUBBER INSTALLED ONBOARD MT "SUULA" - Public test report,

LIST OF APPENDED DOCUMENTS

APP_A: Data from measurements on LSFO

APP_B: Data from measurements on HFO

APP_C: Determination of SFOC

APP_D: Fuel analysis report, 1st Feb

APP_E: Fuel analysis report, 2nd Feb

APP_F: Fuel analysis report, 3rd Feb

APP_G: Fuel analysis report, 4th Feb

APP_H: Lub oil analysis report, Feb

APP_I: Fuel analysis report 19th Sep

APP_J: Lub oil analysis, Sep

APP_K: Hourly log scrubber parameters 19th -20th of September

APP_L: Hourly log scrubber parameters 20th -21st of September

APP_M: Hourly log scrubber parameters 21st of September

APP_N: Pitot tube measurements and calculations of exhaust flow

Appendix A.

Data from measurements on LSFO

List of Tables:

List of Figures

A8. Dilution for sampling of filter 20 and 21, at 50% engine load. Concentrations of NOX in diluted and undiluted gas.

A9. Dilution for sampling of filter 20 and 21, 50% engine load Concentrations of CO2 in diluted gas and dilution ratio are shown. CO2 in raw exhaust gas = 5.518%, CO2 in ambient air = 420 ppm.

A10. Dilution for sampling of filter 22. Concentrations of CO2 in diluted gas and dilution ratio are shown. CO2 in raw exhaust gas = 5.659%, CO2 in ambient air = 420 ppm.

A11. Dilution for sampling of filter 23. Concentrations of CO2 in diluted gas and dilution ratio are shown. CO2 in raw exhaust gas = 5.417%, CO2 in ambient air = 420 ppm.

A12. Dilution for sampling of filter 24. Concentrations of CO2 in diluted gas and dilution ratio are shown. CO2 in raw exhaust gas = 5.417%, CO2 in ambient air = 420 ppm.

A13. Dilution for sampling of filter "QH 113" and "QH 114". Concentrations of CO2 in diluted gas and dilution ratio are shown. CO2 in raw exhaust gas = 5.66%, CO2 in ambient air = 420 ppm.

A14. Dilution for sampling of filter "QH 119" and "QH 120". Concentrations of CO2 in diluted gas and dilution ratio are shown. CO2 in raw exhaust gas = 5.42%, CO2 in ambient air = 420 ppm.

Table A1. Noted fuel consumption during measurement periods for the four tested engine loads. Entries to the protocol were made by crew members.

Date/Time	Fuel cons at 85% engine load (kg/h)	Date/Time	Fuel cons at 75% engine load (kg/h)	Date/Time	Fuel cons at 50% engine load (kg/h)	Date/Time	Fuel cons at 34% engine load (kg/h)
2017-02-04 11:00	1591	2017-02-01 22:05	1383	2017-02-02 22:00	1047	2017-02-03 22:00	1791*
2017-02-04 14:00	1604	2017-02-01 23:15	1159*	2017-02-02 time not noted	1030	2017-02-03 23:15	894
2017:02:04 15:00	1592	2017-02-01 01:15	1382	2017-02-02 01:53	1029	2017-02-03 01:50	762
		2017-02-01 02:45	1426	2017-02-02 02:45	1046	2017-02-03 02:50	735

*suspected misreading

Table A2. Fuel consumption during the trials at combustion of LSFO, data from the ship owner’s log.

Date/Time	Fuel cons at 85% engine load (kg/h)	Date/Time	Fuel cons at 75% engine load (kg/h)	Date/Time	Fuel cons at 50% engine load (kg/h)	Date/Time	Fuel cons at 34% engine load (kg/h)
2017-02-04 11:09	1506.00	2017-02-01 22:09	1355.00	2017-02-02 21:59	964.00	2017-02-03 22:09	880.00
2017-02-04 11:19	1520.00	2017-02-01 22:19	1347.00	2017-02-02 22:09	973.00	2017-02-03 22:19	855.00
2017-02-04 11:29	1517.00	2017-02-01 22:29	1321.00	2017-02-02 22:19	975.00	2017-02-03 22:29	845.00
2017-02-04 11:39	1515.00	2017-02-01 22:39	1316.00	2017-02-02 22:29	980.00	2017-02-03 22:39	948.00
2017-02-04 11:49	1519.00	2017-02-01 22:49	1318.00	2017-02-02 22:39	994.00	2017-02-03 22:49	830.00
2017-02-04 11:59	1516.00	2017-02-01 22:59	1348.00	2017-02-02 22:49	980.00	2017-02-03 22:59	859.00
2017-02-04 12:09	1522.00	2017-02-01 23:09	1334.00	2017-02-02 22:59	996.00	2017-02-03 23:09	848.00
2017-02-04 12:19	1536.00	2017-02-01 23:19	1333.00	2017-02-02 23:09	999.00	2017-02-03 23:19	863.00
2017-02-04 12:29	1534.00	2017-02-01 23:29	1334.00	2017-02-02 23:19	978.00	2017-02-03 23:29	875.00
2017-02-04 12:39	1501.00	2017-02-01 23:39	1339.00	2017-02-02 23:29	975.00	2017-02-03 23:39	834.00
2017-02-04 12:49	1539.00	2017-02-01 23:49	1325.00	2017-02-02 23:39	999.00	2017-02-03 23:49	869.00
2017-02-04 12:59	1540.00	2017-02-01 23:59	1347.00	2017-02-02 23:49	977.00	2017-02-03 23:59	837.00
2017-02-04 13:09	1558.00	2017-02-02 00:09	1331.00	2017-02-02 23:59	960.00	2017-02-04 00:09	850.00
2017-02-04 13:19	1519.00	2017-02-02 00:19	1311.00	2017-02-03 00:09	989.00	2017-02-04 00:19	838.00
2017-02-04 13:29	1564.00	2017-02-02 00:29	1311.00	2017-02-03 00:19	965.00	2017-02-04 00:29	830.00
2017-02-04 13:39	1531.00	2017-02-02 00:39	1334.00	2017-02-03 00:29	991.00	2017-02-04 00:39	793.00
2017-02-04 13:49	1532.00	2017-02-02 00:49	1312.00	2017-02-03 00:39	977.00	2017-02-04 00:49	798.00
2017-02-04 13:59	1517.00	2017-02-02 00:59	1353.00	2017-02-03 00:49	976.00	2017-02-04 00:59	810.00
2017-02-04 14:09	1531.00	2017-02-02 01:09	1346.00	2017-02-03 00:59	966.00	2017-02-04 01:09	788.00
2017-02-04 14:19	1496.00	2017-02-02 01:19	1351.00	2017-02-03 01:09	983.00	2017-02-04 01:19	742.00
2017-02-04 14:29	1527.00	2017-02-02 01:29	1325.00	2017-02-03 01:19	1003.00	2017-02-04 01:29	738.00
2017-02-04 14:39	1486.00	2017-02-02 01:39	1342.00	2017-02-03 01:29	968.00	2017-02-04 01:39	724.00
2017-02-04 14:49	1522.00	2017-02-02 01:49	1341.00	2017-02-03 01:39	1001.00	2017-02-04 01:49	732.00
2017-02-04 14:59	1045.00	2017-02-02 01:59	1318.00	2017-02-03 01:49	984.00	2017-02-04 01:59	726.00
2017-02-04 15:09	2501.00	2017-02-02 02:09	1328.00	2017-02-03 01:59	966.00	2017-02-04 02:09	736.00
		2017-02-02 02:19	1378.00	2017-02-03 02:09	989.00	2017-02-04 02:19	711.00
		2017-02-02 02:29	1345.00	2017-02-03 02:19	992.00	2017-02-04 02:29	747.00
		2017-02-02 02:39	1366.00	2017-02-03 02:29	973.00	2017-02-04 02:39	725.00
		2017-02-02 02:49	1332.00	2017-02-03 02:39	977.00	2017-02-04 02:49	707.00
Average	**1544**		**1336**		**981**		**805**

Table A3. Engine parameters at trials using LSFO.

The parameters used in calculation of emission factors are marked in bold and calculated values are in italics. For all calculations, average values on relevant parameters are calculated from the three or four entries made at each steady state engine load.

Date	2017-02-04	2017-02-04	2017-02-04	01-feb	02-feb	02-feb	2017-02-02	2017-02-02	2017-02-03	2017-02-03	2017-02-03	2017-02-03	2017-02-04	2017-02-04
Time	11:00	14:00	15:00	22:05	01:15	02:45	22:00		01:53	02:45	22:00	23:15	01:50	02:50
Engine ID	ME4	ME4	ME4	ME 4	ME 4	ME 4	ME4	ME4	ME4	ME4	ME4	ME4	ME4	ME4
Power load (%)	**85%**	**85%**	**85%**	**75%**	**75%**	**75%**	**50%**	**50%**	**50%**	**50%**	**36%**	**36%**	**30%**	**n.a.**
Approximate loss at gearbox	**3%**	**3%**	**3%**	**3%**	**3%**	**3%**	**3%**	**3%**	**3%**	**3%**	**3%**	**3%**	**3%**	**3%**
inlet air temp (°C)														
1	20.1	19.1	18.8	23.9	23.1	20.9	23	20.8	25.6	20.9	19.3	20.6	19.3	18
2	20.3	19.9	20.1	19.9	20.3	20.6	21.5	19.5	21.1	21.5	17.7	18.4	17.4	18.8
3	22.7	25.3	21.7	19.7	21.4	21.4	22.5	24	23.6	20.3	21	20.5	19.8	18
4	21.3	22.3	23	30.9	30.1	27.6	22.6	30.9	31	28.2	26.2	26.3	23.5	21.7
Average	***21.1***	***21.7***	***20.9***	***23.6***	***23.7***	***22.6***	***22.4***	***23.8***	***25.3***	***22.7***	**21.1**	**21.5**	**20.0**	**19.1**
Inlet air Relative Humidity (%)														
1	36.5	37.8	37.2	33.6	35.6	40.6	33	39.4	31.1	37.9	38.4	35.6	30.1	37
2	37.3	36.6	36.4	42.9	37.7	36.7	40.6	43.2	41.8	36.9	42.2	40.7	38.2	33.6
3	32.6	29.2	31.3	40	38.3	42.1	40.5	35.5	43.6	44.1	36.7	38.5	35.2	39.2
4	29.8	26.7	27.3	23.9	25.1	28.2	33.7	25.3	26	30.1	26.8	26.3	29	29.7
Average	***34.1***	***32.6***	***33.1***	***35.1***	***34.2***	***36.9***	***37.0***	***35.9***	***35.6***	***37.3***	**36.0**	**35.3**	**33.1**	**34.9**

*The values in the protocol are not used. Instead, average fuel consumption log from the ship owner’s office is be used.

Table A4. Overview of sampling details for Teflon filters sampled for gravimetric analyses at tests using LSFO.

Filter reference number //Notes	Engine load	T at filter (°C)	Dilution system	DR	Start	Stop	Mass unexposed (g)	Mass exposed (g)	Mass exposed-unexposed (g)	Volume in	Volume out	Volume in-out (m3)	Notes Lab	Conc before dilution (g/m3)
1// Stena Brittanica PM2,5 NOR 100	75%	29°C	DT	15.9	2017-02-02 00:10	2017-02-02 01:56	0.309035	0.309545	0.000510	3944.057	3944.503	0.44600		0.018
2// Stena Brittanica TSP NOR 200	75%	29°C	DT	15.9	2017-02-02 00:10	2017-02-02 01:56	0.313712	0.314669	0.000957	5603.5	5604.307	0.80700	grease	0.019
3// Stena Brittanica PM2,5 NOR 101	75%	n.a.	DT	16.3	2017-02-02 02:40	2017-02-02 03:20	0.318938	0.31941	0.000472	3944.499	3944.87	0.37100		0.021
4// Stena Brittanica TSP NOR 201	75%	n.a.	DT	16.3	2017-02-02 02:40	2017-02-02 03:20	0.323035	0.324091	0.001056	5604.307	5605.093	0.78550		0.022
5// Stena Brittanica TSP NOR 202	50%	33°C	DT	16.7	2017-02-02 22:38	2017-02-03 12:13	0.308473	0.309376	0.000903	5605.658	5606.226	0.56750		0.027
6// Stena Brittanica PM2,5 NOR 102	50%	33°C	DT	16.7	2017-02-02 22:38	2017-02-03 23:13	0.309636	0.310141	0.000505	3945.171	3945.499	0.32750		0.026
7// Stena Brittanica PM2,5 NOR 103	50%	33°C	DT	16.8	2017-02-02 23:52	2017-02-03 00:28	0.307158	0.307568	0.000410	3945.499	3945.792	0.29300		0.024
8// Stena Brittanica TSP NOR 203	50%	33°C	DT	16.8	2017-02-02 23:52	2017-02-03 00:28	0.316504	0.317358	0.000854	5606.226	5606.851	0.62500		0.023
9//Stena Brittanica PM2,5 NOR 106	34%	29°C	DT	20.2	not noted	2017-02-04 00:37	0.322217	0.3225	0.000283	3947.363	3947.707	0.34450		0.017
10// Stena Brittanica TSP NOR 206	34%	29°C	DT	20.2	not noted	2017-02-04 00:37	0.318158	0.31868	0.000522	5609.8	5610.455	0.65500	grease	0.016
11// Stena Brittanica PM2,5 NOR 104 -air-	n.a.	n.a.	DT	n.a	2017-02-03 22:32	2017-02-04 23:12	0.316724	0.316772	0.000048	3946.652	3946.989	0.33700		
12// Stena Brittanica TSP NOR 204 - air -	n.a.	n.a.	DT	n.a	2017-02-03 22:32	2017-02-04 23:12	0.316222	0.31633	0.000108	5608.824	5609.119	0.29450		
13// Stena Brittanica PM2,5 NOR 105 – 9.5 L/min	34%	31°C	DT	23.8	2017-02-03 23:44	2017-02-04 00:23	0.321386	0.321718	0.000332	3946.994	3947.363	0.36850		0.021
14// Stena Brittanica TSP NOR 205	34%	31°C	DT	23.8	2017-02-03 23:44	2017-02-04 00:27	0.322736	0.323392	0.000656	5609.119	5609.8	0.68150		0.023
15// Stena Brittanica PM2.5 NOR 107	85%	33°C	DT	15.9	2017-02-04 10:51	2017-02-04 11:30	0.311906	0.312392	0.000486	3948	3948	0.30250		0.026
16// Stena Brittanica TSP NOR 207	85%	33°C	DT	15.9	2017-02-04 10:51	2017-02-04 11:30	0.312565	0.3136	0.001035	5611	5612	0.63950	grease	0.026
17// Stena Brittanica PM2.5 NOR 108	85%	32.5°C	DT	16.4	2017-02-04 12:13	2017-02-04 12:53	0.317352	0.317734	0.000382	3948	3949	0.30100		0.021
18// Stena Brittanica TSP NOR 208	85%	32.5°C	DT	16.4	2017-02-04 12:13	2017-02-04 12:53	0.318687	0.319485	0.000798	5612	5613	0.70950		0.018
19// Stena Brittanica TSP NOR 209 Blank	n.a.	n.a.		n.a	2017-02-04 15:22	2017-02-04 16:07	0.316108	0.316295	0.000187	5614	5614	0.80700		
20// Stena Brittanica PM2,5 FPS 2	50%		FPS	40	2017-02-03 03:19	2017-02-03 04:18	0.319528	0.319945	0.000417	3946.159	3946.652	0.49300		0.034
21// Stena Brittanica TSP FPS 1	50%		FPS	40	2017-02-03 03:19	2017-02-03 4:18	0.315019	0.315868	0.000849	5607.735	5608.824	1.08900		0.031
22// Stena Brittanica TSP FPS 3	34%		FPS	80	2017-02-03 03:43	2017-02-04 04:21	0.318458	0.319065	0.000607	6853.162	6854.146	0.98400		0.049
23// Stena Brittanica TSP FPS 4	85%		FPS	92	2017-02-04 10:51	2017-02-04 11:30	0.310667	0.311061	0.000394	6854	6855	1.08300	wrinkly	0.033
24// Stena Brittanica TSP FPS 5	85%		FPS	82	2017-02-04 12:12	2017-02-04 12:54	0.315667	0.315965	0.000298	6855	6856	0.75600		0.079

Table A5. Details on the sampling and analyses results of the quartz filters at tests on LSFO.

Dilution ratios for each filter are given and results are presented before dilution (calculated) and after dilution (measured). Calculated values are only given for one filter per pair, condensate mass is subtracted and results are multiplied with the dilution factor.

Sample ID	**Primary /Secondary**	**Engine load**	Dilution	Exposed filter area (cm^2)	Dilution ratio	Time start	Time stop	Volume passed through filter (Nm^3)	TC [μg/m3] After dilution	**TC real [mg/m3] Before dilution**	OC [μg/m3] After dilution	**OC [mg/m3] Before dilution**	EC [μg/m3] After dilution	**EC [mg/m3] Before dilution**	Sampled mass (mg) After dilution	**Conc. PM (mg/m3) Before dilution**
QH_102	**TSP Primary**	**75%**	DT	8.55	15.7	**03:19**	**03:49**	0.566	1027	**16.1**	977	**15.3**	102.88	**0.80**	0.033	**25.1**
QH_101	***Secondary***	***75%***	*DT*	8.55	*15.7*	***03:19***	***03:49***	*0.566*	*91*		*90*		*1.02*		*0.905*	
QH_104	**PM2.5 Primary**	**75%**	DT	8.55	15.7	**03:19**	**03:49**	0.301	899	**14.1**	743	**11.7**	315.52	**2.44**	0.006	**26.2**
QH_103	***Secondary***	***75%***	*DT*	8.55	*15.7*	***03:19***	***03:49***	*0.301*	*124*		*124*		*0.13*		*0.502*	
QH_106	**TSP Primary**	**50%**	DT	8.55	16.6	**01:27**	**02:13**	0.885	1031	**17.1**	988	**16.4**	87.18	**0.71**	-0.033	**23.6**
QH_105	***Secondary***	***50%***	*DT*	8.55	*16.6*	***01:27***	***02:13***	*0.885*	*75*		*75*		*0.11*		*1.257*	
QH_108	**PM2.5 Primary**	**50%**	DT	8.55	16.6	**01:27**	**02:13**	0.368	846	**14.0**	805	**13.4**	82.77	**0.68**	0.056	**23.5**
QH_107	***Secondary***	***50%***	*DT*	8.55	*16.6*	***01:27***	***02:13***	*0.368*	*94*		*94*		*0.07*		*0.520*	
QH_110	**PM2.5 Primary**	**34%**	DT	8.55	20.1	**02:27**	**03:12**	0.417	1033	**20.8**	994	**20.0**	79.93	**0.79**	0.043	**32.1**
QH_109	***Secondary***	***34%***	*DT*	8.55	*20.1*	***02:27***	***03:12***	*0.417*	*150*		*150*		*0.02*		*0.666*	
QH_112	**TSP Primary**	**34%**	DT	8.55	20.1	**02:27**	**03:12**	0.870	1181	**23.7**	1140	**22.9**	83.77	**0.83**	0.026	**41.2**
QH_111	***Secondary***	***34%***	*DT*	8.55	*20.1*	***02:27***	***03:12***	*0.870*	*130*		*116*		*27.24*		*1.785*	
QH_114	**TSP Primary**	**34%**	FPS	13.2	71.9	**02:27**	**03:12**	1.358	656	**47.2**	638	**45.8**	24.23	**1.33**	1.118	**59.2**
QH_113	***Secondary***	***34%***	*FPS*	13.2	*71.9*	***02:27***	***03:12***	*1.358*	*119*		*119*		*0.08*		*0.132*	
QH_116	**TSP Primary**	**85%**	DT	8.55	22.8	**13:35**	**14:24**	0.935	821	**18.7**	788	**18.0**	68.23	**0.77**	-0.170	**27.0**
QH_115	***Secondary***	***85%***	*DT*	8.55	*22.8*	***13:35***	***14:24***	*0.935*	*82*		*80*		*3.01*		*1.107*	
QH_118	**PM2.5 Primary**	**85%**	DT	8.55	22.8	**13:35**	**14:24**	0.374	641	**14.6**	605	**13.8**	73.48	**0.83**	0.057	**20.6**
QH_117	***Secondary***	***85%***	*DT*	8.55	*22.8*	***13:35***	***14:24***	*0.374*	*157*		*157*		*-0.05*		*0.339*	
QH_120	**TSP Primary**	**85%**	FPS	13.2	83.9	**13:35**	**14:24**	1.451	209	**17.5**	201	**16.9**	10.39	**0.66**	0.128	**33.7**
QH_119	***Secondary***	***85%***	*FPS*	13.2	*83.9*	***13:35***	***14:24***	*1.451*	*106*		*106*		*0.14*		*0.583*	

Table A6. Analysis of S on filters sampled at LSFO combustion, upstream and downstream the scrubber. Calculated share of sulphur on particles.

Filter no	S (µg/ sample)	Engine load (%)	Volume/ sample (nm3)	DR	S µg/m3	PM conc on filter (µg/m3)	S share of PM tot
11	0.048	Surrounding air	0.337	n.a.	0.1	n.a.	n.a.
5	1.1	0.5	0.5675	16.7	31.2	27000	0.12%
14	1.2	0.35	0.6815	23.8	42.6	23000	0.19%
19	4.9	0.75	0.807	16.3	99.8	19000	0.53%
16	7.7	0.85	0.6395	16.4	197.0	26000	0.76%

Table A7. Metal concentrations from particle sampling. Correction made for dilution with a factor of 16.3 for filter no 4, and 23.8 for filter no 13.

Sample (see filter numbers in Table)	Engine load	V	Ni	Fe	Al	Co	Ba	Mn	Zn	Cr	Sr	Cd	Cu	As	Se	Pb	Mo	P	Si	Li	S
		ng/m³	ng/m³	ng/m³	ng/m³	ng/m³	ng/m³	ng/m³	ng/m³	ng/m³	ng/m³	ng/m³	ng/m³	ng/m³	ng/m³	ng/m³	ng/m³	ng/m³	ng/m³	ng/m³	ng/m³
Filter no 4	75%	8 150	211 900	179 300	24 450	29 340	30 970	44 010	138 550	2 282	10 758	440 100	146 700	2 445	1 157	6 357	-	-	-	-	-
Filter no 13	34%	4 998	142 800	88 060	-	18 326	20 706	26 180	-	2 618	6 664	1 689	-	1 570	761	-	-	-	-	-	-
Filter no 12	Surrounding air	190	890	10 000	9 700	20	100	240	53 000	1 600	17	24 000	8 600	-	-	540	-	-	-	-	-

Table A81. Values on input parameters for calculation of dry/wet correction factor, exhaust flow using the carbon balance method, NOx correction factor for ambient conditions, gaseous emissions, and particulate emissions. The Table contains calculated values as well as constants used and data on engine performance. Emission factors are marked in coloured cells with bold text.

Date/Test	**170204**	**170201-170202**	**170202-170203**	**170203-170204**
Sulphur content of fuel	0.100	0.100	0.101	0.100
MCR (100 % load), MCR of engine (brake kW) =	9600	9600	9600	9600
Load, Brake Load during test (%) =	85%	75%	50%	34%
P, Brake Power or effect during test (kW) =	8160	7200	4800	3264
Calculation of dry/wet correction factor as in annex 2.6, version 3:				
GFUEL, Fuel consumption (kg/hr) =	1524	1336	981	805
Fuel consumption (g/kWh) =	181	180	198	239
BET, Fuel Oil Carbon (%) =	86.8	86.8	86.8	86.8
ALF, Fuel Oil Hydrogen (%) =	12.9	12.9	12.9	12.9
wDEL_G, Fuel Gas Nitrogen (%)	0.2	0.2	0.2	0.2
wEPS_G, Fuel Gas Oxygen (%)	0.1	0.1	0.1	0.1
CO2D, Measured CO2 dry (%) =	5.4	5.4	5.5	5.7
Ra, Relative humidity of inlet air (%) =	33	35	36	35
pB, Barometric Pressure of inlet air (kPa) =	101.3	101.3	101.3	101.3
Ta, Temperature of inlet air (oC) =	21.22	23.32	23.56	20.41
pa, Saturated Vapour press. of inlet air (kPa)* =	2.52	2.86	2.91	2.40
Ha, Humidity of inlet air (g H2O/kg dry air) =	5.18	6.29	6.57	5.17
ALPHA	1.77	1.77	1.77	1.77
cH2d	0.00058	0.00068	0.00107	0.00105
kw2	0.00284	0.00284	0.00284	0.00284
NUE, Water content of inlet air (% mass) =	0.516	0.625	0.653	0.514
Kwr3, dry/wet corr. factor in raw gas =	0.959	0.959	0.958	0.957
H2O in raw exhaust gas (%) =	4.11	4.05	4.19	4.31
Calculation of exhaust flow using Carbon balance in annex 2.2:				
GFUEL, Fuel consumption (kg/hr) =	1524	1336	981	805
BET, Fuel Oil Carbon (%) =	86.8	86.8	86.8	86.8
CO2D, Measured CO2 dry (%) =	5.42	5.35	5.52	5.66
Kwr3, dry/wet corr. factor in raw gas =	0.946	0.945	0.944	0.945
ffd, fuel-spec. constant (-H+N+O %) dry gas	-0.714919	-0.715	-0.715	-0.715
ffw, fuel-spec.constant (H+N+O%) wet gas	0.719	0.719	0.719	0.719
fc, carbon factor	2.93	2.89	2.99	3.063167
Qmew, Exhaust mass flow wet (kg/h)	61553	54658	38968	31158
Qmaw, Intake air mass flow wet (kg/h)	60029	53322	37987	30353
ρ_{ew}, Exhaust density wet (kg/m3)	1.280	1.280	1.280	1.280
Qvew, Exhaust volume flow wet (m3/h)	48094	42730	30475	24352
Calculation of NOx correction factor for ambient conditions as in clause 13.3 version b) & other IMO parameters:				
HREF, Ref. value of humidity set by ISO =	10.71	10.71	10.71	10.71
Ha, Humidity of the inlet air (g H2O/kg dry air) =	5.18	6.29	6.57	5.17
Ta, Temperature of the inlet air (deg. K) =	294	296	297	293
TSC, Temperature of the intercooled air (deg. K) =	321	319	315	313
TSCRef, Intercooled air ref. temp. {ISO 3046-1} (deg. K)	298	298	298	298
KHDIES, NOx corr. fact. for diesel with air cooler =	0.91	0.93	0.94	0.91
Dry atmospheric pressure, Ps (kPa) =	100.5	100.3	100.2	100.5
Atmospheric factor (fa) =	0.971	0.983	0.984	0.967

Table A8 contd. Calculation of gaseous emissions:

	85%	75%	50%	34%
Measured CO2 dry (%) =	5.42	5.35	5.52	5.66
Measured O2 dry (%) =	13.3	13.6	13.3	13.1
Measured CO dry (ppm) =	59.7	74.2	115	108
Measured NOx dry (ppm) =	1223	962	1087	1259
MEasured SO2 (ppm)	15.6	13.4	15.6	18.7
Measured SO3	0	0	0	0
Measured THC wet (ppm) =	65.1	No data	77.0	98.5
Measured nmHC wet (ppm) =	64.6	No data	76.4	97.7
Measured CH4 wet (ppm) =	0.50	No data	0.58	0.77
Qvew, Exhaust volume flow wet (m3/h)	48094	42730	30475	24352
Kwr3, dry/wet corr. factor in raw gas =	0.959	0.959	0.958	0.957
KHDIES, NOx corr. fact. for diesel with air cooler =	0.91	0.93	0.94	0.91
P, Power or effect during test (kW) =	8160	7200	4800	3264
Constants used: (divide with density 1.280 to have w)				
KwCO2, factor for CO2 to convert % to g/nm3 wet = 19.64				
KwO2, factor for O2 to convert % to g/nm3 wet = 14.29				
KwCO, factor for CO to convert ppm to g/nm3 wet =0.00125				
KwNOx, factor for NOx to convert ppm to g/nm3 wet =0.002053				
KwSO2 factor for SO2 to convert ppm to g/nm3 wet = 0.00291				
KwHC, factor for HC to convert ppmC to gHC/nm3 wet =0.000619				
CO2, Mass flow (kg/hr) =	4848	4250	3120	2560
O2, Mass flow (kg/hr) =	8687	7861	5480	4322
CO, Mass flow (kg/hr) =	3.4	3.8	4.2	3.1
NOx, Mass flow (kg/hr) =	114.4	79.9	64.2	59.5
SO2, Mass flow (kg/hr) =	2.1	1.6	1.3	1.3
SO3, Mass flow (kg/hr=	0	0	0	0
THC, Mass flow (kg/hr) =	1.9	n.d.	1.5	1.5
nmHC, Mass flow (kg/hr) =	1.9	n.d.	1.4	1.5
CH4, Mass flow (kg/hr) =	0.0015	n.d.	0.011	0.012
Calculated emission factors:				
CO2 Specific emission (g/kWh) =	**601**	**598**	**659**	**793**
O2 Specific emission (g/kWh) =	**1078**	**1106**	**1157**	**1339**
CO Specific emission (g/kWh) =	**0.42**	**0.53**	**0.88**	**0.96**
NOx Specific emission (g/kWh) =	**12.96**	**10.46**	**12.68**	**16.84**
NOx Specific emission (g/kWh) (corrected) =	**11.84**	**9.73**	**11.85**	**15.38**
SO2 Specific emission measured (g/kWh) =	**0.26**	**0.22**	**0.28**	**0.39**
SO2 Specific emission calculated (g/kWh)	**0.36**	**0.36**	**0.40**	**0.48**
SO3 Specific emission (g/kWh) =	**b.d-l.**	**b.d-l.**	**b.d-l.**	**b.d-l.**
THC Specific emission (g/KWh) =	**0.24**	**n.d.**	**0.30**	**0.45**
nmHC Specific emission (g/kWh)=	**0.24**	**n.d.**	**0.30**	**0.45**
CH4 Specific emission (g/kWh)=	**0.0018**	**n.d.**	**0.0023**	**0.0035**

Table A8 contd. Calculation of particulate emissions (numbers in parenthesis indicate filter number with reference to Table):

	85%	75%	50%	34%
KP, PM corr. fact. (when 0,98 < fa < 1,02) =	1.08	1.00	1.00	1.08
P, Brake Power or effect during test (kW) =	8160	7200	4800	3264
Qvew, Exhaust volume flow wet (m3/h)	48094	42730	30475	24352
PMtot, Dilution = DT (g/m3)=	0.026 (15)	0.019 (2)	0.027 (5)	0.016 (10)
PMtot, Dilution = DT (g/m3)=	0.018 (18)	0.022 (4)	0.023 (8)	0.023 (14)
PMtot, Dilution = DT (g/m3)=				
PMtot, Dilution = FPS (g/m3)=	0.033 (23)		0.031 (21)	0.049 (22)
PMtot, Dilution = FPS (g/m3)=	0.032 (24)			
PM+cyclone, Dilution = DT (g/m3)=	0.026 (16)	0.018 (1)	0.026 (6)	0.017 (9)
PM+cyclone, Dilution = DT (g/m3)=	0.020 (17)	0.021 (3)	0.024 (7)	0.021 (13)
PM+cyclone, Dilution = FPS (g/m3)=			0.034 (20)	
PMtot, Dilution = DT (g/hr)=	1238 (15)	803 (2)	810 (5)	392 (10)
PMtot, Dilution = DT (g/hr)=	887 (18)	936 (4)	700 (8)	557 (14)
PMtot, Dilution = DT (g/hr)=				
PMtot, Dilution = FPS (g/hr)=	1610 (23)		950 (21)	1195 (22)
PMtot, Dilution = FPS (g/hr)=	1545 (24)			
PM+cyclone, Dilution = DT (g/hr)=	1268 (16)	775 (1)	785 (6)	404 (9)
PM+cyclone, Dilution = DT (g/hr)=	972 (17)	886 (3)	717 (7)	521 (13)
PM+cyclone, Dilution = FPS (g/hr)=			1031 (20)	
PMtot Specific emission, Dilution = DT (g/kWh)	**0.16 (15)**	**0.11 (2)**	**0.17 (5)**	**0.13 (10)**
PMtot Specific emission, Dilution = DT (g/kWh)	**0.12 (18)**	**0.13 (4)**	**0.15 (8)**	**0.18 (14)**
PMtot Spec. emission, Dilution = FPS (g/kWh)	**0.20 (23)**		**0.20 (21)**	**0.37 (22)**
PMtot Spec. emission, Dilution = FPS (g/kWh)=	**0.19 (24)**			
PM + cyclone spec. emission, Dilution = DT (g/kWh)	**0.17 (16)**	**0.11 (1)**	**0.16 (6)**	**0.13 (9)**
PM + cyclone Spec. emission, Dilution = DT (g/kWh)	**0.13 (17)**	**0.12 (4)**	**0.15 (7)**	**0.17 (13)**
PM + cyclone Spec. emission, Dilution = FPS (g/kWh)			**0.21 (20)**	

Table A8 contd. Calculation of particulate emissions from quartz filter, EC, and OC emission factors, BC emissions and PAH emissions

	85%	75%	50%	34%
Qvew, Exhaust volume flow wet (m3/h)	48094	42730	30475	24352
P, Brake Power or effect during test (kW)	8160	7200	4800	3264
Concentration PMtot, Dilution with tunnel (g/m3)	0.027	0.0251	0.0236	0.0412
Concentration PMtot, Dilution with FPS (g/m3)	0.0337			0.0592
Concentration PM (size cutoff with cyclone) Dilution with tunnel (g/m3)	0.0206	0.0262	0.0235	0.0321
Mass flow, PMtot Dilution with tunnel (g/hr)	1299	1073	719	1003
Mass flow PMtot, Dilution with FPS (g/hr)	1621	n.a.	n.a.	1442
Mass flow PM (size cutoff with cyclone) Dilution with tunnel (g/hr)	991	1120	716	782
PMtot Specific emission from quartz filters, Dilution with tunnel **(g/kWh)**	**0.17**	**0.15**	**0.15**	**0.33**
PMtot Spec. emission from quartz filters, Dilution with FPS **(g/kWh)**	**0.20**	**n.a.**	**n.a.**	**0.44**
PM (size cutoff with cyclone) from quartz filters, Dilution with tunnel **(g/kWh)**	**0.13**	**0.16**	**0.15**	**0.26**
Concentration TC, Dilution with tunnel (g/m3)=	0.0187	0.0161	0.0171	0.0237
Concentration TC, Dilution with FPS (g/m3)=	0.0175	n.a.	n.a.	0.0470
Concentration TC (size cutoff with cyclone), Dilution with tunnel (g/m3)	0.0146	0.0141	0.0140	0.0208
Mass flow TC(g/hr), Dilution with tunnel	901	689	522	578
Mass flow TC (g/hr), Dilution with FPS	843	n.a.	n.a.	1148
Mass flow TC (size cutoff with cyclone) (g/hr), Dilution with tunnel	703	603	428	506
TC Specific emission, Dilution with tunnel (g/kWh)	**0.116**	**0.093**	**0.106**	**0.186**
TC Spec. emission, Dilution with FPS (g/kWh)	**0.100**	**n.a.**	**n.a.**	**0.342**
TC spec. emission (size cutoff with cyclone), Dilution with tunnel (g/kWh)	**0.090**	**0.081**	**0.087**	**0.162**
Concentration OC, Dilution with tunnel (g/m3)	0.0180	0.0153	0.0164	0.0229
Concentration OC, Dilution with FPS (g/m3)	0.0138	n.a.	n.a.	0.0458
Concentration OC, (size cutoff with cyclone), Dilution with tunnel (g/m3)	0.0169	0.0117	0.0134	0.0200
Mass flow OC(g/hr), Dilution with tunnel	864	655	500	558
Mass flow OC (g/hr), Dilution with FPS	812	n.a.	n.a.	1116
Mass flow OC (size cutoff with cyclone) (g/hr), Dilution with tunnel	663	499	407	486
OC Specific emission, Dilution in tunnel (g/kWh)	**0.111**	**0.088**	**0.101**	**0.179**

OC Spec. emission, Dilution with FPS (g/kWh)	**0.079**	**n.a.**	**n.a.**	**0.332**
OC spec. emission (size cutoff with cyclone), Dilution in tunnel (g/kWh)	**0.104**	**0.067**	**0.082**	**0.156**
Concentration EC, Dilution with tunnel (g/m3)	0.00077	0.00080	0.00071	0.00083
Concentration EC, Dilution with FPS (g/m3)	0.00066	n.a.	n.a.	0.00133
Concentration EC, (size cutoff with cyclone), Dilution with tunnel (g/m3)	0.00083	0.00244	0.00068	0.00079
Mass flow EC(g/hr), Dilution with tunnel	37	34	22	20
Mass flow EC (g/hr), Dilution with FPS	32	n.a.	n.a.	32
Mass flow EC (size cutoff with cyclone) (g/hr), Dilution with tunnel	40	104	21	19
EC Specific emission, Dilution in tunnel (g/kWh)	**0.0047**	**0.0046**	**0.0044**	**0.0065**
EC Spec. emission, Dilution in FPS (g/kWh)	**0.0038**	**n.a.**	**n.a.**	**0.0096**
EC spec. emission (size cutoff with cyclone), Dilution in tunnel (g/kWh)	**0.0051**	**0.0141**	**0.0042**	**0.0062**

Table A8 contd. Calculation of BC emissions. Dilution with FPS.

	85%	75%	50%	34%
Qvew, Exhaust volume flow wet (m3/h)	48094	42730	30475	24352
P, Brake Power or effect during test (kW)	8160	7200	4800	3264
Concentration BC (g/m3)	0.0010	0.0006	0.0016	0.0015
Concentration BC using Thermodenuder	0.000582-0.000732			0.000875-0.001100
Mass flow BC (g/hr)	49.0	27.6	48.5	37.0
Mass flow BC using thermodenuder (g/hr)	28-35			21-27
BC Spec emission (g/kWh)	**0.006**	**0.004**	**0.010**	**0.012**
BC Spec emission using thermodenuder (g/kWh)	**0.0037-0.0047**			**0.0071-0.0089**

Table A81 contd. Calculation of PAH (sum USEPA 16 PAH) emissions

	85%	75%	50%	34%
P, Brake Power or effect during test (kW)	8160	7200	4800	3264
Qvew, Exhaust volume flow wet (m3/h)	48094	42730	30475	24352
PM from PAH filter (g/m3)	0.083	0.076	0.062	0.056
PAH (mg/m3)	0.042	0.0400	0.055	0.063
Mass flow PM from PAH filter (g/hr)	4012	3233	1884	1367
Mass flow PAH (mg/hr)	2022	1711	1678	1536
PM mass from PAH filter Spec emission (g/kWh)	0.492	0.449	0.393	0.419
PAH Spec emission (mg/kWh)	0.248	0.238	0.350	0.471

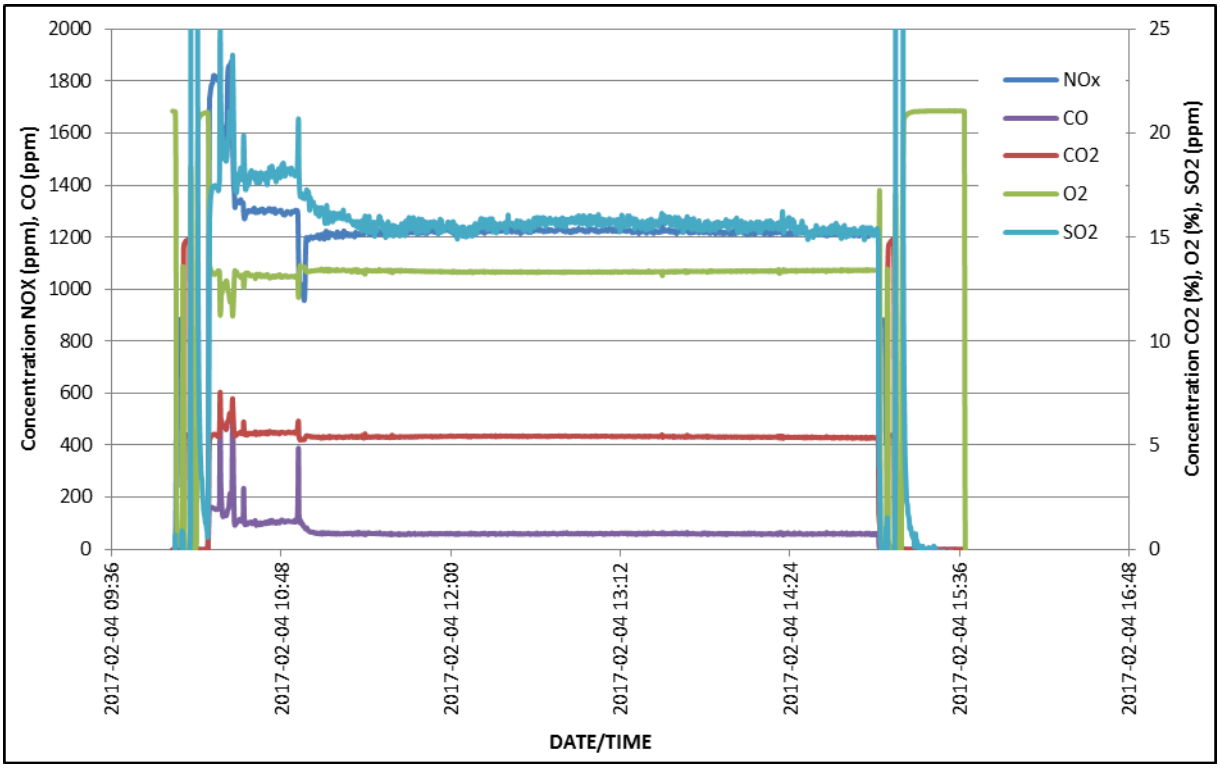


Figure A1. Gaseous emission concentrations of NOx, CO, CO₂, O₂, and SO₂ at 85% engine load at combustion of LSFO. Gas concentrations for time period 12:00 to 14:30 are used for further analysis

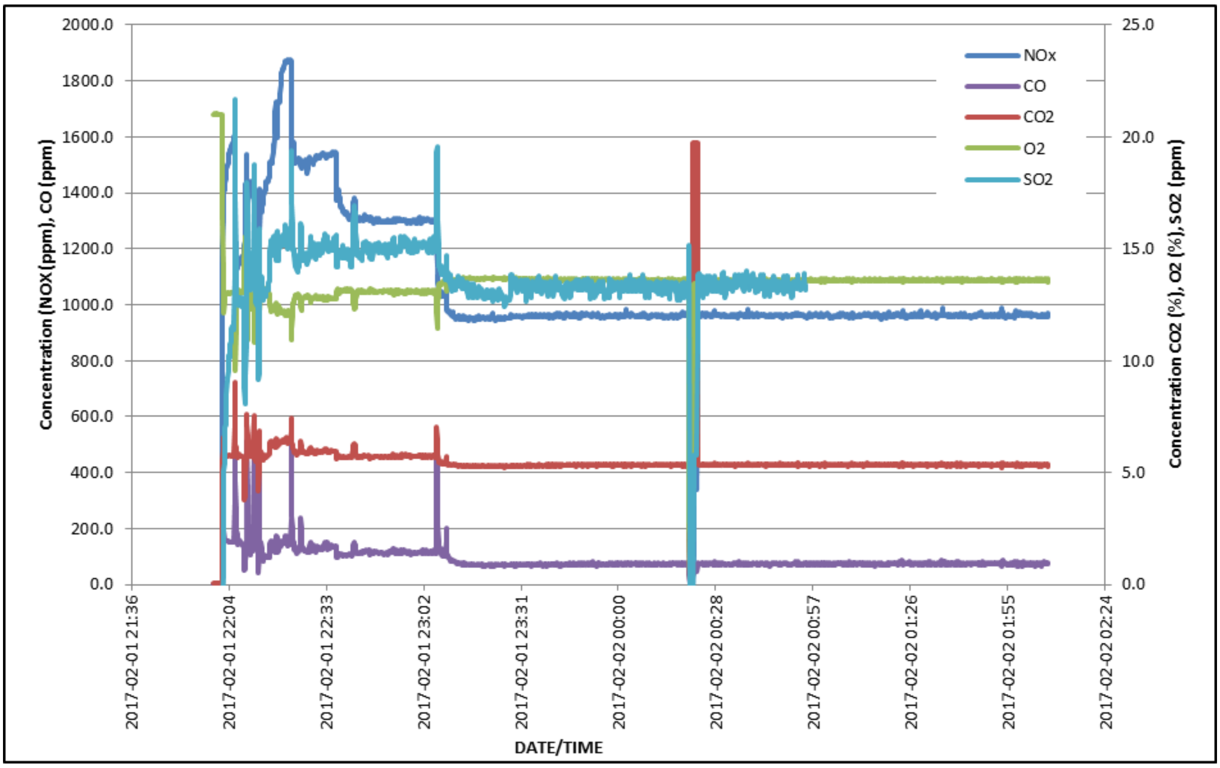
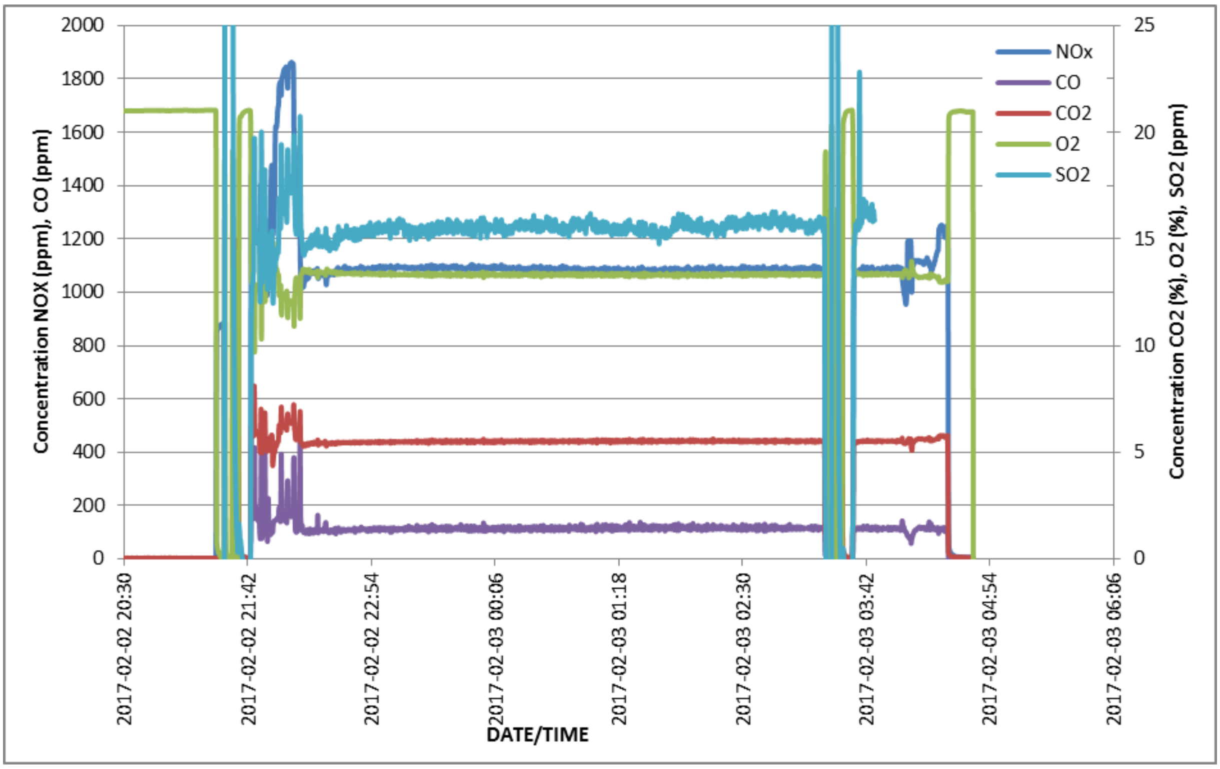
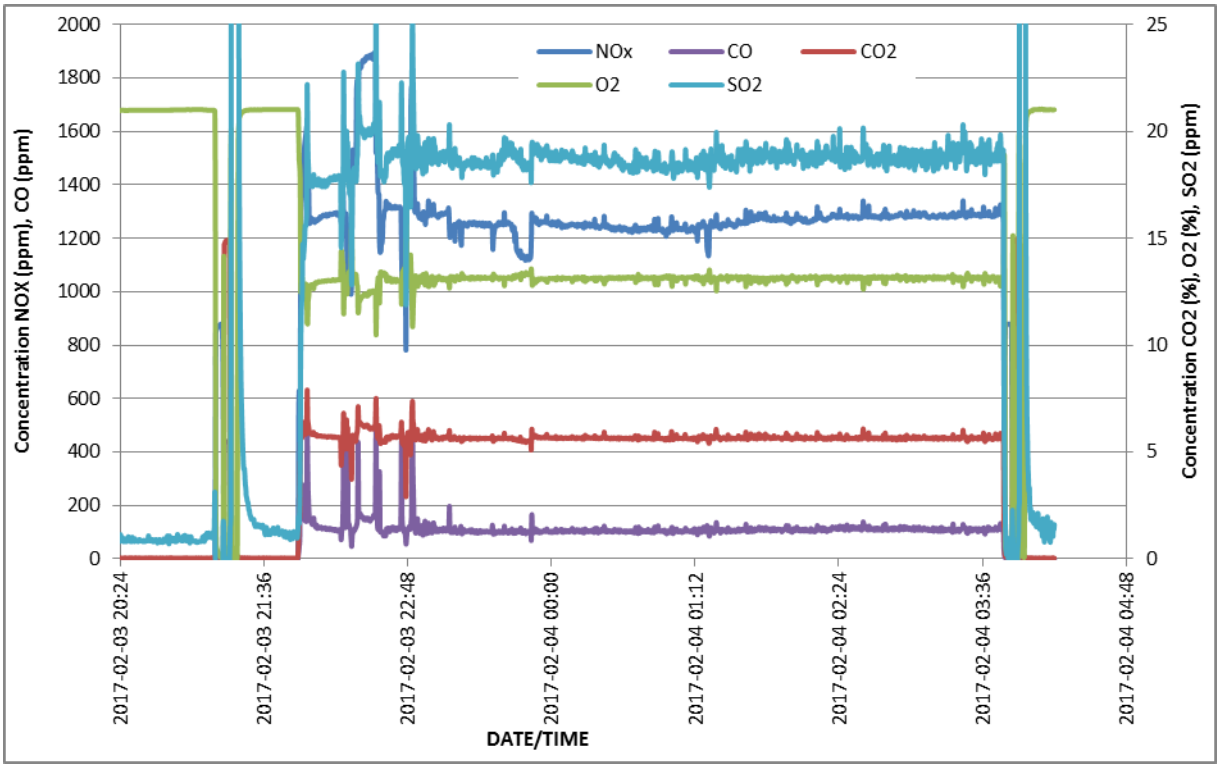


Figure A2. Gaseous emission concentrations of NOx, CO, CO₂, O₂, and SO₂ at 75% engine load at combustion of LSFO. Gas concentrations for time period 00:30 to 02:00 are used for further analysis.



FigureA3. Gaseous emission concentrations of NOx, CO, CO_2, O_2, and SO_2 at 50% engine load at combustion of LSFO. Gas concentrations for time period 00:00 to 03:00 are used for further analysis



FigureA4. Gaseous emission concentrations of NOx, CO, CO_2, O_2, and SO_2 at 34% engine load at combustion of LSFO. Gas concentrations for time period 00:00 to 03:00 are used for further analysis

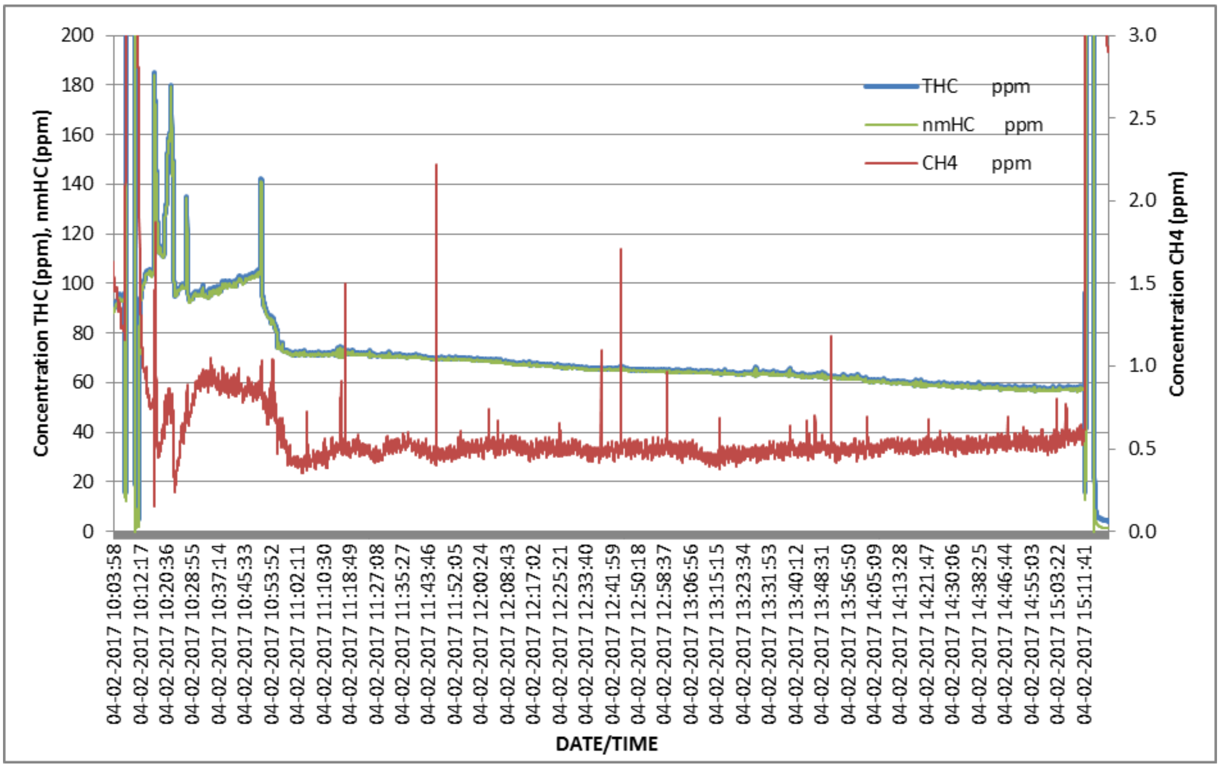


Figure A5. Hydrocarbon emission concentrations at 85% engine load at combustion of LSFO. Gas concentrations for time period 11:00 to 15:00 are used for further analysis

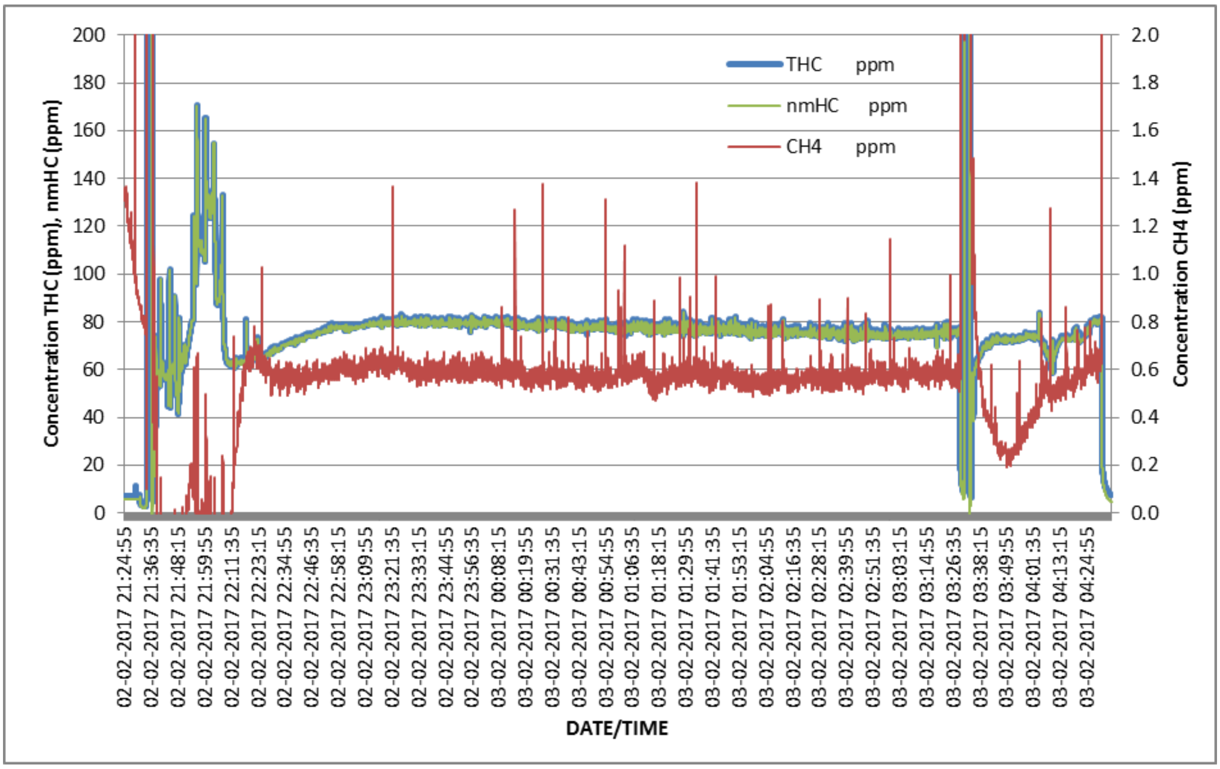


Figure A6. Hydrocarbon emission concentrations at 50 % engine load at combustion of LSFO. Gas concentrations for time period 22:20 to 03:20 are used for further analysis

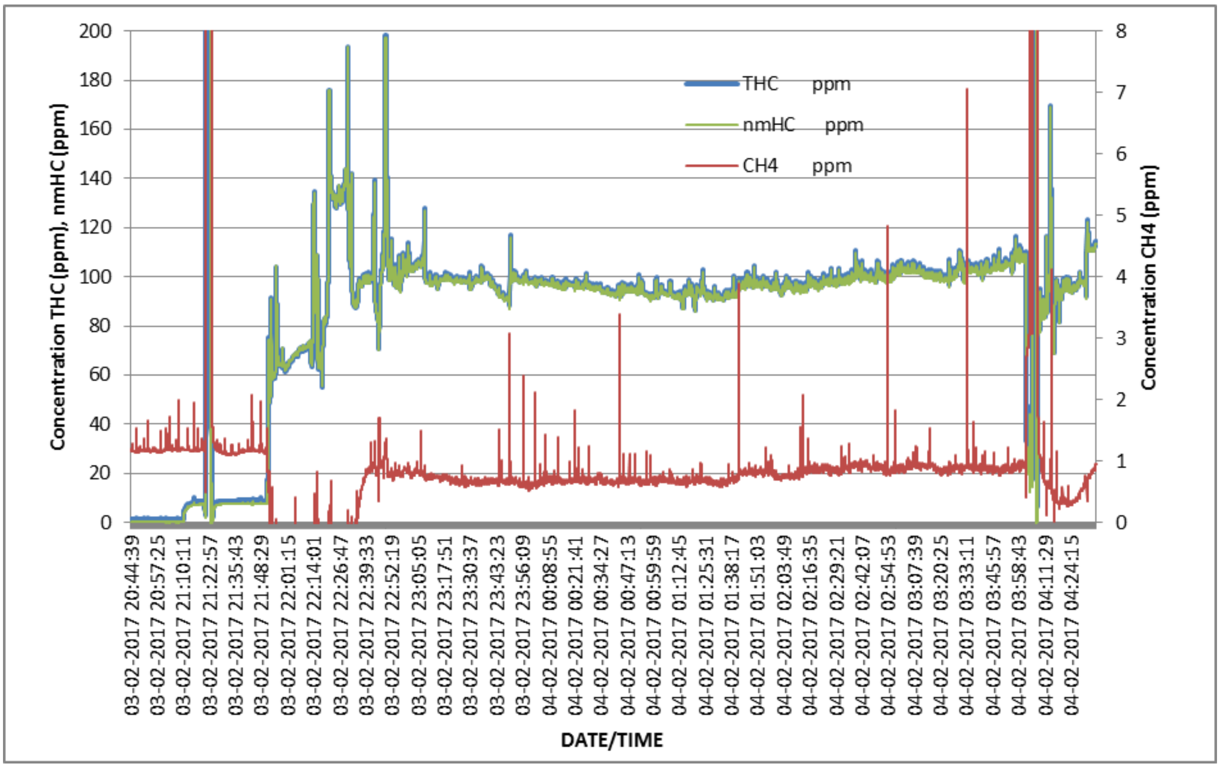


Figure A7. Hydrocarbon emission concentrations at 34% engine load at combustion of LSFO. Gas concentrations for time period 22:59 to 03:59 are used for further analysis

Figure A8 and Figure A9Figure present the dilution ratio for sampling filters 20 and 21, at 50% engine load. Figure A8Figure presents the signals from a NO_X instrument, the NO_X concentrations registered by the HORIBA and the calculated dilution ratio (DR) when NO_X is used as trace gas. Average dilution during the period is calculated to 37.5 times. Figure A9 presents values from a CO_2 instrument and the calculated DR from the same period. Average dilution during the period is calculated to 42.6 times. A dilution ratio of 40 is an average of the DRs given by the NO_X instrument and CO_2 instrument, and used for further analyses of results.

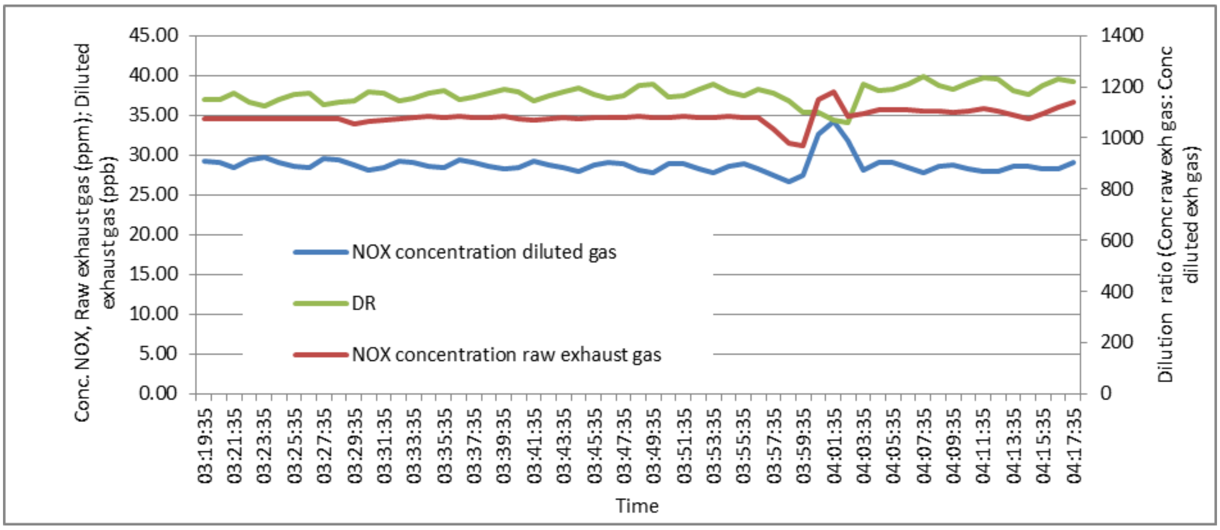


Figure A8. Dilution for sampling of filter 20 and 21, at 50% engine load. Concentrations of NO_X in diluted and undiluted gas.

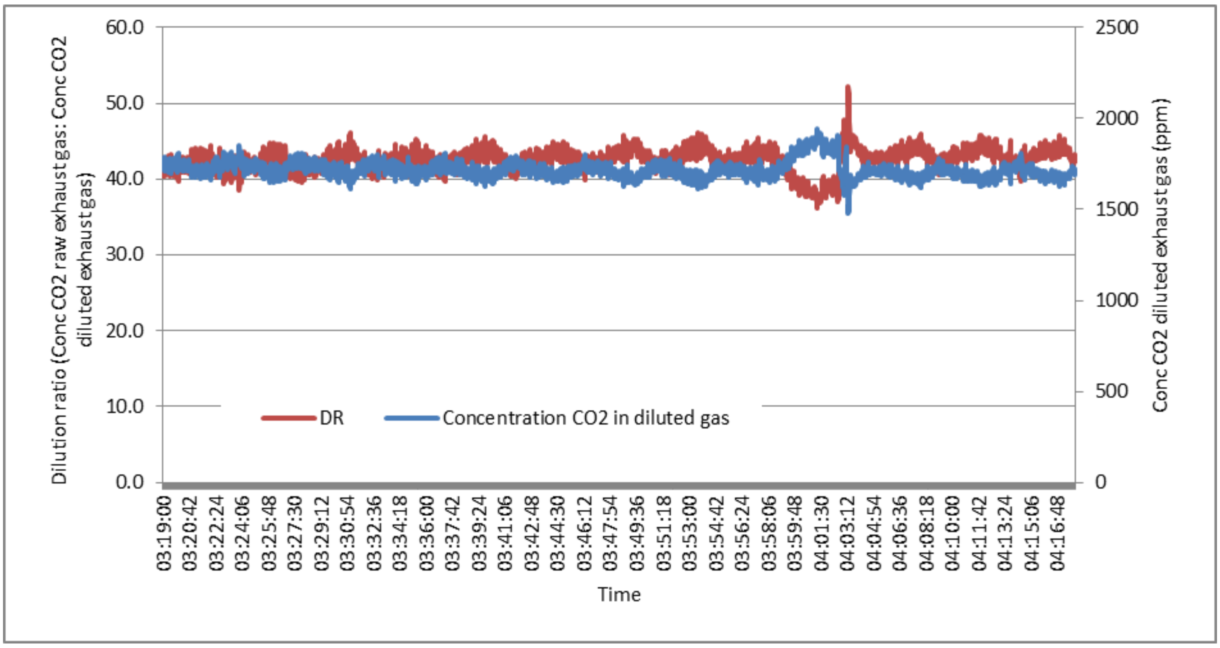


Figure A9. Dilution for sampling of filter 20 and 21, 50% engine load Concentrations of CO_2 in diluted gas and dilution ratio are shown. CO_2 in raw exhaust gas = 5.518%, CO_2 in ambient air = 420 ppm.

Figure A10Figure presents the dilution for sampling filter 22, at 34% engine load. CO_2 is used as trace gas. Average dilution during the period is calculated to 80 times. The time period between 03:47 and 04:08 is not included in the average due to several disturbances from removing the tube to the CO_2 instrument.

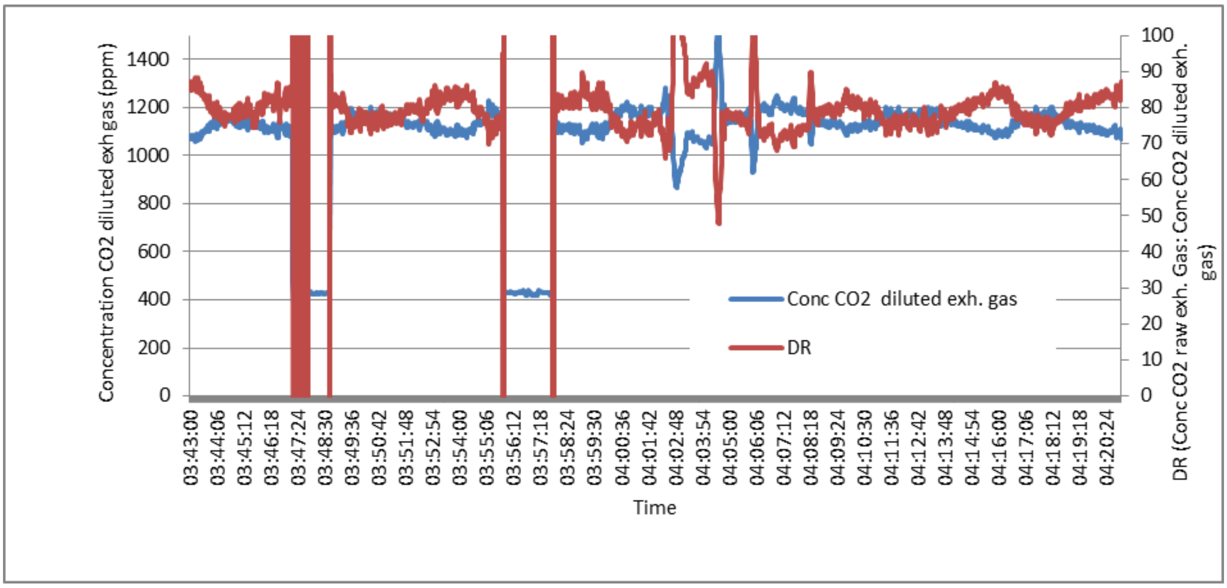


Figure A10. Dilution for sampling of filter 22. Concentrations of CO_2 in diluted gas and dilution ratio are shown. CO_2 in raw exhaust gas = 5.659%, CO_2 in ambient air = 420 ppm.

Figure A11 presents the dilution at sampling of filter 23, at 85% engine load. CO_2 is used as trace gas. Average dilution during the period is calculated to 92 times. The time period between 10:57 and 11:02 is not included in the average due to disturbances from removing the tube to the CO_2 instrument.

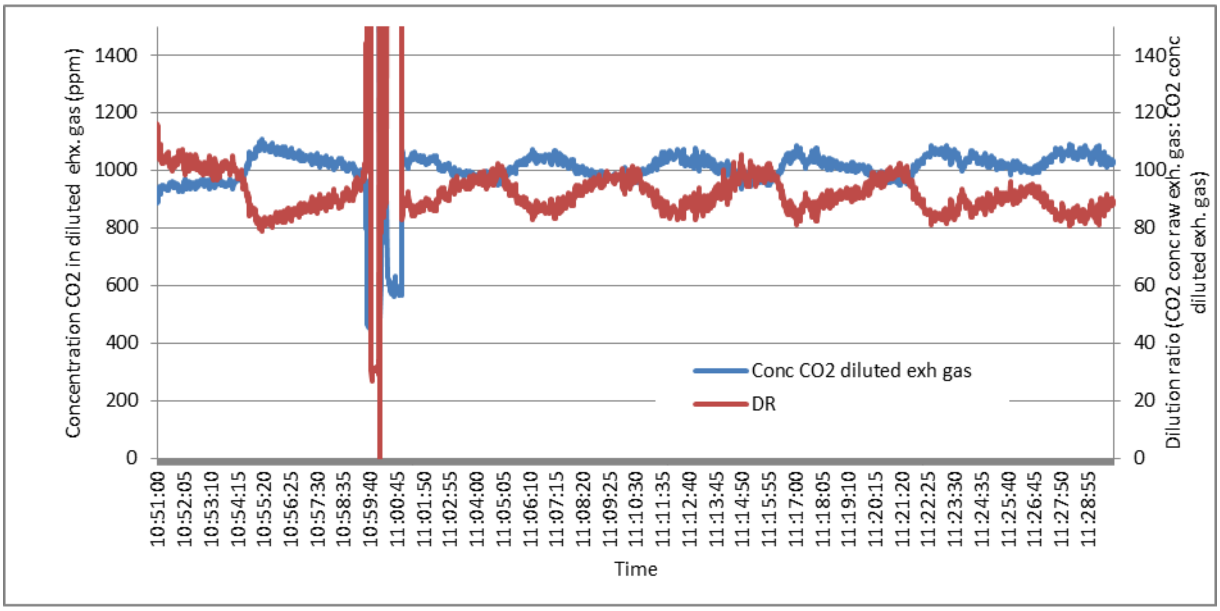


Figure A11. Dilution for sampling of filter 23. Concentrations of CO_2 in diluted gas and dilution ratio are shown. CO_2 in raw exhaust gas = 5.417%, CO_2 in ambient air = 420 ppm.

Figure A12 presents the dilution for sampling filter 24, at 85% engine load. CO_2 is used as trace gas. Average dilution during the period is calculated to 82 times, time period between 12:17 and 12:19 is not included in the average due to disturbances from removing the tube to the CO_2 instrument.

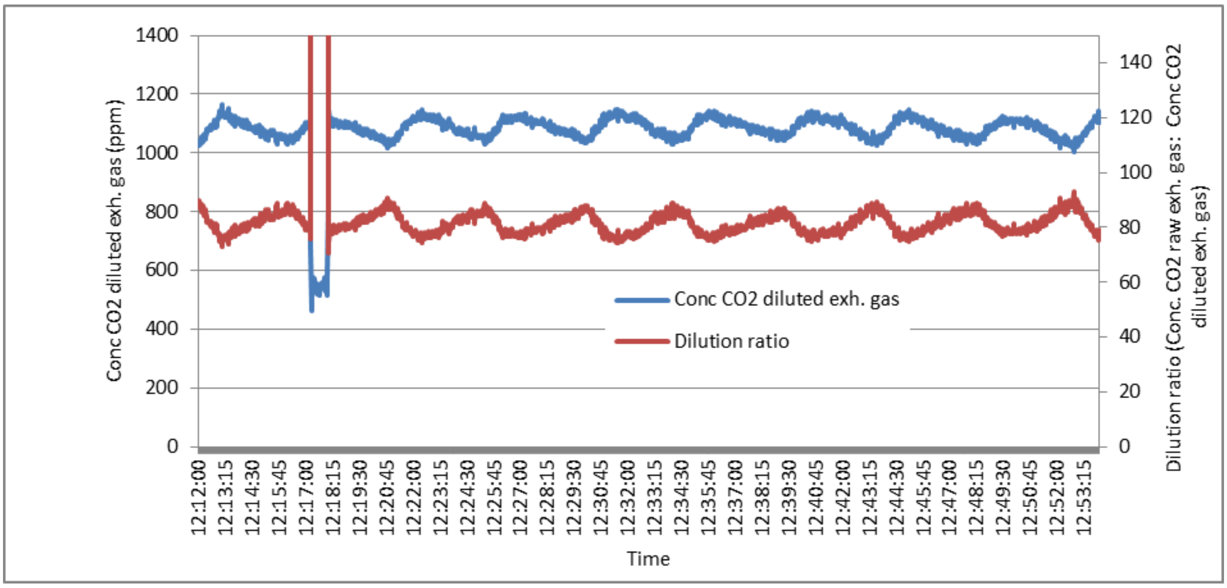


Figure A12. Dilution for sampling of filter 24. Concentrations of CO_2 in diluted gas and dilution ratio are shown. CO_2 in raw exhaust gas = 5.417%, CO_2 in ambient air = 420 ppm.

Figure A13 presents dilution at sampling filter “QH 113” and “QH 114”, at 34% engine load. CO_2 is used as trace gas. Average dilution during the period is calculated to 72 times. The time period between 02:37 and 02:42 is not included in the average due to disturbances from removing the tube to the CO_2 instrument.

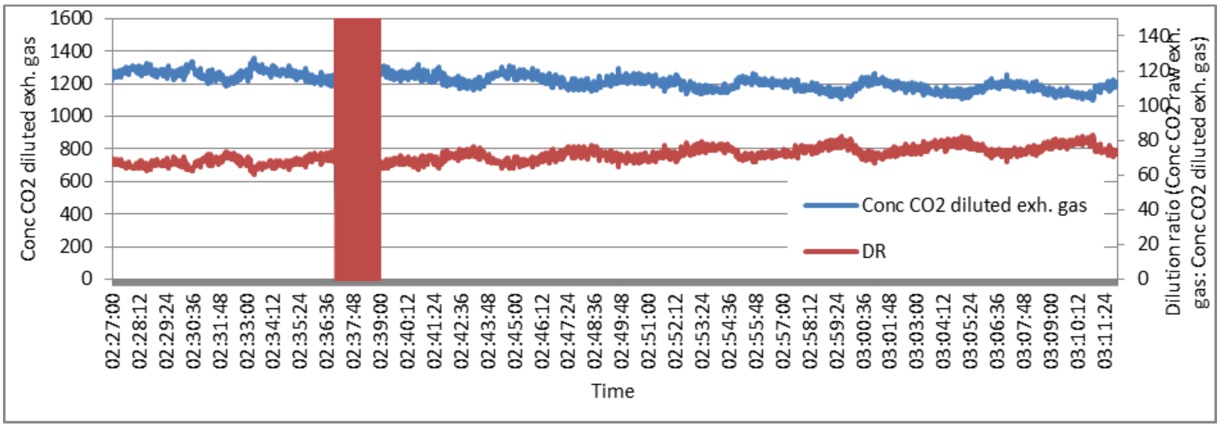


Figure A13. Dilution for sampling of filter “QH 113” and “QH 114”. Concentrations of CO_2 in diluted gas and dilution ratio are shown. CO_2 in raw exhaust gas = 5.66%, CO_2 in ambient air = 420 ppm.

Figure A14 presents dilution at sampling of filter “QH 119” and “QH 120”, at 85% engine load. CO_2 is used as trace gas. Average dilution during the period is calculated to 84 times. The time period between 02:37 and 02:42 is not included in the average due to disturbances from removing the tube to the CO_2 instrument.

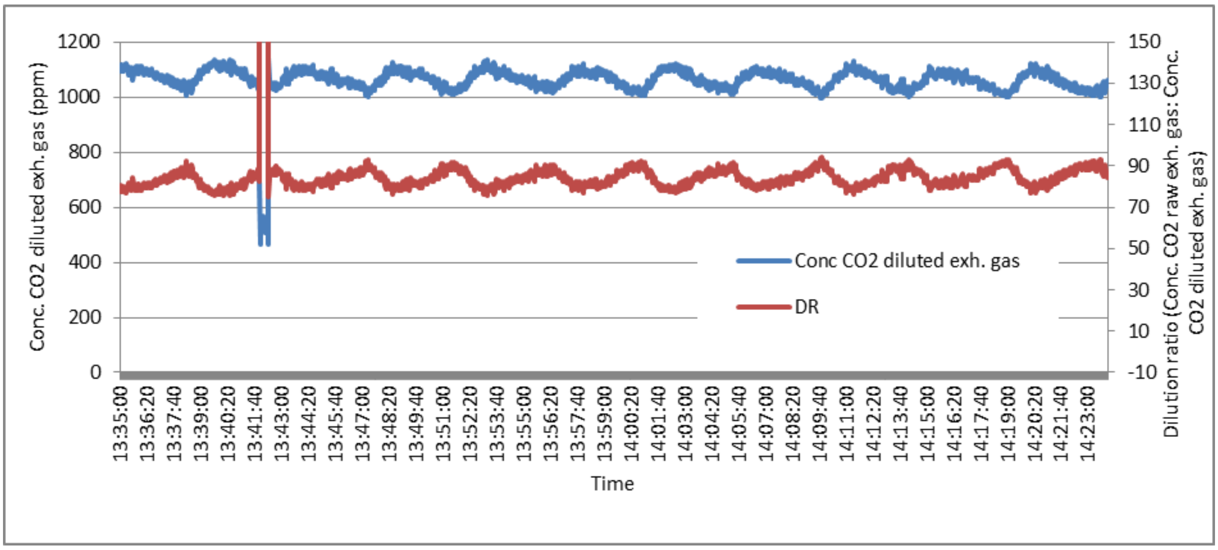


Figure A14. Dilution for sampling of filter "QH 119" and "QH 120". Concentrations of CO_2 in diluted gas and dilution ratio are shown. CO_2 in raw exhaust gas = 5.42%, CO_2 in ambient air = 420 ppm.

Appendix B.

Data from measurements on HFO

List of Tables:

B11. Fuel consumption during the trials downstream and upstream the scrubber. Data from the ship owner’s log.

B2. Engine parameters from trials downstream the scrubber

B3. Engine parameters from trials upstream the scrubber

B4. Average dilution ratios used in the calculations of emissions for different time periods and tests.

B5. Overview of sampling details for Teflon filters sampled for gravimetric analyses at tests using HFO, downstream the scrubber.

B6. Overview of sampling details for Teflon filters sampled for gravimetric analyses at tests using HFO, upstream the scrubber.

B7. Details on the sampling and analyses results of the quartz filters at tests on HFO, downstream and upstream scrubber.

B8. Analysis of SO_2 on filters sampled at HFO combustion, upstream and downstream the scrubber. Calculated share of sulphur on particles.

B9. Metal concentrations from particle sampling at tests at combustion of HFO upstream and downstream scrubber

B102. Values on input parameters for calculation of dry/wet correction factor, exhaust flow using the carbon balance method, NOx correction factor for ambient conditions, gaseous emissions, and particulate emissions. The Table contains calculated values as well as constants used and data on engine performance. Emission factors are marked in coloured cells.

List of Figures:

B13. Fuel consumption during trials according to data from ship owner’s office. The periods for the trials are indicated by red circles and the respective engine loads are given.

B2. Gaseous emission concentrations of NOX, CO, CO2, O2, and SO2 at 49% engine load, tests upstream the scrubber. Gas concentrations for time period 21:16:09 to 00:44:24 are used for further analysis

B3. Gaseous emission concentrations of NOX, CO, CO2, O2, and SO2 at 48% engine load, tests downstream the scrubber. N.B. Scrubber concentration is to be read from secondary axis. Gas concentrations for time period 21:30:14 to 04:00:54 are used for further analysis

B4. Gaseous emission concentrations of NOX, CO, CO2, O2, and SO2 at 76% engine load, tests upstream the scrubber. Gas concentrations for time period 11:02:51 and 12:10:06 are used for further analysis

B5. Gaseous emission concentrations of NOX, CO, CO2, O2, and SO2 at 76% engine load, tests downstream the scrubber. N.B. Scrubber concentration is to be read from secondary axis. Gas concentrations for time period 09:29:45 to 15:04.05 are used for further analysis

B6. Gaseous emission concentrations of NOX, CO, CO2, O2, and SO2 at 32% engine load, tests upstream the scrubber. Gas concentrations for time period 22:27:12 to 01:05:27 are used for further analysis

B7. Gaseous emission concentrations of NOX, CO, CO2, O2, and SO2 at 41% engine load, tests downstream the scrubber. N.B. Scrubber concentration is to be read from secondary axis. Gas concentrations for time period 22:28:07 to 02:36:22 are used for further analysis

B8. Hydrocarbon emission concentrations at 76% engine load, tests upstream the scrubber. Gas concentrations for time period 11:15 to 12:09 are used for further analysis.

B9. Hydrocarbon emission concentrations at 76% engine load, tests downstream the scrubber. Gas concentrations for time period 12:50 to 14:25 are used for further analysis.

B10. Hydrocarbon emission concentrations at 49% engine load, tests upstream the scrubber. Gas concentrations for time period 22:17 to 23:35 are used for further analysis.

B11. Hydrocarbon emission concentrations at 48% engine load, tests downstream the scrubber. Gas concentrations for time period 22:20 to 23:00 are used for further analysis.

B12. Hydrocarbon emission concentrations at 32% engine load, tests upstream the scrubber. Gas concentrations for time period 22:50 to 23:20 are used for further analysis.

B13. Concentration of CO2 in diluted sample gas and, dilution ratio at tests downstream the scrubber at 41% engine load.

B14. Concentration of CO2 in diluted sample gas and, dilution ratio at tests downstream the scrubber at 48% engine load.

B15. Concentration of CO2 in diluted sample gas and, dilution ratio at tests downstream the scrubber at 76% engine load.

B16. Concentration of CO2 in diluted sample gas and, dilution ratio at tests upstream the scrubber at 32% engine load.

B17. Concentration of CO2 in diluted sample gas and, dilution ratio at tests upstream the scrubber at 49% engine load.

B18. Concentration of CO2 in diluted sample gas and, dilution ratio at tests upstream the scrubber at 76% engine load.

Table B14. Fuel consumption during the trials downstream and upstream the scrubber. Data from the ship owner's log.

Date Time	Fuel cons at 76% engine load (kg/h) (measurements downstream scrubber)	Date Time	Fuel cons at 48% engine load (kg/h) (measurements downstream scrubber)	Date Time	Fuel cons at 41% engine load (kg/h) (measurements downstream scrubber)
2017-09-21 07:32	0.00	2017-09-20 19:42	0.00	2017-09-19 19:42	0.00
2017-09-21 07:42	654.00	2017-09-20 19:52	482.00	2017-09-19 19:52	1246.00
2017-09-21 07:52	715.00	2017-09-20 20:02	1274.00	2017-09-19 20:02	943.00
2017-09-21 08:02	685.00	2017-09-20 20:12	809.00	2017-09-19 20:12	1034.00
2017-09-21 08:12	834.00	2017-09-20 20:22	1039.00	2017-09-19 20:22	968.00
2017-09-21 08:22	1401.00	2017-09-20 20:32	1099.00	2017-09-19 20:32	738.00
2017-09-21 08:32	1409.00	2017-09-20 20:42	1000.00	2017-09-19 20:42	700.00
2017-09-21 08:42	1492.00	2017-09-20 20:52	1030.00	2017-09-19 20:52	679.00
2017-09-21 08:52	1492.00	2017-09-20 21:02	1015.00	2017-09-19 21:02	714.00
2017-09-21 09:02	1413.00	2017-09-20 21:12	975.00	2017-09-19 21:12	773.00
2017-09-21 09:12	1419.00	2017-09-20 21:22	1028.00	2017-09-19 21:22	957.00
2017-09-21 09:22	1465.00	2017-09-20 21:32	1067.00	2017-09-19 21:32	937.00
2017-09-21 09:32	1433.00	2017-09-20 21:42	1059.00	2017-09-19 21:42	911.00
2017-09-21 09:42	1421.00	2017-09-20 21:52	1012.00	2017-09-19 21:52	953.00
2017-09-21 09:52	1374.00	2017-09-20 22:02	1045.00	2017-09-19 22:02	848.00
2017-09-21 10:02	1497.00	2017-09-20 22:12	1028.00	2017-09-19 22:12	910.00
2017-09-21 10:12	1450.00	2017-09-20 22:22	1012.00	2017-09-19 22:22	950.00
2017-09-21 10:22	1427.00	2017-09-20 22:32	1044.00	2017-09-19 22:32	890.00
2017-09-21 10:32	1430.00	2017-09-20 22:42	1041.00	2017-09-19 22:42	889.00
2017-09-21 10:42	1381.00	2017-09-20 22:52	1026.00	2017-09-19 22:52	988.00
2017-09-21 10:52	1383.00	2017-09-20 23:02	1026.00	2017-09-19 23:02	996.00
2017-09-21 11:02	1422.00	2017-09-20 23:12	991.00	2017-09-19 23:12	953.00
2017-09-21 11:12	1419.00	2017-09-20 23:22	1012.00	2017-09-19 23:22	942.00
2017-09-21 11:22	1410.00	2017-09-20 23:32	999.00	2017-09-19 23:32	983.00
2017-09-21 11:32	1404.00	2017-09-20 23:42	1033.00	2017-09-19 23:42	957.00
2017-09-21 11:42	1413.00	2017-09-20 23:52	1064.00	2017-09-19 23:52	907.00
2017-09-21 11:52	1413.00	2017-09-21 00:02	1009.00	2017-09-20 00:02	876.00
2017-09-21 12:02	1391.00	2017-09-21 00:12	998.00	2017-09-20 00:12	931.00
2017-09-21 12:12	1443.00	2017-09-21 00:22	1013.00	2017-09-20 00:22	895.00
2017-09-21 12:22	1418.00	2017-09-21 00:32	1044.00	2017-09-20 00:32	1066.00
2017-09-21 12:32	1382.00	2017-09-21 00:42	1631.00	2017-09-20 00:42	987.00
2017-09-21 12:42	1393.00	2017-09-21 00:52	1381.00	2017-09-20 00:52	986.00
2017-09-21 12:52	1451.00	2017-09-21 01:02	1169.00	2017-09-20 01:02	896.00
2017-09-21 13:02	1435.00	2017-09-21 01:12	1237.00	2017-09-20 01:12	982.00
2017-09-21 13:12	1407.00	2017-09-21 01:22	1196.00	2017-09-20 01:22	904.00
2017-09-21 13:22	1461.00	2017-09-21 01:32	1177.00	2017-09-20 01:32	1079.00
2017-09-21 13:32	1383.00	2017-09-21 01:42	1140.00	2017-09-20 01:42	1038.00
2017-09-21 13:42	1402.00	2017-09-21 01:52	1330.00	2017-09-20 01:52	1071.00
2017-09-21 13:52	1404.00	2017-09-21 02:02	1839.00	2017-09-20 02:02	1824.00
2017-09-21 14:02	1395.00	2017-09-21 02:12	2145.00	2017-09-20 02:12	2032.00
2017-09-21 14:12	1519.00	2017-09-21 02:22	2424.00	2017-09-20 02:22	1994.00
2017-09-21 14:22	1290.00	2017-09-21 02:32	2733.00	2017-09-20 02:32	1969.00
2017-09-21 14:32	1299.00	2017-09-21 02:42	2324.00	2017-09-20 02:42	1949.00
2017-09-21 14:42	1439.00	2017-09-21 02:52	2180.00	2017-09-20 02:52	1999.00
2017-09-21 14:52	868.00	2017-09-21 03:02	2166.00	2017-09-20 03:02	1943.00

2017-09-21 15:02	1093.00	2017-09-21 03:12	708.00	2017-09-20 03:12	916.00
2017-09-21 15:12	291.00	2017-09-21 03:22	871.00	2017-09-20 03:22	776.00
2017-09-21 15:22	0.00	2017-09-21 03:32	720.00	2017-09-20 03:32	862.00
2017-09-21 15:32	89.00	2017-09-21 03:42	2166.00	2017-09-20 03:42	2624.00
2017-09-21 15:42	0.00	2017-09-21 03:52	1013.00	2017-09-20 03:52	1092.00
2017-09-21 15:52	0.00	2017-09-21 04:02	846.00	2017-09-20 04:02	959.00
2017-09-21 16:02	0.00	2017-09-21 04:12	948.00	2017-09-20 04:12	613.00
2017-09-21 16:12	0.00	2017-09-21 04:22	0.00	2017-09-20 04:22	79.00
2017-09-21 16:22	0.00	2017-09-21 04:32	0.00	2017-09-20 04:32	0.00

Date Time	Fuel cons at 76% engine load (kg/h) (measurements upstream scrubber)	Date Time	Fuel cons at 49% engine load (kg/h) (measurements upstream scrubber)	Date Time	Fuel cons at 32% engine load (kg/h) (measurements upstream scrubber)
2017-09-24 08:32	0.00	2017-09-23 19:32	0.00	2017-09-22 20:32	0.00
2017-09-24 08:42	0.00	2017-09-23 19:42	0.00	2017-09-22 20:42	734.00
2017-09-24 08:52	0.00	2017-09-23 19:52	0.00	2017-09-22 20:52	647.00
2017-09-24 09:02	0.00	2017-09-23 20:02	0.00	2017-09-22 21:02	1235.00
2017-09-24 09:12	0.00	2017-09-23 20:12	0.00	2017-09-22 21:12	865.00
2017-09-24 09:22	0.00	2017-09-23 20:22	0.00	2017-09-22 21:22	833.00
2017-09-24 09:32	0.00	2017-09-23 20:32	0.00	2017-09-22 21:32	879.00
2017-09-24 09:42	0.00	2017-09-23 20:42	0.00	2017-09-22 21:42	883.00
2017-09-24 09:52	0.00	2017-09-23 20:52	0.00	2017-09-22 21:52	913.00
2017-09-24 10:02	0.00	2017-09-23 21:02	0.00	2017-09-22 22:02	790.00
2017-09-24 10:12	0.00	2017-09-23 21:12	0.00	2017-09-22 22:12	883.00
2017-09-24 10:22	0.00	2017-09-23 21:22	0.00	2017-09-22 22:22	918.00
2017-09-24 10:32	0.00	2017-09-23 21:32	0.00	2017-09-22 22:32	827.00
2017-09-24 10:42	0.00	2017-09-23 21:42	0.00	2017-09-22 22:42	820.00
2017-09-24 10:52	0.00	2017-09-23 21:52	0.00	2017-09-22 22:52	911.00
2017-09-24 11:02	0.00	2017-09-23 22:02	0.00	2017-09-22 23:02	791.00
2017-09-24 11:12	0.00	2017-09-23 22:12	0.00	2017-09-22 23:12	886.00
2017-09-24 11:22	0.00	2017-09-23 22:22	0.00	2017-09-22 23:22	830.00
2017-09-24 11:32	0.00	2017-09-23 22:32	0.00	2017-09-22 23:32	820.00
2017-09-24 11:42	0.00	2017-09-23 22:42	0.00	2017-09-22 23:42	838.00
2017-09-24 11:52	0.00	2017-09-23 22:52	0.00	2017-09-22 23:52	1037.00
2017-09-24 12:02	0.00	2017-09-23 23:02	0.00	2017-09-23 00:02	947.00
2017-09-24 12:12	0.00	2017-09-23 23:12	0.00	2017-09-23 00:12	695.00
2017-09-24 12:22	0.00	2017-09-23 23:22	0.00	2017-09-23 00:22	686.00
2017-09-24 12:32	0.00	2017-09-23 23:32	0.00	2017-09-23 00:32	789.00
2017-09-24 12:42	0.00	2017-09-23 23:42	0.00	2017-09-23 00:42	1192.00
2017-09-24 12:52	0.00	2017-09-23 23:52	0.00	2017-09-23 00:52	1159.00
2017-09-24 13:02	0.00	2017-09-24 00:02	0.00	2017-09-23 01:02	1692.00
2017-09-24 13:12	0.00	2017-09-24 00:12	0.00	2017-09-23 01:12	1652.00
2017-09-24 13:22	0.00	2017-09-24 00:22	0.00	2017-09-23 01:22	1674.00
2017-09-24 13:32	0.00	2017-09-24 00:32	0.00	2017-09-23 01:32	1655.00
2017-09-24 13:42	0.00	2017-09-24 00:42	0.00	2017-09-23 01:42	2275.00
2017-09-24 13:52	0.00	2017-09-24 00:52	0.00	2017-09-23 01:52	2777.00
2017-09-24 14:02	0.00	2017-09-24 01:02	0.00	2017-09-23 02:02	1427.00
2017-09-24 14:12	0.00	2017-09-24 01:12	0.00	2017-09-23 02:12	2929.00
2017-09-24 14:22	0.00	2017-09-24 01:22	0.00	2017-09-23 02:22	2423.00

2017-09-24 14:32	0.00	2017-09-24 01:32	0.00	2017-09-23 02:32	1705.00
2017-09-24 14:42	0.00	2017-09-24 01:42	0.00	2017-09-23 02:42	1736.00
2017-09-24 14:52	0.00	2017-09-24 01:52	0.00	2017-09-23 02:52	1856.00
2017-09-24 15:02	0.00	2017-09-24 02:02	0.00	2017-09-23 03:02	981.00
2017-09-24 15:12	0.00	2017-09-24 02:12	0.00	2017-09-23 03:12	736.00
2017-09-24 15:22	0.00	2017-09-24 02:22	0.00	2017-09-23 03:22	884.00
2017-09-24 15:32	0.00	2017-09-24 02:32	0.00	2017-09-23 03:32	785.00
2017-09-24 15:42	0.00	2017-09-24 02:42	0.00	2017-09-23 03:42	1683.00
2017-09-24 15:52	0.00	2017-09-24 02:52	0.00	2017-09-23 03:52	801.00
2017-09-24 16:02	0.00	2017-09-24 03:02	0.00	2017-09-23 04:02	758.00
2017-09-24 16:12	0.00	2017-09-24 03:12	0.00	2017-09-23 04:12	656.00
2017-09-24 16:22	0.00	2017-09-24 03:22	0.00	2017-09-23 04:22	0.00

Table B2. Engine parameters from trials downstream the scrubber. The parameters used in calculation of emission factors are marked in bold and calculated values are in italics. For all calculations, average values of relevant parameters are calculated from the two to four entries made at each steady state engine load.

Date	21-sep	21-sep	20-sep	21-sep	21-sep	19-sep	20-sep	20-sep
Time	13:00	15:00	23:15	00:15	01:15	23:00	00:00	01:00
Engine ID	ME 4	ME 4	ME4	ME4	ME4	ME4	ME4	ME4
Power load (%)	**76%**	**76%**	**49%**	**48%**	**48%**	**40%**	**42%**	**42%**
Approximate loss at gearbox	**3%**	**3%**	**3%**	**3%**	**3%**	**3%**	**3%**	**3%**
inlet air temp (°C)								
1	29.2	30.2	30.3	32.1	31.2	39	43	39
2	25.9	26.9	27.9	28	27.4	32	30	30
3	25.4	26.4	25.6	26.5	26.4	28	26	27
4	32.9	30.4	28.6	29.9	30.6	30	35	30
Average	***28.35***	***28.48***	**28.1**	**29.1**	**28.9**	***32.3***	***33.5***	***31.5***
Inlet air Relative Humidity (%)								
1	33.2	32.5	38.6	33.6	31	20	15	18
2	40.6	41.7	40.7	40.3	37.2	27	30	28
3	41.3	40.6	45.3	45.4	39.7	35	35	30
4	28.7	33.6	39.2	36.4	33.7	32	24	28
Average	***36.0***	***37.1***	**41.0**	***38.9***	***35.4***	***28.5***	***26.0***	***26.0***

Table B3. Engine parameters from trials upstream the scrubber The parameters used in calculation of emission factors are marked in bold and calculated values are in italics. For all calculations, average values of relevant parameters are calculated from the two to four entries made at each steady state engine load.

Date	24-sep	24-sep	23-sep	23-sep	24-sep	24-sep	22-sep	23-sep	23-sep
Time		13:15	22:00	23:00	00:00	01:00	23:30	00:30	01:30
Engine ID	ME 4	ME 4	ME4	ME4	ME4	ME4	ME4	ME4	ME4
Power load (%)	**74%**	**76%**	**49%**	**49%**	**48%**	**48%**	**35%**	**36%**	**25%**
Approximate loss at gearbox	**3%**	**3%**	**3%**	**3%**	**3%**	**3%**	**3%**	**3%**	**3%**
inlet air temp (°C)									
1	42.5	39.1	37.3	38.5	37.9	40.6	38	35.8	34.3
2	31.2	29.8	31.8	33.5	32.8	33.1	30.3	29.6	28.7
3	25.1	25.6	29	28.6	28.9	28.8	26.1	28.4	27
4	32.9	35.7	35	36.8	29.9	30.8	28.5	30.5	28.1
Average	***32.93***	***32.55***	***33.3***	***34.4***	***32.4***	***33.3***	***30.7***	***31.1***	***29.5***
Inlet air Relative Humidity (%)									
1	20.9	22.1	22.5	20	18.7	18.8	22.9	21.8	25.4
2	33.3	37.2	28.9	25.7	26.8	27.6	29.6	30.6	34.4
3	45.9	44.4	32.7	32.7	33.2	33.7	34	32.4	37.5
4	31.1	29.3	23.3	21.4	29.5	30.8	29.5	28.6	35.2
Average	***32.8***	***33.3***	***26.9***	***25.0***	***27.1***	***27.7***	***29.0***	***28.4***	***33.1***

Table B4. Average dilution ratios used in the calculations of emissions for different time periods and tests.

Engine load	Downstream/ Upstream	Date start	Time start	Date stop	Time stop	Average DR from Licor
41%	Downstream	2017-09-19	23:04	2017-09-20	01:00	131
41%	Downstream	2017-09-20	01:28	2017-09-20	02:18	44
48%	Downstream	2017-09-20	21:52	2017-09-20	22:05	157
48%	Downstream	2017-09-20	21:59	2017-09-20	23:12	165
48%	Downstream	2017-09-20	23:13	2017-09-20	23:50	167
48%	Downstream	2017-09-21	00:00	2017-09-21	03:40	54
76%	Downstream	2017-09-21	09:47	2017-09-21	09:52	192
76%	Downstream	2017-09-21	10:02	2017-09-21	10:19	297
76%	Downstream	2017-09-21	10:27	2017-09-21	10:39	358
76%	Downstream	2017-09-21	10:33	2017-09-21	10:58	422
76%	Downstream	2017-09-21	11:03	2017-09-21	11:14	434
76%	Downstream	2017-09-21	11:23	2017-09-21	11:32	406
76%	Downstream	2017-09-21		2017-09-21	11:50	High and varying
76%	Downstream	2017-09-21	11:50	2017-09-21	15:15	71
32%	Upstream	2017-09-22	22:51	2017-09-22	22:59	198.5
32%	Upstream	2017-09-22	23:03	2017-09-22	23:12	230
32%	Upstream	2017-09-22	23:10	2017-09-24	01:30	251
32%	Upstream	2017-09-22	23:43	2017-09-24	00:43	246
49%	Upstream	2017-09-23	21:45	2017-09-23	22:45	255
49%	Upstream	2017-09-23	21:50	2017-09-23	22:20	257
49%	Upstream	2017-09-23	22:23	2017-09-23	22:39	252
49%	Upstream	2017-09-24	22:58	2017-09-24	23:09	212
49%	Upstream	2017-09-23	23:03	2017-09-23	23:48	190
49%	Upstream	2017-09-24	00:10	2017-09-24	00:52	162
76%	Upstream	2017-09-24	10:01	2017-09-24	11:43	174
76%	Upstream	2017-09-24	11:20	2017-09-24	12:15	149
76%	Upstream	2017-09-24	12:01	2017-09-24	12:50	154
76%	Upstream	2017-09-24	12:20	2017-09-24	12:50	163
76%	Upstream	2017-09-24	14:15	2017-09-24	15:00	60

Table B5. Overview of sampling details for Teflon filters sampled for gravimetric analyses at tests using HFO, downstream the scrubber. In order to follow the discussion on results, filters are given numbers from 25 to 41.

Notes/Field measurements	**Engine load**	**T at filter (°C)**	**Dilution system**	**DR**	**Start**	**Stop**	**Mass unexposed (g)**	**Mass exposed (g)**	**Mass exposed-unexposed (g)**	**Volume in**	**Volume out**	**Volume in-out (m3)**	**Notes Lab**	**Conc before dilution (g/m3)**
25//Stena Britannica, PMtot, FPS, 76822	41%	n.a.	FPS	131	2017-09-19 23:04	2017-09-20 01:00	0.301119	0.301755	0.000636	1086.875	1089.145	2.27		0.0367
26//Stena Britannica PM2.5, FPS, 76823	41%	n.a.	FPS	131	2017-09-19 23:04	2017-09-20 01:00	0.312549	0.313003	0.000454	5854.99	5856.729	1.739		0.0342
27//Stena Britannica PM2.5, FPS, 76826	41%	n.a.	FPS	55	2017-09-20 01:19	2017-09-20 02:18	0.314415	0.315133	0.000718	5856.729	5857.679	0.95		0.0416
28//Stena Britannica PMtot, FPS, 76827	41%	n.a.	FPS	55	2017-09-20 01:19	2017-09-20 02:18	0.304553	0.305403	0.00085	1089.145	1090.237	1.092		0.0428
29//Stena Britannica PMtot, FPS, 76806	48%	n.a.	FPS	55	2017-09-20 02:44	2017-09-20 03:42	0.309124	0.310022	0.000898	1094.904	1096.0155	1.1115		0.0444
30//Stena Britannica PM2.5, FPS, 76807	48%	n.a.	FPS	55	2017-09-20 02:44	2017-09-20 03:42	0.312837	0.313527	0.00069	5861.829	5862.781	0.952		0.0399
31//Stena Britannica PMtot, FPS, 76820	48%	n.a.	FPS	165	2017-09-20 21:59	2017-09-20 23:12	0.304388	0.304665	0.000277	1091.239	1092.713	1.474		0.0310
32//Stena Britannica PM2.5, FPS, 76821	48%	n.a.	FPS	165	2017-09-20 21:59	2017-09-20 23:12	0.311178	0.311479	0.000301	5858.608	5859.851	1.243		0.0400
33//Stena Britannica PMtot, FPS, 76824	48%	n.a.	FPS	53	2017-09-20 23:56	2017-09-21 01:05	0.321179	0.3221	0.000921	1092.713	1093.93	1.217		0.0401
34//Stena Britannica PM2.5, FPS, 76825	48%	n.a.	FPS	53	2017-09-20 23:56	2017-09-21 01:05	0.30803	0.308763	0.000733	5859.851	5860.99	1.139		0.0341
35//Stena Britannica PMtot, FPS, 76804	76%	n.a.	FPS	348	2017-09-21 09:40	2017-09-21 11:40	0.311333	0.311736	0.000403	1096.015	1098.373	2.358		0.0595
36//Stena Britannica PM2.5, FPS, 76805	76%	n.a.	FPS	348	2017-09-21 09:40	2017-09-21 11:40	0.301215	0.301488	0.000273	5862.781	5864.813	2.032		0.0467
37//Stena Britannica PM2.5, FPS, 76802	76%	n.a.	FPS	69	2017-09-21 12:00	2017-09-21 13:08	0.311529	0.312215	0.000686	5864.813	5865.964	1.151		0.0412
38//Stena Britannica PMtot, FPS, 76861	76%	n.a.	FPS	69	2017-09-21 12:00	2017-09-21 13:08	0.304613	0.305515	0.000902	1098.373	1099.703	1.33		0.0469

39//Stena Britannica PM2.5, FPS, 76884	76%	n.a.	FPS	74	2017-09-21 14:43	2017-09-21 15:13	0.302456	0.302729	0.000273	5867.044	5867.564	0.52		0.0388
40//Stena Britannica PMtot, FPS, 76885	76%	n.a.	FPS	74	2017-09-21 14:43	2017-09-21 15:13	0.305835	0.306213	0.000378	1100.963	1101.565	0.602		0.0465
41// Stena Britannica PMtot, FPS, 76852	Filter missing													

Table B6. Overview of sampling details for Teflon filters sampled for gravimetric analyses at tests using HFO, upstream the scrubber. In order to follow the discussion on results, filters are given numbers from 42 to 58.

Notes/Field measurements	**Engine load**	**T at filter (°C)**	**Dilution system**	**DR**	**Start**	**Stop**	**Mass unexposed (g)**	**Mass exposed (g)**	**Mass exposed-unexposed (g)**	**Volume in**	**Volume out**	**Volume in-out (m3)**	**Notes Lab**	**Conc before dilution (g/m3)**
42//Stena Britannica PM2.5, FPS, 76801	32%	n.a.	FPS	151	2017-09-22 22:30	2017-09-22 23:08	0.30783	0.308309	0.000479	1101.5645	1102.28	0.7155		0.1011
43//Stena Britannica PMtot, Norska, 76800	32%	n.a.	Norska	14	2017-09-22 22:55	2017-09-22 22:56	0.316141	0.317274	0.001133	0.447	0.445867	0.2		0.0816
44//Stena Britannica PM2.5, FPS, 76854	32%	n.a.	FPS	246	2017-09-22 23:43	2017-09-23 00:43	0.306144	0.306383	0.000239	1102.28	1103.267	0.987		0.0596
45//Stena Britannica PMtot, FPS, 76855	32%	n.a.	FPS	246	2017-09-22 23:43	2017-09-23 00:43	0.307285	0.307523	0.000238	4275.167	4276.427	1.26		0.0465
46//Stena Britannica PMtot, Norska, 75394	32%	n.a.	Norska	14	2017-09-22 23:50	2017-09-22 23:55	0.306421	0.307411	0.00099	0.447	0.647	0.200		0.0713
47//Stena Britannica PMtot, Norska, 76810	49%	n.a.	Norska	16	2017-09-23 21:19	2017-09-23 22:22	0.304266	0.305146	0.00088	0.7	0.9	0.2		0.0708
48//Stena Britannica PMtot, Norska, 75385	49%	n.a.	Norska	16	2017-09-23 22:10	2017-09-23 22:29	0.325674	0.326416	0.000742	5669.894	5670.094	0.2		0.0597
49//Stena Britannica PMtot, FPS, 76818	49%	n.a.	FPS	190	2017-09-23 23:03	2017-09-23 23:48	0.305372	0.30569	0.000318	4278.5686	4279.6087	1.0401		0.0581
50//Stena Britannica PM2.5, FPS, 76819	49%	n.a.	FPS	190	2017-09-23 23:03	2017-09-23 23:48	0.301255	0.301514	0.000259	1105.019	1105.8425	0.8235		0.0598
51//Stena Britannica PMtot, FPS, 76814	49%	n.a.	FPS	162	2017-09-24 00:10	2017-09-24 00:52	0.308478	0.308763	0.000285	4279.6087	4280.4736	0.8649		0.0534
52//Stena Britannica PM2.5, FPS, 76815	49%	n.a.	FPS	162	2017-09-24 00:10	2017-09-24 00:52	0.309236	0.309487	0.000251	1105.8425	1106.5336	0.6911		0.0588
53//Stena Britannica PMtot, FPS, 76870	76%	n.a.	FPS	174	2017-09-24 10:01	2017-09-24 11:43	0.307537	0.307921	0.000384	4280.474	4281.3585	0.8845		0.0755
54//Stena Britannica PM2.5, FPS, 76871	76%	n.a.	FPS	174	2017-09-24 10:01	2017-09-24 11:43	0.308718	0.308995	0.000277	4281.3586	4282.362	1.0034		0.0480
55//Stena Britannica PMtot, Norska, 76868	76%	n.a.	Norska	14	2017-09-24 11:04	2017-09-24 12:12	0.31386	0.314622	0.000762	5670.094	5670.264	0.17		0.0645

56//Stena Britannica PMtot, Norska, 76833	76%	n.a.	Norska	14	2017-09-24 11:50	2017-09-24 12:09	0.303273	0.304342	0.001069	0.264	0.464	0.2		0.0770
57//Stena Britannica PMtot, FPS, 76879	76%	n.a.	FPS	154	2017-09-24 12:01	2017-09-24 12:50	0.30814	0.308522	0.000382	1106.5344	1107.235	0.7006		0.0840
58//Stena Britannica PM2.5, FPS, 76878	76%	n.a.	FPS	154	2017-09-24 12:50	2017-09-24 12:50	0.30712	0.307452	0.000332	1107.235	1108.0554	0.8204		0.0623

Table B7. Details on the sampling and analyses results of the quartz filters at tests on HFO, downstream and upstream scrubber.

Sample ID	Primary/Secondary	Engine load(Up stream /Downstream)	Dilution	Exposed filter area (cm^2)	Dilution ratio	Time start	Time stop	Volume passed through filter (Nm^3)	TC [µg/m3] After dilution	TC real [mg/m3] Before dilution	OC [µg/m3] After dilution	OC [mg/m3] Before dilution	EC [µg/m3] After dilution	EC [mg/m3] Before dilution	Sampled mass (mg) After dilution	Conc. PM (mg/m3) Before dilution
QH 124	TSP Primary	41%(DS)	FPS	13.2	44	02:44	03:30	2.094	178.31	8	147.49	6.5	30.81	1.4	0.993	20.9
QH 123	Secondary	41%(DS)	FPS	13.2	44	02:44	03:30	2.094	75.14		54.64		20.50		0.1893	
QH 128	PM2.5 Primary	48%(DS)	FPS	13.2	54	01:29	02:15	0.97	398.70	22	346.04	15.2	52.66	2.3	0.992	55.0
QH 127	Secondary	48%(DS)	FPS	13.2	54	01:29	02:15	0.97	90.81		87.13		3.68		0.128	
QH 130	TSP Primary	48%(DS)	FPS	13.2	54	01:29	02:15	0.84	343.55	19	295.92	13.0	47.63	2.1	0.554	35.7
QH 129	Secondary	48%(DS)	FPS	13.2	54	01:29	02:15	0.84	86.74		80.91		5.83		0.2517	
QH 132	PM2.5 Primary	76%(DS)	FPS	13.2	71	13:26	14:25	1.26	274.20	19	235.22	10.3	38.99	1.7	0.8467	47.7
QH 131	Secondary	76%(DS)	FPS	13.2	71	13:26	14:25	1.26	75.30		35.19		40.12		0.181	
QH 134	PM2.5 Primary	76%(DS)	FPS	13.2	71	13:26	14:25	1.08	210.75	15	178.12	7.8	32.63	1.4	0.7476	49.1
QH 133	Secondary	76%(DS)	FPS	13.2	71	13:26	14:25	1.08	49.68		40.85		8.83		0.054	
QH 135	TSP Primary	32%(US)	FPS	13.2	230	01:02	01:49	0.74	204.13	47	149.48	6.6	54.65	2.4	0.256	79.5
	Missing sec. filter														0	
QH 136	TSP Primary	32%(US)	FPS	13.2	230	01:02	01:49	0.86	198.97	46	143.20	6.3	55.77	2.5	-0.2076	n.a.
	Missing sec. filter														0	
QH 137	TSP Primary	49%(US)	FPS	13.2	255	21:45	22:45	1.28	102.96	26	71.61	3.2	31.34	1.4	0.4337	86.4
QH 138	Secondary	49%(US)	FPS	13.2	255	21:45	22:45	1.28	90.02		39.90		50.12		0.22	
QH 139	PM2.5 Primary	49%(US)	FPS	13.2	255	21:45	22:45	1.01	128.09	33	94.16	4.1	33.93	1.5	0.4727	118.9
QH 140	Secondary	49%(US)	FPS	13.2	255	21:45	22:45	1.01	49.03		43.70		5.33		0.0907	
QH 143	TSP Primary	76%(US)	FPS	13.2	60	14:10	14:43	0.48	307.19	18	242.52	10.7	64.67	2.8	0.6197	76.9
QH 144	Secondary	76%(US)	FPS	13.2	60	14:10	14:43	0.48	94.99		90.17		4.82		0.149	
QH 145	TSP Primary	76%(US)	FPS	13.2	60	14:10	14:43	0.57	377.53	23	204.33	9.0	173.20	7.6	-1.7104	n.a.
QH 146	Secondary	76%(US)	FPS	13.2	60	14:10	14:43	0.57	115.84		104.37		11.47		-0.0056	

Table B8. Analysis of SO_2 on filters sampled at HFO combustion, upstream and downstream the scrubber. Calculated share of sulphur on particles.

Filter no	SO_2 (µg/ sample)	Upstream/ Downstream	Engine load (%)	Volume/ sample (nm3)	DR	µg S/m3	PM conc. on filter (µg/m3)	S share of PM tot
28	51	Downstream	0.41	1.092	55	2583	42830	6.03%
58	26	Upstream	0.76	0.8204	154	4887	71700	6.82%
38	70	Downstream	0.76	1.33	69	3654	46900	7.79%
56	96	Upstream	0.76	0.2	14.4	6919	76970	8.99%
45	6.8	Upstream	0.32	1.26	246	1326	46500	2.85%

Table B9. Metal concentrations from particle sampling at tests at combustion of HFO upstream and downstream scrubber. Correction has been made for dilution of the sample gas. “0” indicates levels below detection limit.

Sample (see filter numbers in **Error! Reference source not found.** and Table)	engine load	Downstream/ Upstream scrubber	V	Ni	Fe	Al	Co	Ba	Mn	Zn	Cr	Sr	Cd	Cu	As	Se	Pb	Mo	P	Si	Li	S
			ng/m^3	ng/m^3	ng/m^3	ng/m^3	ng/m^3	ng/m^3	ng/m^3	ng/m^3	ng/m^3	ng/m^3	ng/m^3	ng/m^3	ng/m^3	ng/m^3	ng/m^3	ng/m^3	ng/m^3	ng/m^3	ng/m^3	ng/m^3
Filter no 25	41%	Downstream	2882000	956300	275100	576400	3668	8122	1703	23580	3275	1283.8	0	6812	1441	943.2	0	9039	0	0	0	0
Filter no 40	76%	Downstream	2886000	888000	266400	31820	3034	8140	1924	0	5846	1332	0	0	666	0	0	0	0	0	0	0
Filter no 45	32%	Upstream	3444000	984000	369000	0	3690	10086	3198	0	15990	1820.4	492	0	0	0	0	0	0	0	0	0
Filter no 55	76%	Upstream	705600	216000	116640	38880	921.6	3024	1224	17280	3600	590.4	0	0	0	0	0	0	0	0	0	0
Filter no 53	76%	Upstream	2436000	730800	313200	60900	6090	8874	7656	0	14790	2436	0	0	0	0	0	0	0	0	0	0

Table B105. Values on input parameters for calculation of dry/wet correction factor, exhaust flow using the carbon balance method, NOx correction factor for ambient conditions, gaseous emissions, and particulate emissions. The Table contains calculated values as well as constants used and data on engine performance. Emission factors are marked in coloured cells.

Date/Test	**170921**	**170920-170921**	**170919-170920**	**170924**	**170923-170924**	**170922-170923**
Sulphur content of fuel (%)	2.77	2.77	2.77	2.77	2.77	2.77
	Downstream scrubber			**Upstream scrubber**		
MCR (100 % load), MCR of engine (brake kW) =	9600	9600	9600	9600	9600	9600
Load, Brake Load during test (%) =	76%	48%	41%	76%	49%	32%
P, Brake Power or effect during test (kW) =	7296	4640	3968	7296	4672	3072
Calculation of dry/wet correction factor as in annex 2.6, version 3:						
GFUEL, Fuel consumption (kg/hr) =	1405	995	915	1405	1006	812
Fuel consumption (g/kWh) =	187	211	230	187	208	253
BET, Fuel Oil Carbon (%) =	85.4	85.4	85.4	85.4	85.4	85.4
ALF, Fuel Oil Hydrogen (%) =	10.5	10.5	10.5	10.5	10.5	10.5
wDEL_G, Fuel Gas Nitrogen (%)	0.4	0.4	0.4	0.4	0.4	0.4
wEPS_G, Fuel Gas Oxygen (%)	0.9	0.9	0.9	0.9	0.9	0.9
CO2D, Measured CO2 dry (%) =	5.7	5.9	6.2	5.7	6.0	6.0
Ra, Relative humidity of inlet air (%) =	37	38	27	33	26	30
pB, Barometric Pressure of inlet air (kPa) =	101.3	101.3	101.3	101.3	101.3	101.3
Ta, Temperature of inlet air (oC) =	28.41	28.71	32.42	33.43	33.33	30.44
pa, Saturated Vapour press. of inlet air (kPa)* =	3.87	3.94	4.87	5.15	5.13	4.35
Ha, Humidity of inlet air (g H2O/kg dry air) =	8.81	9.43	8.25	10.62	8.38	8.16
ALPHA	1.47	1.47	1.47	1.47	1.47	1.47
cH2d	0.00088	0.00144	0.00195	0.00112	0.00233	0.00192
kw2	0.00235	0.00235	0.00235	0.00235	0.00235	0.00235
NUE, Water content of inlet air (% mass) =	0.873	0.934	0.819	1.051	0.831	0.810
Kwr3, dry/wet corr. factor in raw gas =	0.965	0.964	0.962	0.965	0.963	0.963
H2O in raw exhaust gas (%) =	3.46	3.60	3.81	3.48	3.69	3.71
Calculation of exhaust flow using Carbon balance in annex 2.2:						
GFUEL, Fuel consumption (kg/hr) =	1405	995	915	1405	1006	812
BET, Fuel Oil Carbon (%) =	85.4	85.4	85.4	85.4	85.4	85.4
CO2D, Measured CO2 dry (%) =	5.65	5.86	6.17	5.69	5.98	6.02
Kwr3, dry/wet corr. factor in raw gas =	0.965	0.964	0.962	0.965	0.963	0.963
ffd, fuel-spec. constant (-H+N+O %) dry gas	-0.573908	-0.574	-0.574	-0.573908	-0.574	-0.574
ffw, fuel-spec.constant (H+N+O%) wet gas	0.593	0.593	0.593	0.593	0.593	0.593
fc, carbon factor	3.06	3.17	3.34	3.08	3.24	3.26

Qmew, Exhaust mass flow wet (kg/h)	53637	36671	32099	53346	36338	29133
Qmaw, Intake air mass flow wet (kg/h)	52232	35676	31184	51940	35332	28321
ρ_{ew}, Exhaust density wet (kg/m3)	1.28	1.28	1.28	1.28	1.28	1.28
Qvew, Exhaust volume flow wet (m3/h)	42013	28741	25151	41830	28468	22822
Calculation of NOx correction factor for ambient conditions as in clause 13.3 version b) & other IMO parameters:						
HREF, Ref. value of humidity set by ISO =	10.71	10.71	10.71	10.71	10.71	10.71
Ha, Humidity of the inlet air (g H2O/kg dry air) =	8.81	9.43	8.25	10.62	8.38	8.16
Ta, Temperature of the inlet air (deg. K) =	301	302	305	306	306	303
TSC, Temperature of the intercooled air (deg. K) =	320	315	321	306	306	303
TSCRef, Intercooled air ref. temp. {ISO 3046-1} (deg. K) =	298	298	298	298	298	298
KHDIES, NOx corr. fact. for diesel with air cooler =	0.97	0.98	0.96	1.00	0.96	0.96
Dry atmospheric pressure, Ps (kPa) =	99.9	99.8	100.0	99.6	100.0	100.0
Atmospheric factor (fa) =	1.011	1.013	1.030	1.038	1.035	1.020

Table B10 contd. Calculation of gaseous emissions:						
	76%	48%	41%	76%	49%	32%
Measured CO2 dry (%) =	5.7	5.9	6.2	5.69	5.98	6.02
Measured O2 dry (%) =	13.6	13.4	12.9	13.44	13.12	13.06
Measured CO dry (ppm) =	114.0	187.3	197.0	134.00	234.75	208.71
Measured NOx dry (ppm) =	1019.0	1056.0	1265.0	974.40	1124.20	1202.49
MEasured SO2 (ppm)	3.7	1.5	1.3	615.20	650.38	648.59
Measured THC wet (ppm) =	45.4	63.4	n.a.	101.500	87.930	82.900
Measured nmHC wet (ppm) =	44.2	62.8	n.a.	101.30	87.000	81.800
Measured CH4 wet (ppm) =	1.1	0.6	n.a.	0.20	0.970	1.100
Qvew, Exhaust volume flow wet (m3/h)	42013	28741	25151	41830	28468	22822
Exhaust flow **measured** (m3/h)	35907	24956	24771			
Kwr3, dry/wet corr. factor in raw gas =	0.965	0.964	0.962	0.965	0.963	0.963
KHDIES, NOx corr. fact. for diesel with air cooler =	0.97	0.98	0.96	1.00	0.96	0.96
P, Power or effect during test (kW) =	7296	4640	3968	7296	4672	3072
Constants used: (divide with density 1.280 to have w)						
KwCO2, factor for CO2 to convert % to g/nm3 wet = 19.64						
KwO2, factor for O2 to convert % to g/nm3 wet = 14.29						
KwCO, factor for CO to convert ppm to g/nm3 wet =0.00125						
KwNOx, factor for NOx to convert ppm to g/nm3 wet =0.002053						
KwSO2 factor for SO2 to convert ppm to g/nm3 wet = 0.00291						
KwHC, factor for HC to convert ppmC to gHC/nm3 wet =0.000619						
CO2, Mass flow (kg/hr) =	4501	3187	2931	4509	3222	2601
O2, Mass flow (kg/hr) =	7883	5302	4451	7754	5144	4104
CO, Mass flow (kg/hr) =	5.8	6.5	6.0	6.8	8.1	5.7
NOx, Mass flow (kg/hr) =	82.3	58.8	60.4	80.7	61.0	52.1
SO2, Mass flow (kg/hr) =	0.4	0.1	0.1	72.3	51.9	41.5
THC, Mass flow (kg/hr) =	1.181	1.127	No data	2.63	1.55	1.17
nmHC, Mass flow (kg/hr) =	1.149	1.117	No data	2.62	1.53	1.16
CH4, Mass flow (kg/hr) =	0.029	0.010	No data	0.01	0.02	0.02

Calculated emission factors:						
CO2 Specific emission (g/kWh) =	617	687	739	618	690	847
O2 Specific emission (g/kWh) =	1080	1143	1122	1063	1101	1336
CO Specific emission (g/kWh/kWh) =	0.79	1.40	1.50	0.93	1.72	1.87
NOx Specific emission (g/kWh) =	11.28	12.68	15.22	11.06	13.06	16.97
NOx Specific emission (g/kWh) (corrected) =	10.9	12.4	14.6	11.0	12.6	16.3
SO2 Specific emission measured (g/kWh) =	0.06	0.03	0.02	9.90	11.11	13.51
SO2 Specific emission calculated (g/kWh)	n.a.	n.a.	n.a.	10.36	11.55	14.06
THC Specific emission (g/kWh) =	0.162	0.243	No data	0.360	0.332	0.382
nmHC Specific emission (g/kWh)=	0.158	0.241	No data	0.36	0.3	0.4
CH4 Specific emission (g/kWh)=	0.004	0.002	No data	0.001	0.004	0.005

Table B10 contd. Calculation of particulate emissions (numbers in parenthesis indicate filter number with reference to Error! Reference source not found. **and Table. Six filters were sampled after the dilution tunnel, these are indicated by specific emissions in bold.**

	Downstream scrubber			Upstream scrubber		
KP, PM corr. fact. (when 0,98 < fa < 1,02) =	1	1	1	1	1	1
P, Brake Power or effect during test (kW) =	7296	4640	3968	7296	4672	3072
Qvew, Exhaust volume flow wet (m3/h)	42013	28741	25151	41830	28468	22822
PMtot, (g/m3)	0.0595 (35)	0.0444 (29)	0.0367 (25)	0.0755 (53)	0.0708 (47)	0.0816 (43)
PMtot, (g/m3)	0.0469 (38)	0.0310 (31)	0.0428 (28)	0.0645 (55)	0.0597 (48)	0.0465 (45)
PMtot, (g/m3)	0.0465 (40)	0.0401 (33)		0.0770 (56)	0.0581 (49)	0.0713 (46)
PMtot, (g/m3)				0.0840 (57)	0.0534 (51)	
PM+cyclone, (g/m3)	0.0467 (36)	0.0400 (32)	0.0342 (26)	0.0480 (54)	0.0598 (50)	0.1011 (42)
PM+cyclone, (g/m3)	0.0412 (37)	0.0399 (30)	0.0416 (27)	0.0623 (58)	0.0588 (52)	0.0596 (44)
PM+cyclone, (g/m3)	0.0388 (39)	0.0341 (34)				
PMtot, (g/hr)=	2499 (35)	1277 (29)	923 (25)	3160 (53)	2017 (47)	1862 (43)
PMtot, (g/hr)=	1966 (38)	891 (31)	1077 (28)	2700 (55)	1700 (48)	1061 (45)
PMtot, (g/hr)=	1952 (40)	1153 (33)		3220 (56)	1654 (49)	2982 (46)
PMtot, (g/hr)=				3512 (57)	1520 (51)	
PM+cyclone, (g/hr)=	1964 (36)	1146 (32)	860 (26)	2009 (54)	1701 (50)	2307 (42)
PM+cyclone, (g/hr)=	1728 (37)	1148 (30)	1046 (27)	2607 (58)	1675 (52)	1360 (44)
PM+cyclone, (g/hr)=	1632 (39)	980 (34)				
PMtot Specific emission (g/kWh)	0.54 (35)	0.28 (29)	0.23 (25)	0.68 (53)	**0.45 (47)**	**0.63 (43)**
PMtot Specific emission (g/kWh)	0.27 (38)	0.19 (31)	0.27 (28)	**0.37 (55)**	**0.38 (48)**	0.35 (45)
PMtot Specific emission (g/kWh)	0.27 (40)	0.16 (33)		0.44 (56)	0.23 (49)	**0.41 (46)**
PMtot Specific emission (g/kWh)				**0.48 (57)**	0.21 (51)	
PM + cyclone spec. emission (g/kWh)	0.27 (36)	0.25 (32)	0.22 (26)	0.28 (54)	0.36 (50	0.75 (42)
PM + cyclone spec. emission (g/kWh)	0.24 (37)	0.25 (30)	0.26 (27)	0.36 (58)	0.36 (52)	0.44 (44)
PM + cyclone spec. emission (g/kWh)	0.22 (39)	0.21 (34)				

Error! Reference source not found. **B10 contd. Calculation of particulate emissions from quartz filter, EC, and OC emission factors, BC emissions and PAH emissions, tests upstream and downstream the scrubber. Dilution with FPS.**

	Downstream scrubber			Upstream scrubber		
Load, Brake Load during test (%)	76%	48%	41%	76%	49%	32%
P, Brake Power or effect during test (kW)	7296	4640	3968	7296	4672	3072
Concentration PM (g/m3)	0.0477	0.0550	0.0209	No data	0.0864	0.0795
Concentration PM (size cutoff with cyclone) (g/m3)	0.0491	0.0357	No data	0.0769	0.119	No data
Mass flow PMtot (g/hr)	2004	1581	525	No data	2460	1815
Mass flow PM (size cutoff with cyclone) (g/hr)	2065	1025	No data	3216	3385	No data
PM Specific emission, from tests on quartz filters, (g/kWh)	0.27	0.34	0.13	No data	0.54	0.61
PM Specific emission (size cutoff with cyclone) from tests on quartz filters, (g/kWh)	0.28	0.22	No data	0.44	0.75	No data
Concentration TC (g/m3)=	0.0195	0.0215	0.0078	0.0227	0.0262	0.0457
Concentration TC (size cutoff with cyclone) (g/m3)	0.0150	0.0186	No data	0.0184	0.0326	0.0469
Mass flow TC(g/hr),	818	6189	197	948	747	1043
Mass flow TC (size cutoff with cyclone) (g/hr)	629	533	No data	771	929	1070
TC Specific emission (g/kWh)	0.11	0.13	0.050	*0.130*	0.165	0.351
TC spec. emission (size cutoff with cyclone) (g/kWh)	0.09	0.11	No data	0.106	0.205	*0.360*
Concentration OC (g/m3)=	0.017	0.019	0.0065	0.012	0.018	0.033
Concentration OC (size cutoff with cyclone) (g/m3)	0.013	0.016		0.015	0.024	0.034
Mass flow OC(g/hr),	702	537	163	513	519	750
Mass flow OC (size cutoff with cyclone) (g/hr)	531	459		609	683	783
OC Specific emission (g/kWh)	**0.096**	**0.116**	**0.041**	***0.070***	**0.115**	**0.253**
OC spec. emission (size cutoff with cyclone) (g/kWh)	**0.073**	**0.099**		**0.084**	**0.151**	***0.264***
Concentration EC (g/m3)=	0.0028	0.0028	0.0014	0.0104	0.0080	0.0128
Concentration EC (size cutoff with cyclone) (g/m3)	0.0023	0.0026		0.0039	0.0086	0.0125
Mass flow EC(g/hr),	116	82	34	435	227	292
Mass flow EC (size cutoff with cyclone) (g/hr)	97	74		162	246	286
EC Specific emission (g/kWh)	**0.016**	**0.018**	***0.009****	***0.060****	**0.050**	**0.0985**
EC spec. emission (size cutoff with cyclone) (g/kWh)	**0.013**	**0.016**		**0.022**	**0.054**	***0.0965****

Table B10 contd. Calculation of BC emissions. Dilution with FPS.

	Downstream scrubber			Upstream scrubber		
Qvew, Exhaust volume flow wet (m3/h)	42013	28741	25151	41830	28468	22822
P, Brake Power or effect during test (kW)	7296	4640	3968	7296	4672	3072
Concentration BC (g/m3)	0.0038	0.0035	0.0044	0.0039	0.0056	0.0085
Concentration BC using Thermodenuder	0.0040	0.0035	0.0045	0.0035	0.0032	0.0080
Mass flow BC (g/hr)	161	100	111	162	161	194
Mass flow BC using thermodenuder(g/hr)	168	101	114	146	90	182
BC Spec emission (g/kWh)	**0.022**	**0.022**	**0.028**	**0.022**	**0.035**	**0.065**
BC Spec emission using thermodenuder (g/kWh)	**0.023**	**0.022**	**0.029**	**0.020**	**0.020**	**0.061**

Error! Reference source not found.**Table B105 contd. Calculation of PN emissions. Measurements with SMPS. Dilution with FPS.**

	Downstream scrubber			Upstream scrubber		
Qvew, Exhaust volume flow wet (m3/h)	42013	28741	25151	41830	28468	22822
P, Brake Power or effect during test (kW)	7296	4640	3968	7296	4672	3072
Concentration PN (#/m3)	1.7E+14	1.3E+14	No data	No data	No data	2.92E+14
Concentration PN, thermodenuder (#/m3)	1.6E+14	9.6E+13	No data	No data	No data	7.98E+13
# flow PN (#/hr)	7E+18	3.77E+18	No data	No data	No data	6.7E+18
# flow PN, thermodenuder (#/hr)	7E+18	2.77E+18	No data	No data	No data	1.8E+18
PN Spec emission (#/kWh)	**1E+15**	**8E+14**	**No data**	**No data**	**No data**	**2E+15**
PN Spec emission, thermodenuder (#/kWh)	**9E+14**	**6E+14**	**No data**	**No data**	**No data**	**6E+14**

Table B10. contd. Calculation of PN emissions. Measurements with EEPS. Dilution with FPS.

	Downstream scrubber			Upstream scrubber		
Qvew, Exhaust volume flow wet (m3/h)	42013	28741	25151	41830	28468	22822
P, Brake Power or effect during test (kW)	7296	4640	3968	7296	4672	3072
Concentration PN (#/m3)	2.0E+14	1.4E+14	3E+14	9.6E+14	7.9E+14	8.9E+14
Concentration PN, thermodenuder (#/m3)	2.1E+14	1.4E+14	1E+14	1.5E+14	2.6E+14	1.2E+14
# flow PN (#/hr)	8E+18	4.00E+18	7.74E+18	4.0E+19	2.3E+19	2.0E+19
# flow PN, thermodenuder (#/hr)	9E+18	3.98E+18	3.26E+18	6.4E+18	7.4E+18	2.6E+18
PN Spec emission (#/kWh)	**1E+15**	**9E+14**	**2E+15**	**6E+15**	**5E+15**	**7E+15**
PN Spec emission, thermodenuder (#/kWh)	**1E+15**	**9E+14**	**8E+14**	**9E+14**	**2E+15**	**9E+14**

Table B10 contd. Calculation of PAH (sum USEPA 16 PAH) emissions

	Downstream scrubber			Upstream scrubber		
Qvew, Exhaust volume flow wet (m3/h)	42013	28741	25151	41830	28468	22822
P, Brake Power or effect during test (kW)	7296	4640	3968	7296	4672	3072
SO_3 (g/m3)	0.014	0.008	0.009	0.064	0.021	0.021
Mass flow SO_3 (mg/hr)	588.19	229.93	226.36	2677	598	479
SO_3 Spec emission (g/kWh)	**0.08**	**0.05**	**0.06**	**0.37**	**0.13**	**0.16**

Table B10 contd. Calculation of SO_3 in gas

	Downstream scrubber			Upstream scrubber		
Qvew, Exhaust volume flow wet (m3/h)	42013	28741	25151	41830	28468	22822
P, Brake Power or effect during test (kW)	7296	4640	3968	7296	4672	3072
SO3 from PAH filter (g/m3)	0.136	0.114	0.118	0.280	0.259	0.263
PAH (mg/m3)	0.134	0.177	0.145	0.240	0.247	0.260
Mass flow PM from PAH filter (g/hr)	5710	3280	2970	11700	7370	6000
Mass flow PAH (mg/hr)	5630	5090	3650	10000	7030	5930
PM mass from PAH filter Spec emission (g/kWh)	0.78	0.71	0.75	1.6	1.6	2.0
PAH Spec emission (mg/kWh)	0.77	1.1	0.92	1.4	1.5	1.9

*Not used in further analysis due to suspected handling errors during sampling

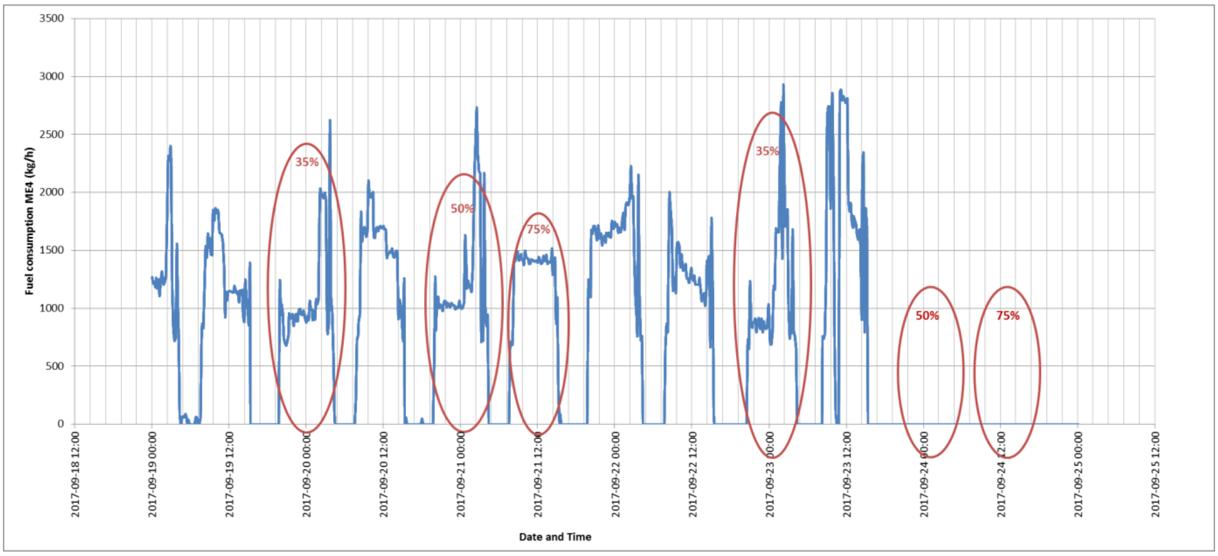


Figure B1. Fuel consumption during trials according to data from ship owner's office. The periods for the trials are indicated by red circles and the respective engine loads are given.

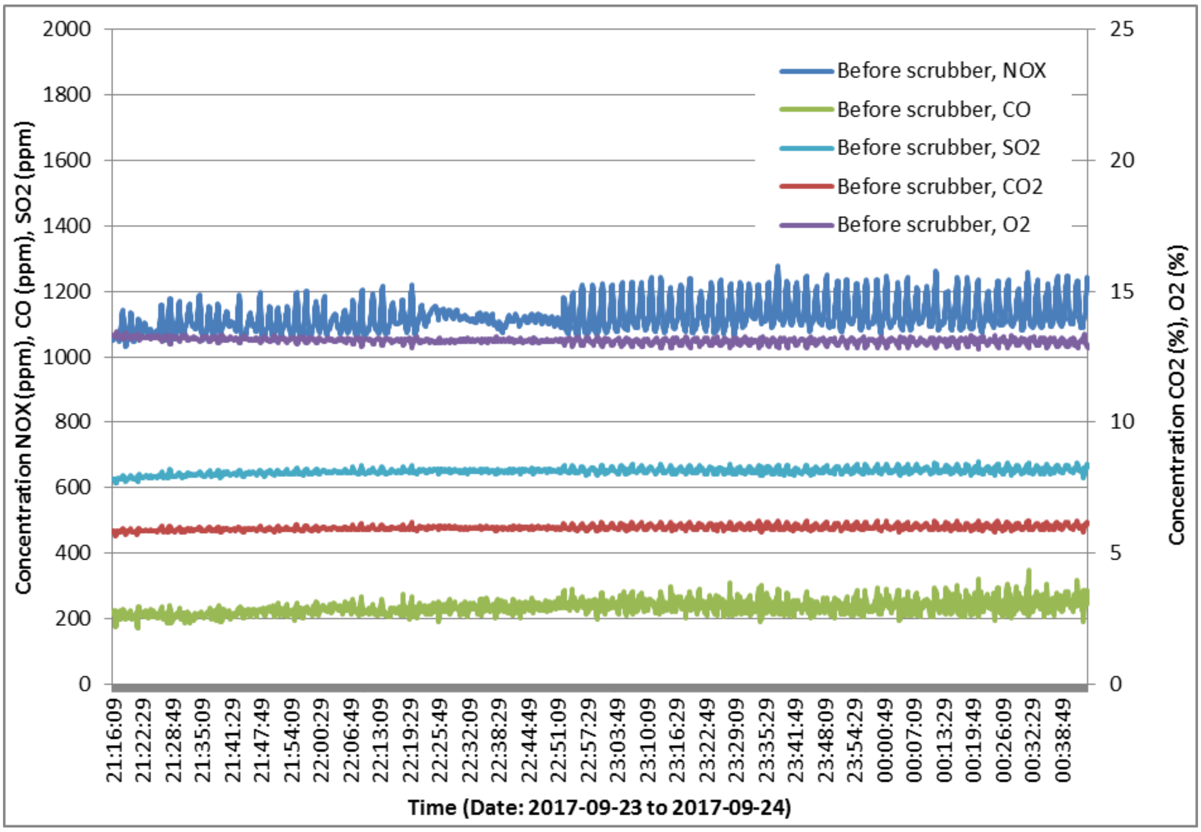


Figure B2. Gaseous emission concentrations of NO_X, CO, CO_2, O_2, and SO_2 at 49% engine load, tests upstream the scrubber. Gas concentrations for time period 21:16:09 to 00:44:24 are used for further analysis

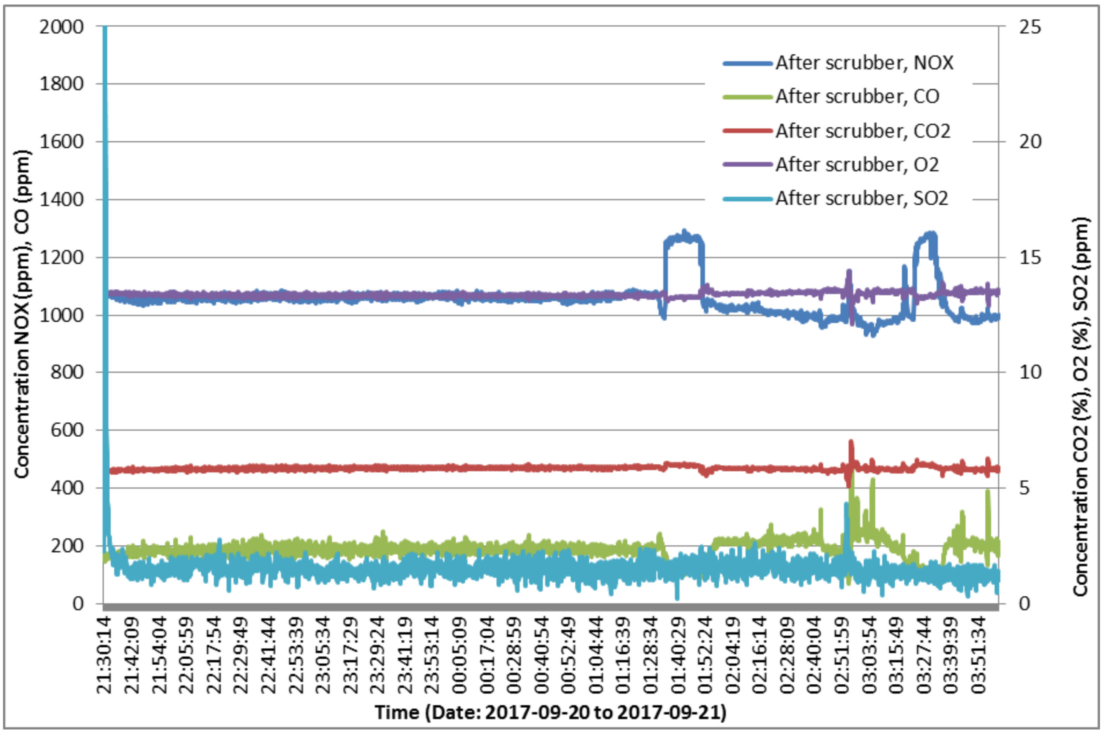


Figure B3. Gaseous emission concentrations of NO_X, CO, CO_2, O_2, and SO_2 at 48% engine load, tests downstream the scrubber. N.B. Scrubber concentration is to be read from secondary axis. Gas concentrations for time period 21:30:14 to 04:00:54 are used for further analysis

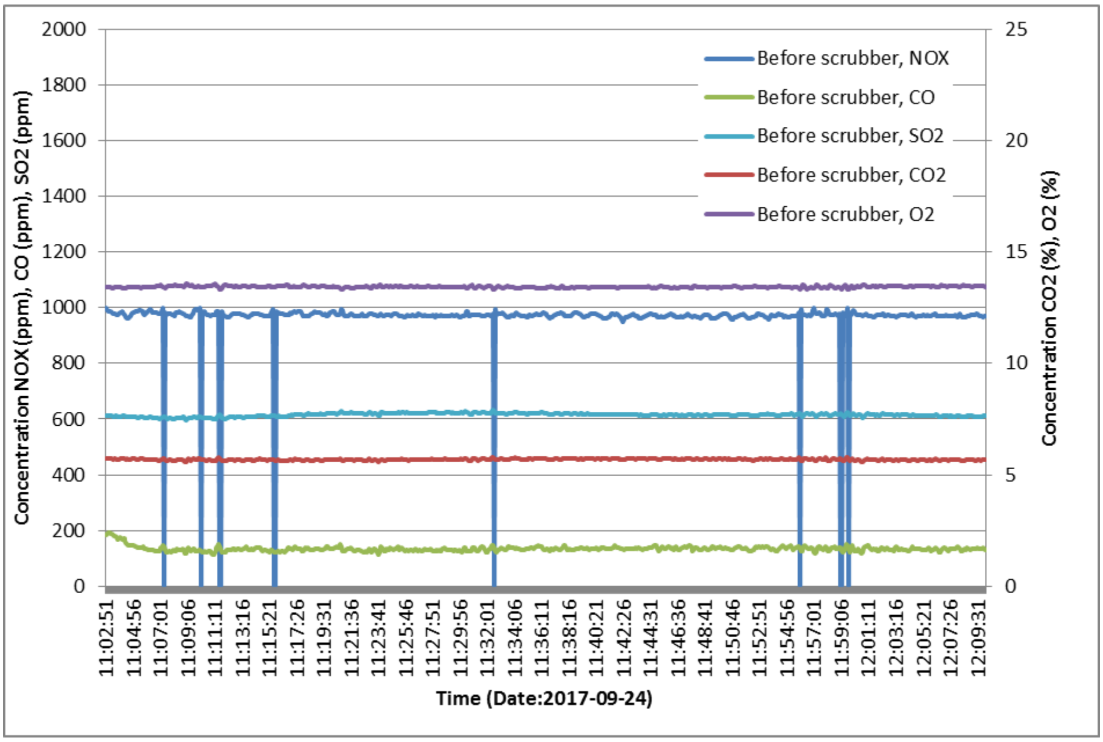
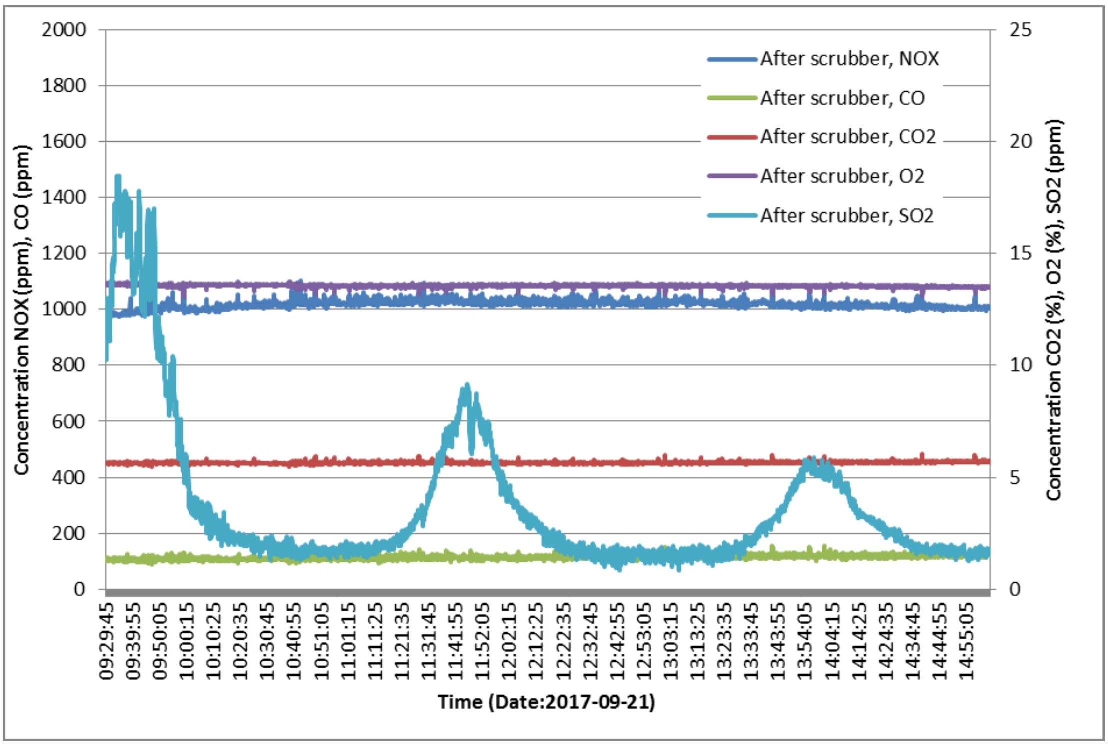


Figure B4. Gaseous emission concentrations of NO_X, CO, CO_2, O_2, and SO_2 at 76% engine load, tests upstream the scrubber. Gas concentrations for time period 11:02:51 and 12:10:06 are used for further analysis



FigureB5. Gaseous emission concentrations of NO_X, CO, CO_2, O_2, and SO_2 at 76% engine load, tests downstream the scrubber. N.B. Scrubber concentration is to be read from secondary axis. Gas concentrations for time period 09:29:45 to 15:04.05 are used for further analysis

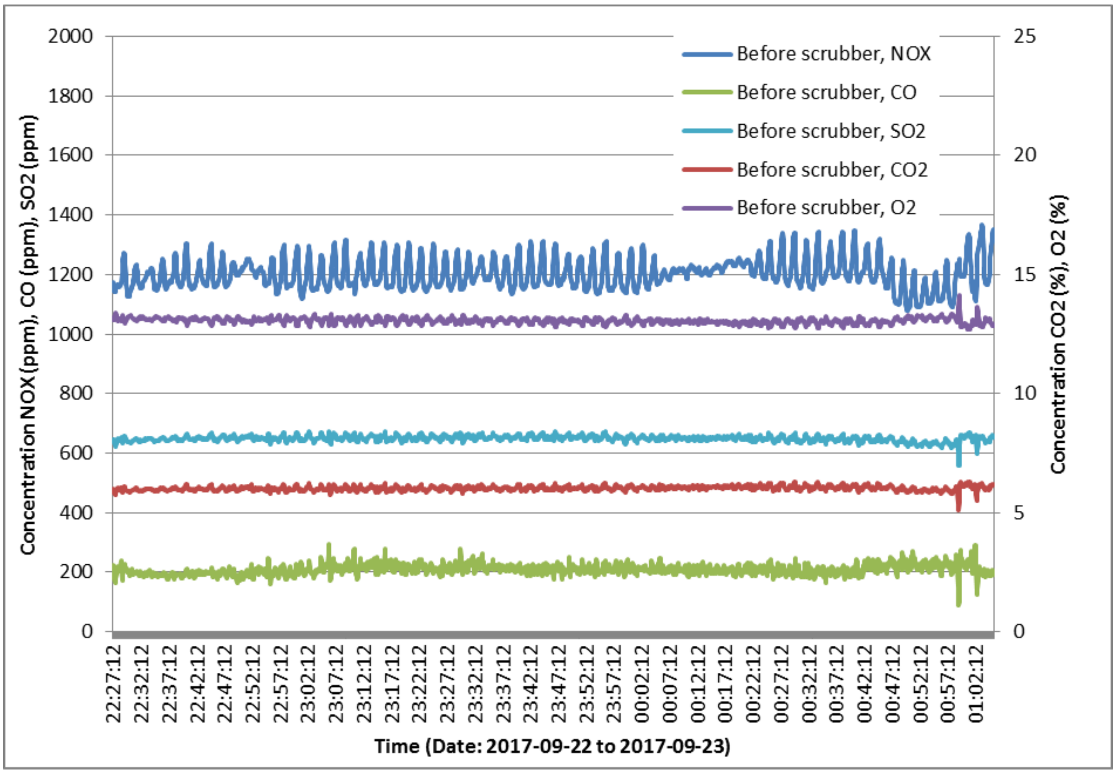


Figure B6. Gaseous emission concentrations of NO_X, CO, CO_2, O_2, and SO_2 at 32% engine load, tests upstream the scrubber. Gas concentrations for time period 22:27:12 to 01:05:27 are used for further analysis

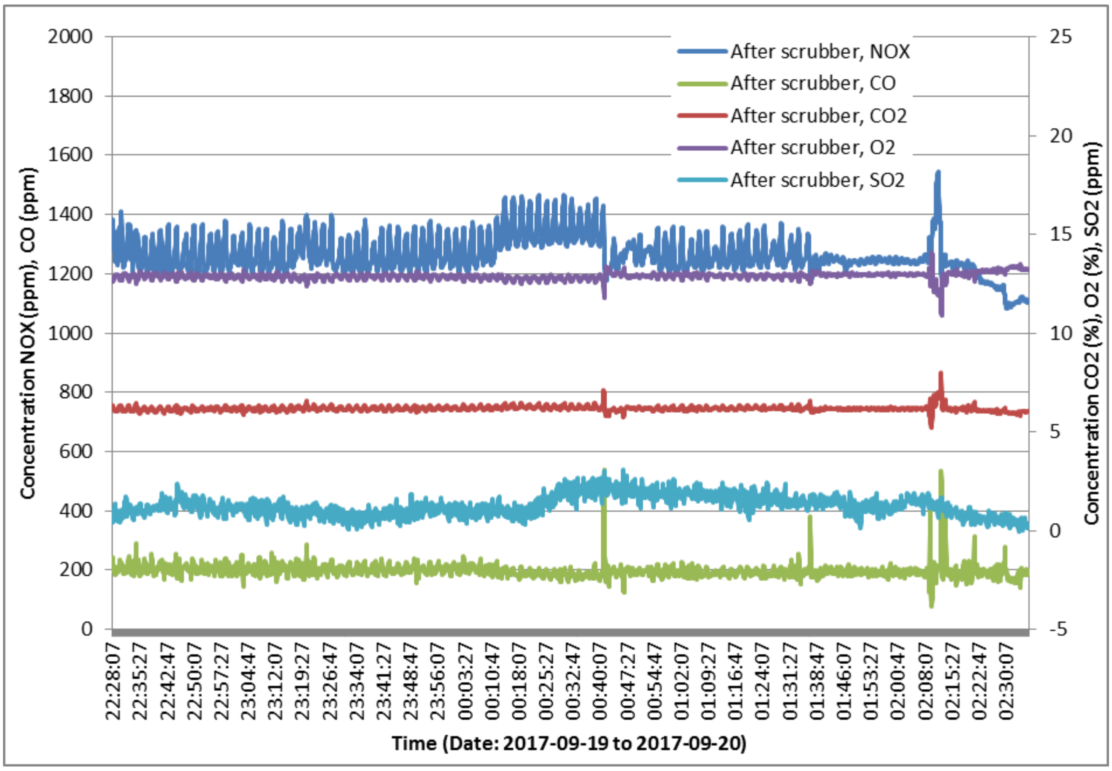


Figure B7. Gaseous emission concentrations of NO_X, CO, CO_2, O_2, and SO_2 at 41% engine load, tests downstream the scrubber. N.B. Scrubber concentration is to be read from secondary axis. Gas concentrations for time period 22:28:07 to 02:36:22 are used for further analysis

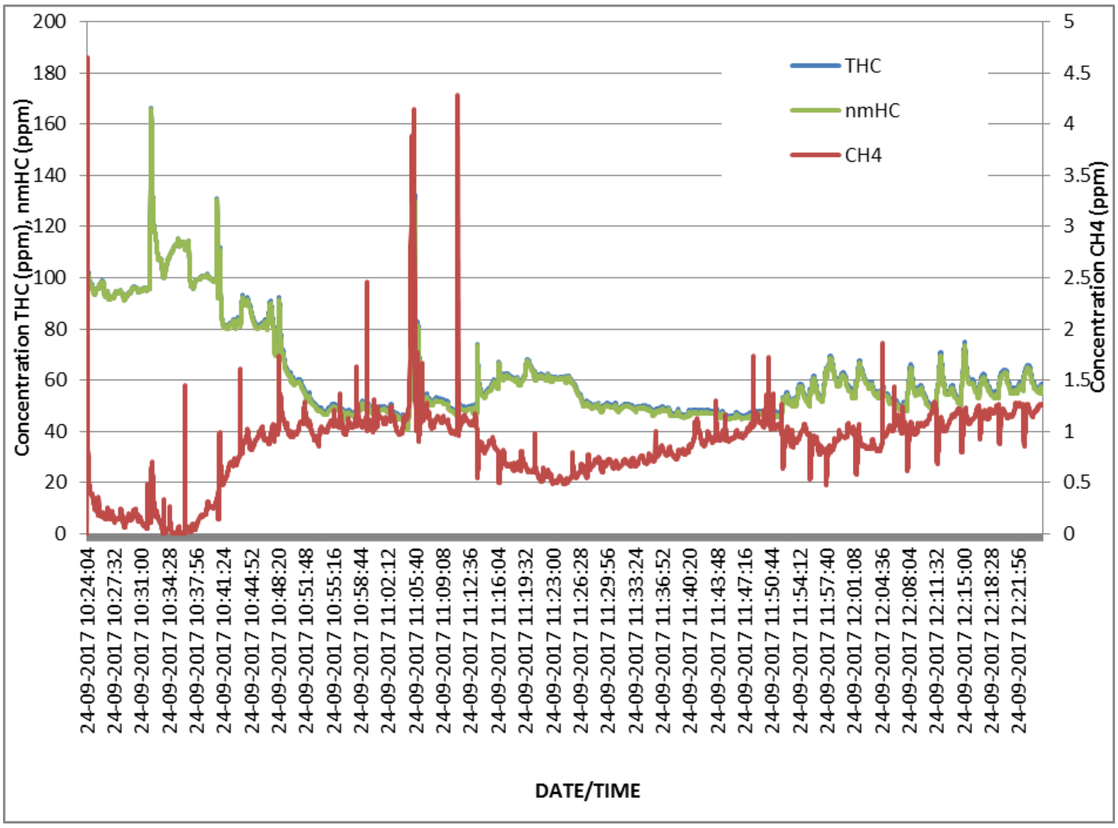


Figure B8. Hydrocarbon emission concentrations at 76% engine load, tests upstream the scrubber. Gas concentrations for time period 11:15 to 12:09 are used for further analysis.

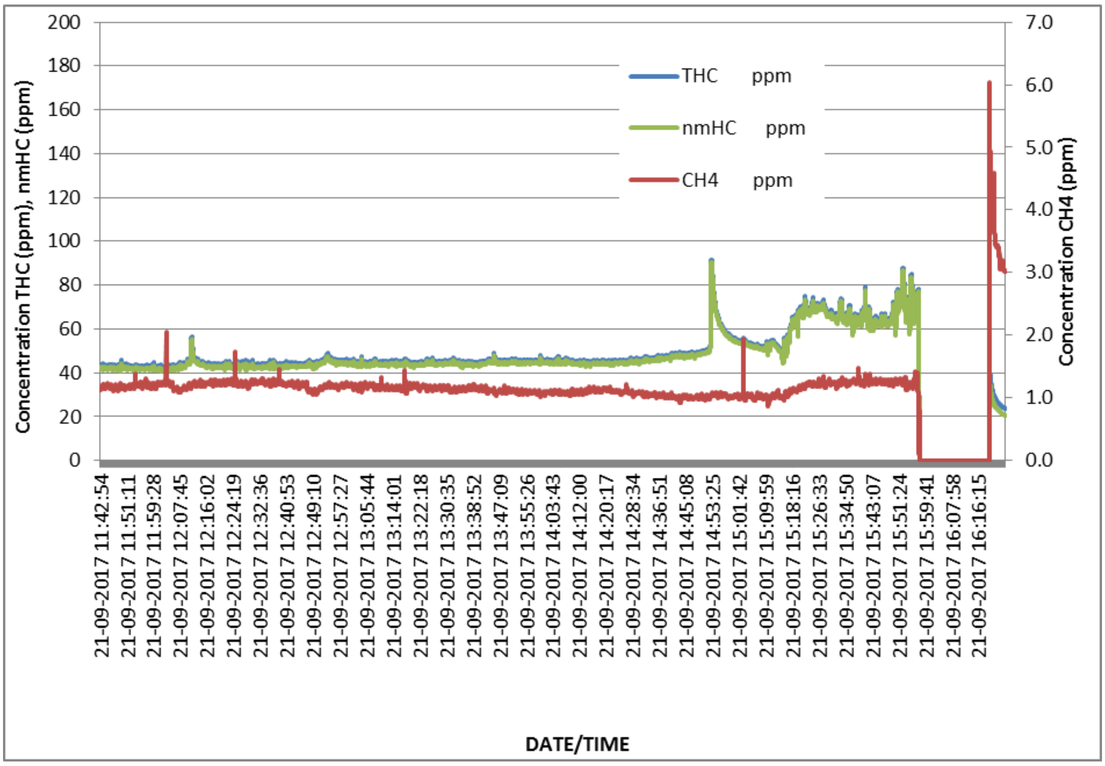


Figure B9. Hydrocarbon emission concentrations at 76% engine load, tests downstream the scrubber. Gas concentrations for time period 12:50 to 14:25 are used for further analysis.

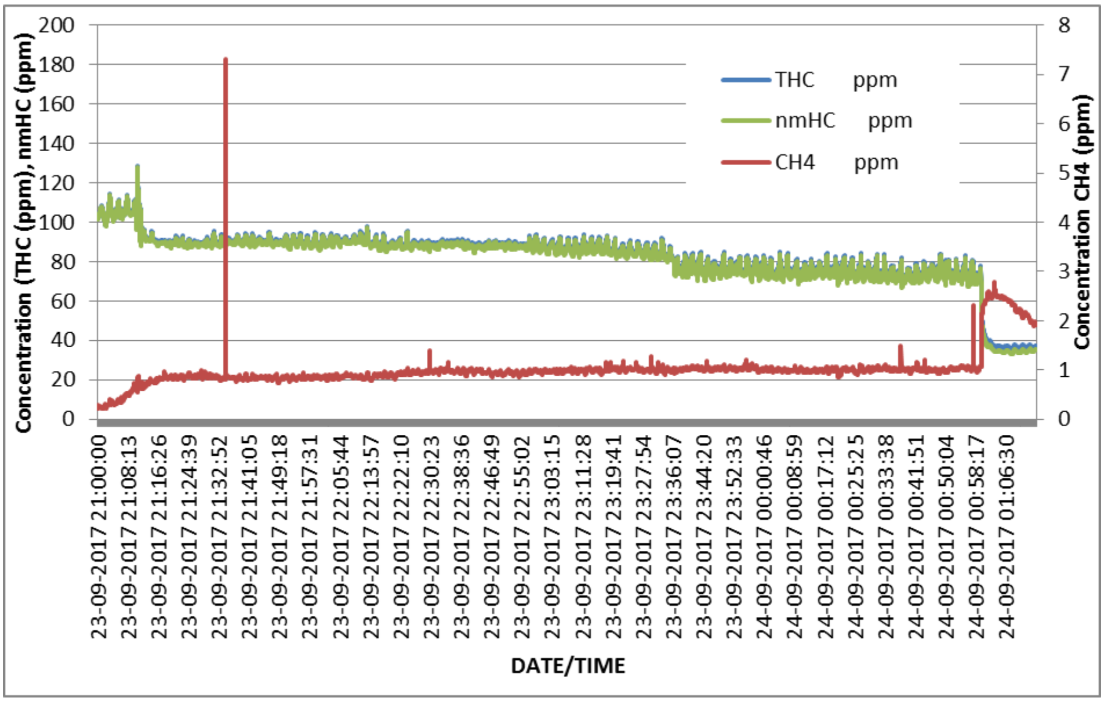


Figure B10. Hydrocarbon emission concentrations at 49% engine load, tests upstream the scrubber. Gas concentrations for time period 22:17 to 23:35 are used for further analysis.

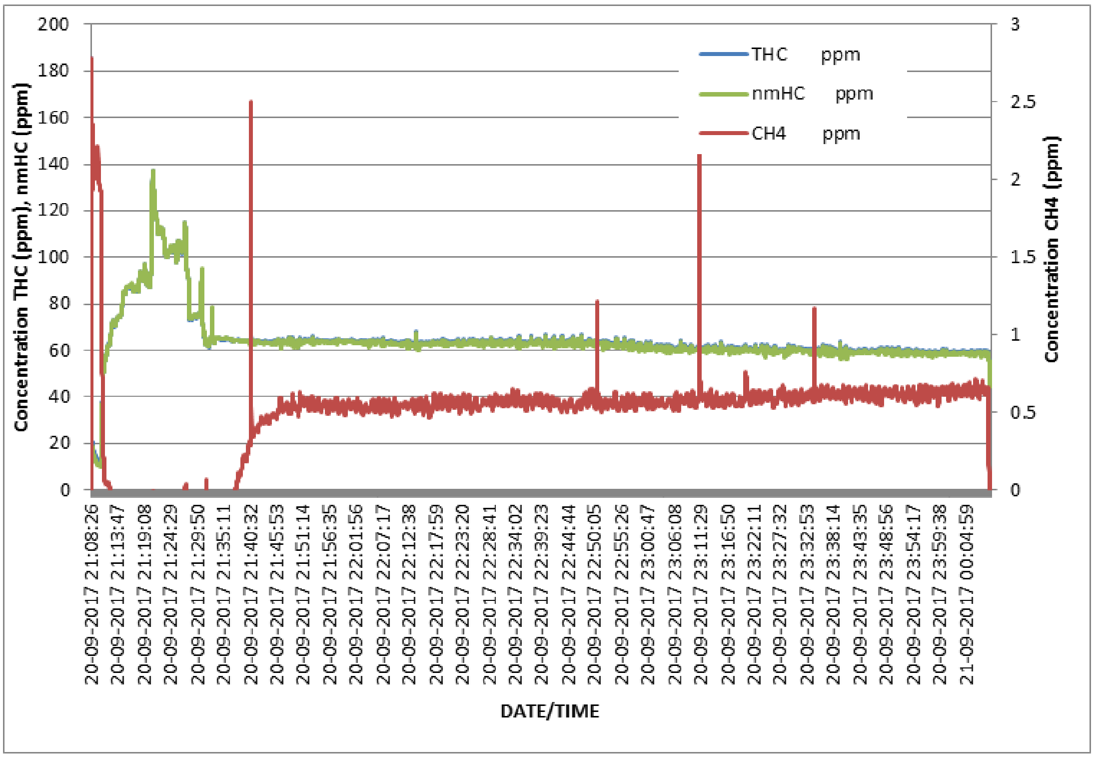


Figure B11. Hydrocarbon emission concentrations at 48% engine load, tests downstream the scrubber. Gas concentrations for time period 22:20 to 23:00 are used for further analysis.

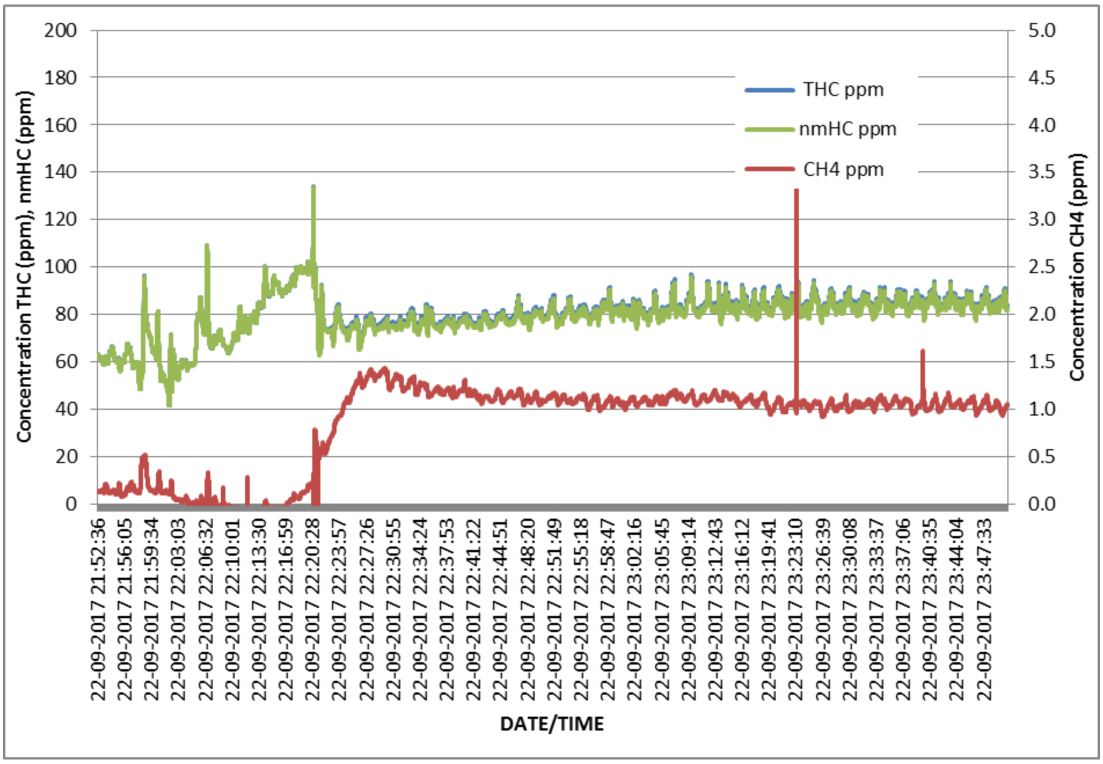


Figure B12. Hydrocarbon emission concentrations at 32% engine load, tests upstream the scrubber. Gas concentrations for time period 22:50 to 23:20 are used for further analysis.

At 41% engine load, measurements downstream the scrubber, two distinct dilution ratios were used in the measurements. One at 131 times dilution for tests between 23:04 and 01:00, and one at 44 times dilution for tests between 01:28 and 02:18. These values are average values for the specified time periods. The levels of CO_2 in the diluted gas and the calculated dilution ratio for these tests are presented in Figure B13. The only dilution system used was the FPS system using pressurized air.

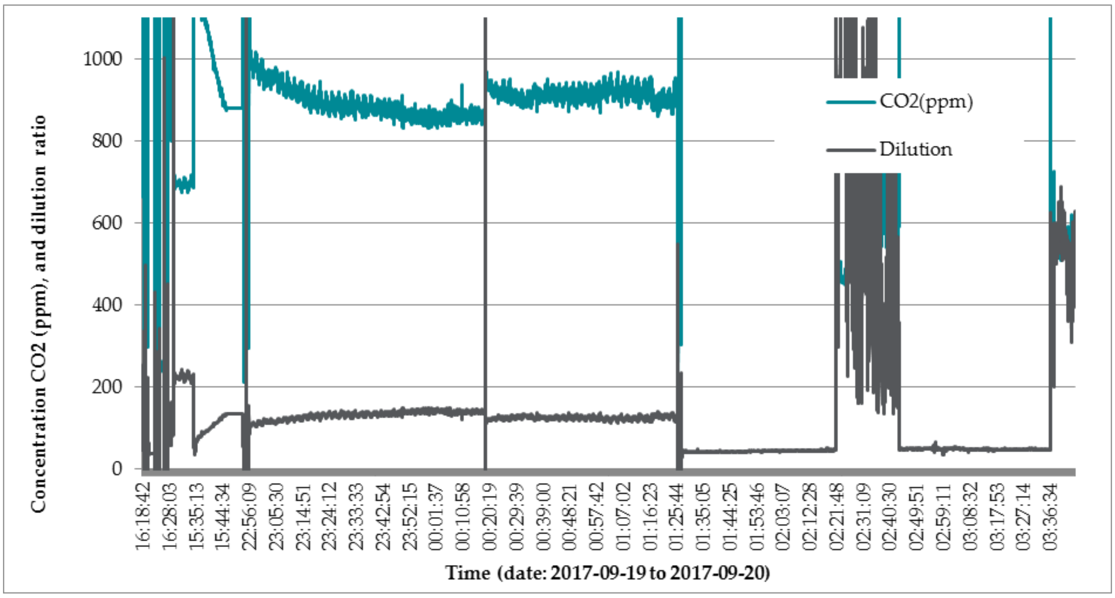


Figure B13. Concentration of CO_2 in diluted sample gas and, dilution ratio at tests downstream the scrubber at 41% engine load.

At 48% engine load, measurements downstream the scrubber, four dilution ratios were used. The two first are from overlapping time periods. The overlap is made to have relevant average values of dilution ratios for the time periods used for certain tests. The time periods and the respective average values of dilution ratios are; 21:52 to 22:05 DR; 157, 21:59 to 23:12 DR 165, 23:13 to 23:50 DR 167, and 00:00 to 03:40 DR54. The CO_2 concentrations and the dilution during the tests are presented in Figure B14. The only dilution system used was the FPS system using pressurized air.

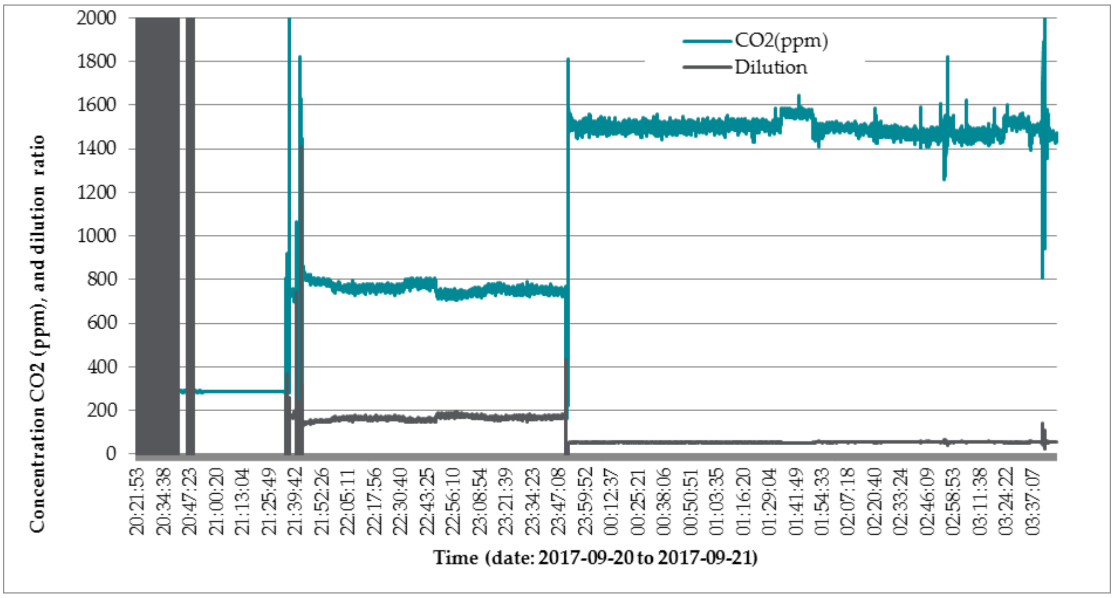


Figure B14. Concentration of CO_2 in diluted sample gas and, dilution ratio at tests downstream the scrubber at 48% engine load.

At 76% engine load, measurements downstream the scrubber, average values on dilution ratios for eight periods were used. The dilution ratio was very high and varying in the beginning of the test period. The time periods and the respective average values of dilution ratios were; 09:47 to 09:52 DR 192, 10:02 to 10:19 DR 297, 10:27 to 10:39 DR 358, 10:33 to 10:58 DR 422, 11:03 to 11:14 DR 434, 11:23 to 11:32 DR 406, 11:50 to 15:15 DR 71. Overlaps between periods for average values of DR are made to have relevant values for the time periods used for certain tests. The CO_2 concentrations and the dilution during the tests are presented in Figure B15. The only dilution system used was the FPS system using pressurized air.

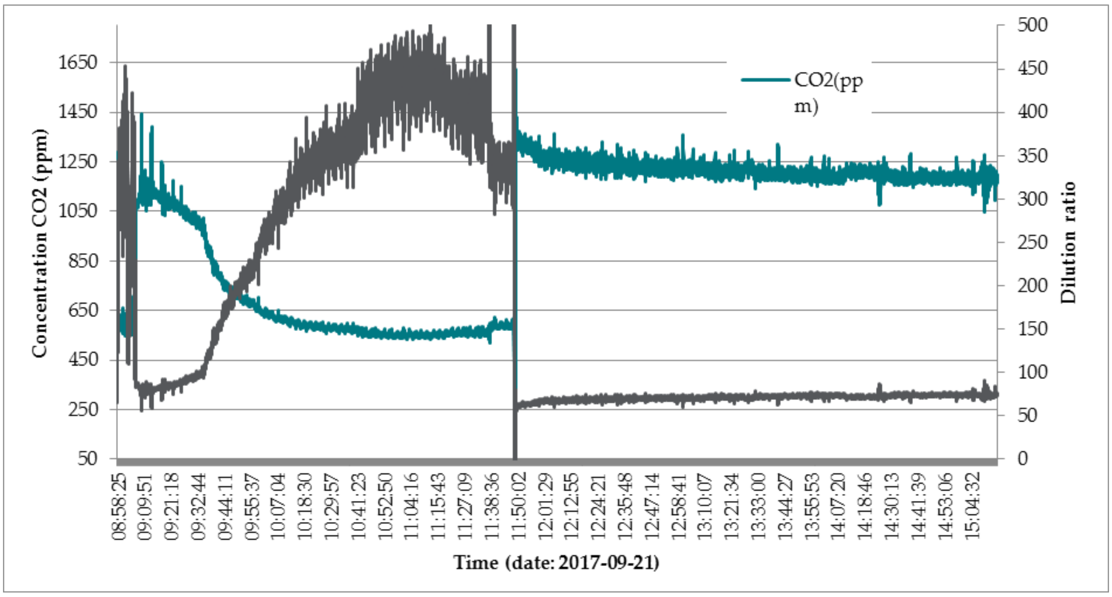


Figure B15. Concentration of CO_2 in diluted sample gas and, dilution ratio at tests downstream the scrubber at 76% engine load.

At 32% engine load, measurements upstream the scrubber, four periods with different average values for dilution ratios were singled out: 22:51 to 22:59 DR 198.5, 23:03 to 23:12 DR 230, 23:10 to 01:30 DR 251, and 23:43 to 00:43 DR 246. The CO_2 concentrations and the dilution during the tests are presented in Figure B16. Since the CO_2 instrument was not logging data prior to 22:50, we assumed DR before this to have been the same as at 22:50, namely 96. A weighted average of dilution ratio between 22:30 and 23:08 gives a dilution ratio for this period of 151 times. This factor is used for filter number 42. In addition to the dilution system with pressurized air, tests were also made using the dilution tunnel. Dilution ratios in the dilution tunnel were 14.4 for two filters sampled at 32% engine load.

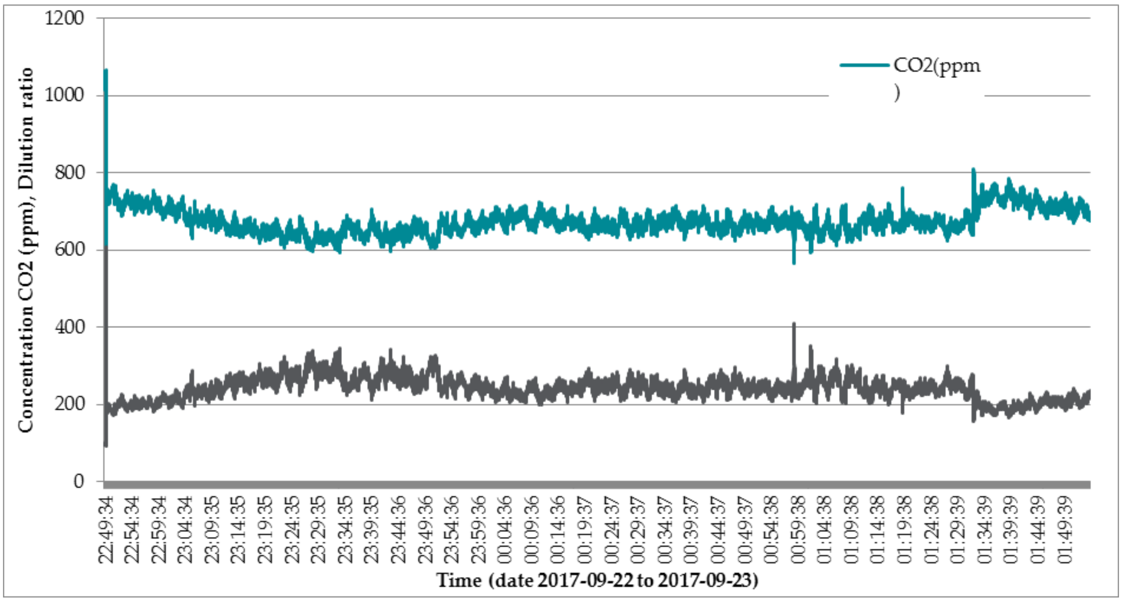


Figure B16. Concentration of CO_2 in diluted sample gas and, dilution ratio at tests upstream the scrubber at 32% engine load.

At 49% engine load, measurements upstream the scrubber, six periods with different average values for dilution ratios were singled out: 21:45 to 22:45 DR 255, 21:50 to 22:20 DR 257, 22:23 to 22:39 DR 252, 22:58 to 23:09 DR 212, 23:03 to 23:48 DR 190, and 0:10 to 00:52 DR 162. The CO_2 concentrations and the dilution during the tests are presented in Figure B17. In addition to the dilution system with pressurized air, tests were also made using the dilution tunnel. Dilution ratios in the dilution tunnel were 16.1 for two filters sampled at 49% engine load.

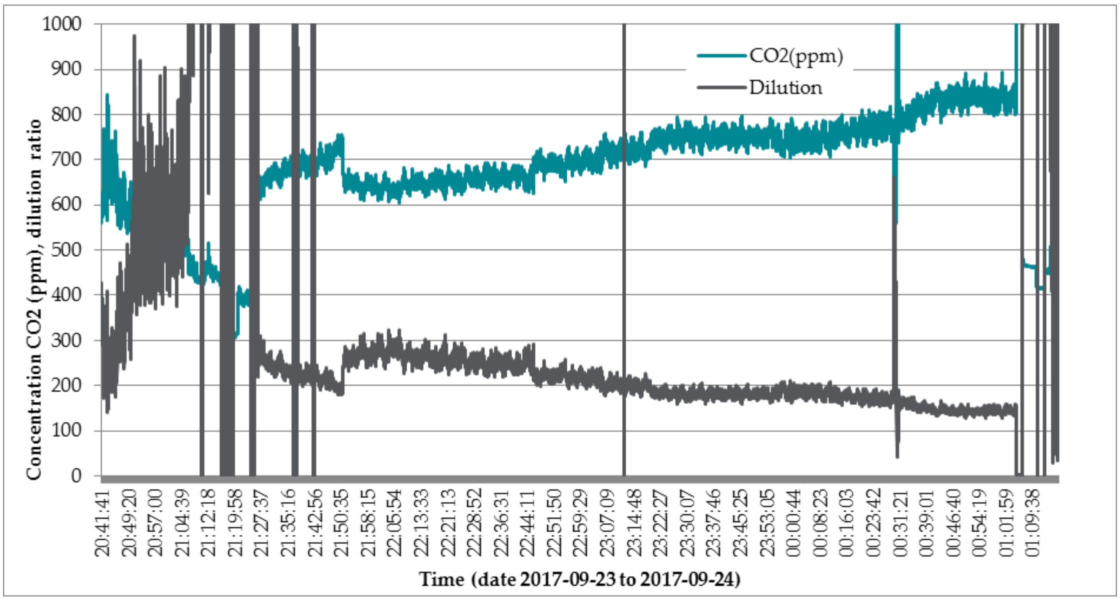


Figure B17. Concentration of CO_2 in diluted sample gas and, dilution ratio at tests upstream the scrubber at 49% engine load.

Also at 76% engine load, measurements upstream the scrubber, five periods with different average values for dilution ratios were used: 10:01 to 11:43 DR 213, 11:20 to 12:15 DR 149, 12:01 to 12:50 DR 154, 12:20 to 12:50 DR 163, and 14:15 to 15:00 DR 60. The CO_2 concentrations and the dilution during the tests are presented in Figure B18. The dilution ratio varied significantly during these tests. In addition to the dilution system with pressurized air, tests were also made using the dilution tunnel. Dilution ratios in the dilution tunnel were 14.4 for two filters sampled at 76% engine load.

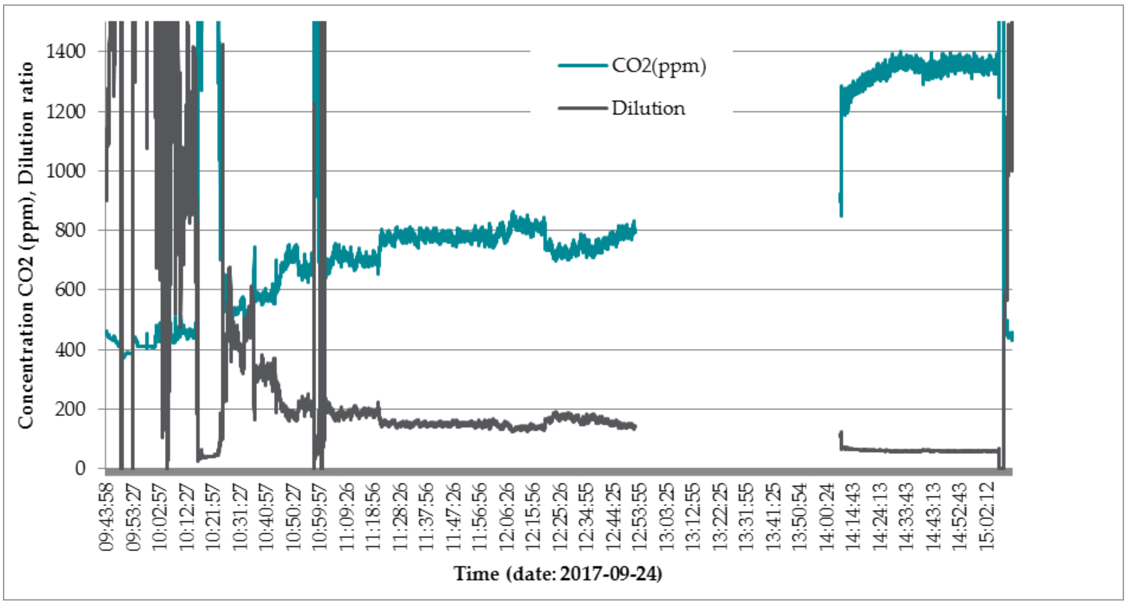


Figure B18. Concentration of CO_2 in diluted sample gas and, dilution ratio at tests upstream the scrubber at 76% engine load.

Appendix C.

Determination of SFOC

SFOC and relevance of values on fuel consumption and engine loads

The correctness of fuel consumption data from the two sources: measurement protocol and log from ship owner's office were assessed together with data on power outtake during trials. The specific fuel oil consumption (SFOC) for potential combinations of fuel consumption and engine loads was calculated. Steady state engine loads noted in the measurement protocol corresponded to the requested engine loads during trials; 85%, 75%, 50%, and 34%. However, with a maximum continuous rating of the engine of 9600 kW, the power at the different loads would be 8160 kW, 7200 kW, 4800 kW, and 3360 kW for each specified load. These are all considerably less than the brake power noted in the protocols for the same engine loads. These instead correspond to 95%, 82%, 60%, and 46% of MCR. There are thus four potential combinations of used engine load and fuel consumption during each test. The four combinations are presented in Table C1.

Table C1. Potential combinations of data on fuel consumption and engine power used to calculate specific fuel oil consumption.

	Origin of fuel consumption data	Origin of engine load data
SFOC, 1st combination	Fuel consumption from Stena office	Engine load noted in measurement protocol
SFOC, 2nd, combination	Fuel consumption from notes in measurement protocol	Engine load noted in measurement protocol
SFOC, 3rd, combination	Fuel consumption from Stena office	Engine load calculated from power noted in measurement protocol
SFOC, 4th, combination	Fuel consumption from notes in measurement protocol	Engine load calculated from power noted in measurement protocol

In Figure C1 the four potential combinations of are plotted as SFOC/engine load together with the shop test protocol values. The most typical SFOC curve is seen when combining fuel consumption data from the ship owner's log with the engine loads in % MCR stated in the protocol. These values are used in the calculations of emission factors and compared with the engine protocol during the second set of trials to avoid misinterpretations.

The shop test protocol of the engine indicates less difference in specific fuel consumption for different engine loads than what was observed during the emission measurements – the light blue line in Figure C1.

A loss of energy over the gearbox between 1% and 5%, of produced energy was estimated by the chief engineer. The gearbox is placed before the output is measured and the SFOC is calculated considering a 3% loss, which was assumed to be the most likely value by the chief engineer. The loss is a rough estimate. It is further unlikely that the loss is a relative value, and more likely an absolute value. The error bars on the SFOCs used in the calculations indicate SFOC at the different engine loads for gear box losses of 1%, and 5% respectively.

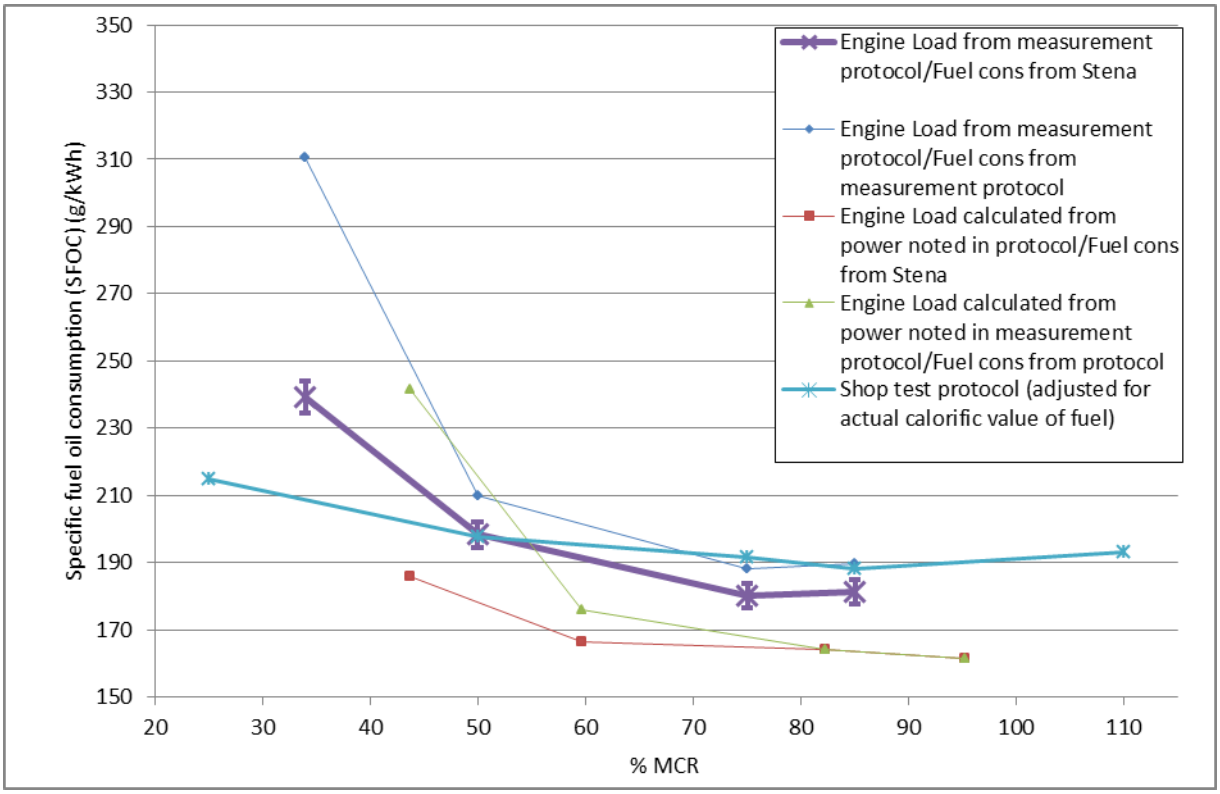


Figure C1. SFOC in relation to % MCR of the engine during trials; the diagram gives combinations of data on fuel consumption from two different sources and two different protocol entries on engine power.

SFOC at the different loads in the trial was calculated to 181, 180, 198, and 239 g/kWh for 85%, 75%, 50% and 34% respectively.

IVL Svenska Miljoinstitutet AB
FE 267
833 83, Stromsund
Sweden

Saybolt
A CORE LABORATORIES COMPANY

Attention of : Mrs. H. Winnes

Analysis Report

Report number	: **11601/00043862.4/L/17**	Submitted date	: 2017-03-15
Main Object	: IVL samples	Sample submitted at	: Saybolt Sweden
Report Date	: 2017-03-27	Date received	: 2017-03-15
Date of issue	: 2017-03-27	Date completed	: 2017-03-24
Sample object	: IVL samples	Sample number	: 4906622
Sample type	: Submitted		
Sample submitted as	: Fuel Oil		
Marked	: Received sample #4 ME 01/02/17		

NAME	METHOD	UNIT	RESULT
Density at 15°C Q	ISO 12185	kg/m³	908.5
Asphaltenes	IP 143 mod	mass %	<0.50
Ash Content Q	ISO 6245	mass %	0.041
Heat of Combustion	ASTM D 240		
Gross Heat of Combustion		MJ/kg	44.25
Net Heat of Combustion		MJ/kg	41.52
Nitrogen	ASTM D 5762	mg/kg	1800
Sulphur Q	EN ISO 8754	mass %	0.10
Viscosity kinematic at 50°C Q	ASTM D 7042	mm²/s	81.49
Elemental analysis	ASTM D 5291		
Carbon		mass %	86.8
Hydrogen		mass %	12.9
Oxygen	Calculated	mass %	<0.1
Metals by ICP after ashing	ICP		
Aluminum (Al)		mg/kg	<5
Cadmium (Cd)		mg/kg	<1
Calcium (Ca)		mg/kg	116
Chromium (Cr)		mg/kg	<1
Copper (Cu)		mg/kg	<1
Iron (Fe)		mg/kg	11
Lead (Pb)		mg/kg	<1
Magnesium (Mg)		mg/kg	1
Nickel (Ni)		mg/kg	21
Posphorous (P)		mg/kg	<1
Potassium (K)		mg/kg	<1
Silicon (Si)		mg/kg	<10
Sodium (Na)		mg/kg	6
Vanadium (V)		mg/kg	<1
Zink (Zn)		mg/kg	1
Metals by ICP	ICP		
Arsenic (As)		mg/kg	<1.0
Mercury (Hg)		mg/kg	<1.0

IVL Svenska Miljoinstitutet AB
FE 267
833 83, Stromsund
Sweden

Attention of : Mrs. H. Winnes

Analysis Report

Report number	: **11601/00043862.4/L/17**	Submitted date	: 2017-03-15
Main Object	: IVL samples	Sample submitted at	: Saybolt Sweden
Report Date	: 2017-03-27	Date received	: 2017-03-15
Date of issue	: 2017-03-27	Date completed	: 2017-03-24
Sample object	: IVL samples	Sample number	: 4906622
Sample type	: Submitted		
Sample submitted as	: Fuel Oil		
Marked	: Received sample #4 ME 01/02/17		

NAME	METHOD	UNIT	RESULT
Aromatic Hydrocarbon Types	EN 12916		
Total aromatics		mass %	15.5

Lab comments:

Q Accredited Analysis. Analysis marked with "Q" are part of the scope of the ISO 17025 accreditation number 1352 of SWEDAC.

Signed by: Almaz Meles - Laboratory Coordinator
Issued by: Saybolt Sweden
Place and date of issue: Göteborg - 2017-03-27

IVL Svenska Miljoinstitutet AB
FE 267
833 83, Stromsund
Sweden

Attention of : Mrs. H. Winnes

Analysis Report

Report number	: **11601/00043862.1/L/17**	Submitted date	: 2017-03-15
Main Object	: IVL samples	Sample submitted at	: Saybolt Sweden
Report Date	: 2017-03-20	Date received	: 2017-03-15
Date of issue	: 2017-03-20	Date completed	: 2017-03-16
Sample object	: IVL samples	Sample number	: 4906679
Sample type	: Submitted		
Sample submitted as	: Fuel Oil		
Marked	: Received sample #4 ME , 02/02/17		

NAME	METHOD	UNIT	RESULT
Density at 15°C Q	ISO 12185	kg/m³	910.6
Sulphur Q	EN ISO 8754	mass %	0.101
Viscosity kinematic at 50°C Q	ASTM D 7042	mm²/s	82.19

Lab comments:

Q Accredited Analysis. Analysis marked with "Q" are part of the scope of the ISO 17025 accreditation number 1352 of SWEDAC.

Signed by: Almaz Meles - Laboratory Coordinator
Issued by: Saybolt Sweden
Place and date of issue: Göteborg - 2017-03-20

Appendix F

IVL Svenska Miljoinstitutet AB
FE 267
833 83, Stromsund
Sweden

Attention of : Mrs. H. Winnes

Analysis Report

Report number	: **11601/00043862.2/L/17**	Submitted date	: 2017-03-15
Main Object	: IVL samples	Sample submitted at	: Saybolt Sweden
Report Date	: 2017-03-20	Date received	: 2017-03-15
Date of issue	: 2017-03-20	Date completed	: 2017-03-15
Sample object	: IVL samples	Sample number	: 4906687
Sample type	: Submitted		
Sample submitted as	: Fuel Oil		
Marked	: Received sample #4 ME , 03/02/17		

NAME	METHOD	UNIT	RESULT
Density at 15°C Q	ISO 12185	kg/m³	908.9
Sulphur Q	EN ISO 8754	mass %	0.100
Viscosity kinematic at 50°C Q	ASTM D 7042	mm²/s	81.52

Lab comments:

Q Accredited Analysis. Analysis marked with "Q" are part of the scope of the ISO 17025 accreditation number 1352 of SWEDAC.

Signed by: Almaz Meles - Laboratory Coordinator
Issued by: Saybolt Sweden
Place and date of issue: Göteborg - 2017-03-20

last week

Appendix G

MAERSK OIL TRADING

BUNKER DELIVERY NOTE

Maersk A/S - Maersk Oil Trading
Esplanaden 50
1098 Copenhagen K
Denmark
Phone: +45 3363 3363

Distribution
- Maersk Oil Trading
- Barging Company
- Customer
- Vessel

Customer No.	
Customer Name	
Customer Order No.	**1074-01-2017**
Port of Delivery	**Rotterdam**
Vessel Name	**Stena Britannica**
Vessel IMO Number	**9419175**
Port of Destination	**Harwich**

Nomination No.		
Date of Delivery		**17-01-2017**
Methode of Delivery (tick appropriate box)		
Pipeline		
Barge	X	**Jaimy V**
Truck		

Quantity Delivered		
Grade	**RMG 18001**	
Metric Tons Vac	**450,631**	
Volume in m3 at 15°C	**497,166**	
Volume in m3 at actual temperature	**506,492**	TEMP **39** °C

Characteristics	
Sulpher % mass	**0.088**
Flash Point °C	**65.5**
Pour Point °C	**+18**
Density kg/m3	**0,9064**
Viscosity cst @ 50 °C	**83.15**
Water % v/v	**0.05**

Retained Samples	Seals Nos
1 Vessel - MARPOL annex VI	**2532756**
2 Vessel	**2532757**
3 Maersk Oil Trading	**2532758**
4 Maersk Oil Trading	**2532759**

Acknowledgements - Vessel Representative

I certify that the above goods in the quantities stated have been ordered and have been received in good order and condition, together with a sealed repesentative sample.

I confirm that i have received the No. 1 and No. 2 samples as indicated above.

Vessel Stamp

Signature of Master, Mate, Chief Engineer or Responsible Officer

Signatory's Name in block letters

R. WEEBOER 2/O.

Acknowledgements - Fuel Supplier

Delivery above quantity in good order and condition for use as bunkers together with a representative sample.

The fuel supplied in this delivery is in conformity with regulation 14(1) or (14(a) and regulation 18(1) of Annex VI of MARPOL 73/78.

MTS JAIMY V.
VERENIGDE TANKREDERIJ B.V.

Signed by Representative of Fuel Supplier

Signatory's Name in block letters

J.de Koning

THIS OIL HAS NOT BORNE EXCISE DUTY AND MUST BE USED ONBOARD VESSELS ON MARINE VOYAGES.
CUSTOMS PERMISSION MUST BE OBTAINED BEFORE DIVERSION TO ALTERNATIVE USAGE.

MOTBDN

Report • PRE TEST

865)

16/01/2017

	RO30785	**Bunker Date**	16/01/2017	**Grade Ordered**	RMG180
	NO NOMINATION	**Sample Date**	16/01/2017	**Sulphur Grade**	0.1% max
	NR	**Fuel Supplier**	Maersk AS	**Quantity Supplied**	2000 M.T.
Lab	16/01/2017	**Barge**	Jaimy V	**Analysis Sample Seal**	
	16/01/2017	**Sample Location**	Barge tank (C1,2,3,4,5,6,7,8)		

eter	Result	Units	Spec Limit	Test Variance (±)	Method
sity (50°C)	83.15	cSt@50°C	180.0 max	7.900	ISO 3104
nsity	906.4	kg/m³@15°C	991.0 max	0.9	ISO 12185
ulphur	0.088	% mass	0.10 max	0.01	ISO 8754
Flash Point	65.5	°C	60.0 min		ISO 2719
Acid Number	2.09	mg KOH/g	2.50 max	0.30	ASTM D664
Total Sediment	<0.01	% mass	0.10 max	0.06	ISO 10307-2
Micro Carbon Residue	5.37	% mass	18.00 max	0.99	ISO 10370
Pour Point	+18	°C	30 max	3	ISO 3016
Water	0.05	% vol	0.50 max	0.10	ISO 3733
Ash	0.062	% mass	0.100 max	0.014	ISO 6245
Vanadium	1	mg/kg	350 max	19	IP 501
Sodium	7	mg/kg	100 max	8	IP 501
Aluminium plus Silicon	5	mg/kg	60 max	12	IP 501
Aluminium	1	mg/kg			IP 501
Silicon	4	mg/kg			IP 501
Compatibility	1	Spot #			ASTM D4740
Polypropylene FTIR	Not Detected				
H2S Vapour Phase	Not Detected				

Sample results have been compared with the nominated specification, RMG180 ISO 8217:2010.

The barge captain has confirmed that the tanks that have been sampled and tested as per these test results are the tanks that are intended for delivery to your vessel.

Please be aware that there may be tanks on the supply barge that contain product nominated for other vessels and these [illegible]nks have not been tested.

We strongly recommend that the Chief Engineer checks that delivery is only made from the tanks stated.

Signed	Paul Martin
Reported By	Paul Martin
Report Date	16/01/2017

most recent

MAERSK OIL TRADING

BUNKER DELIVERY NOTE

aersk A/S - Maersk Oil Trading
Esplanaden 50
1098 Copenhagen K
Denmark
Phone: +45 3363 3363

Distribution
- Maersk Oil Trading
- Barging Company
- Customer
- Vessel

Customer No.	
Customer Name	
Customer Order No.	**1135-01-2017**
Port of Delivery	**Rotterdam**
Vessel Name	**Stena brittanica**
Vessel IMO Number	**9419175**
Port of Destination	**Harwich**

Nomination No.		
Date of Delivery	**27-01-2017**	
Methode of Delivery (tick appropriate box)		
Pipeline		
Barge	**X**	**Jaimy V**
Truck		

Quantity Delivered		
Grade	**RMG 18001**	
Metric Tons Vac	**400,280**	
Volume in m3 at 15°C	**442,005**	
Volume in m3 at actual temperature	**455,088**	TEMP **40** °C

Characteristics	
Sulpher % mass	**0.087**
Flash Point °C	**65.5**
Pour Point °C	**>21**
Density kg/m3	**0,9056**
Viscosity cst @ 50 °C	**74.77**
Water % v/v	**<0.05**

Retained Samples	Seals Nos
1 Vessel - MARPOL annex VI	**2532741**
2 Vessel	**2532742**
3 Maersk Oil Trading	**2532743**
4 Maersk Oil Trading	**2532744**

Acknowledgements - Vessel Representative

rtify that the above goods in the quantities stated have been ordered and have been received in good order and condition, together with a sealed repesentative sample.

I confirm that i have received the No. 1 and No. 2 samples as indicated above.

Vessel Stamp

Signature of Master, Mate, Chief Engineer or Responsible Officer

Signatory's Name in block letters

C [illegible]

Acknowledgements - Fuel Supplier

Delivery above quantity in good order and condition for use as bunkers together with a representative sample.

The fuel supplied in this delivery is in conformity with regulation 14(1) or (14(a) and regulation 18(1) of Annex VI of MARPOL 73/78.

Signed by Representative of Fuel Supplier

MTS JAIMY V

Signatory's Name in block letters

K. Merk

THIS OIL HAS NOT BORNE EXCISE DUTY AND MUST BE USED ONBOARD VESSELS ON MARINE VOYAGES.
CUSTOMS PERMISSION MUST BE OBTAINED BEFORE DIVERSION TO ALTERNATIVE USAGE.

Fuel Quality Report • PRE TEST

JAIMY V (9483865)

Rotterdam • 25/01/2017

Intertek

Sample No.	RO30811	**Bunker Date**	25/01/2017	**Grade Ordered**	RMG380
Received by Lab	25/01/2017	**Sample Date**	25/01/2017	**Sulphur Grade**	0.1% max
Est. Bunker Date	25/01/2017	**Fuel Supplier**	Unknown	**Quantity Supplied**	M.T.
		Barge	Jaimy V	**Analysis Sample Seal**	10699
		Sample Location	Barge tank (1-8 C)		

Parameter	Result	Units	Spec Limit	Test Variance (±)	Method
Viscosity (50°C)	74.77	cSt@50°C	380.0 max	16.60	ISO 3104
Density	905.0	kg/m³@15°C	991.0 max	0.9	ISO 12185
Sulphur	0.087	% mass	0.10 max	0.01	ISO 8754
Flash Point	65.5	°C	60.0 min		ISO 2719
Acid Number	1.94	mg KOH/g	2.50 max	0.30	ASTM D664
Total Sediment	<0.01	% mass	0.10 max	0.06	ISO 10307-2
Micro Carbon Residue	5.23	% mass	18.00 max	0.99	ISO 10370
Pour Point	+21	°C	30 max	3	ISO 3016
Water	<0.05	% vol	0.50 max	0.10	ISO 3733
Ash	0.060	% mass	0.100 max	0.014	ISO 6245
Vanadium	1	mg/kg	350 max	19	IP 501
Sodium	8	mg/kg	100 max	8	IP 501
Aluminium plus Silicon	6	mg/kg	60 max	12	IP 501
Aluminium	1	mg/kg			IP 501
Silicon	5	mg/kg			IP 501
Compatibility	1	Spot #			ASTM D4740
Polypropylene FTIR	Not Detected				
H2S Vapour Phase	Not Detected				

Sample results have been compared with the nominated specification, RMG380 ISO 8217:2010.

The barge captain has confirmed that the tanks that have been sampled and tested as per these test results are the tanks that are intended for delivery to your vessel.

Please be aware that there may be tanks on the supply barge that contain product nominated for other vessels and these tanks have not been tested.

We strongly recommend that the Chief Engineer checks that delivery is only made from the tanks stated.

Signed
Reported By Narinder Singh
Report Date 25/01/2017

IVL Svenska Miljoinstitutet AB
FE 267
833 83, Stromsund
Sweden

Attention of : Mrs. H. Winnes

Analysis Report

Report number	: **11601/00043862.3/L/17**	Submitted date	: 2017-03-15
Main Object	: IVL samples	Sample submitted at	: Saybolt Sweden
Report Date	: 2017-03-20	Date received	: 2017-03-15
Date of issue	: 2017-03-20	Date completed	: 2017-03-15
Sample object	: IVL samples	Sample number	: 4906688
Sample type	: Submitted		
Sample submitted as	: Fuel Oil		
Marked	: Received sample #4 M/E 4/2/17 , 85%		

NAME	METHOD	UNIT	RESULT
Density at 15°C Q	ISO 12185	kg/m³	909.0
Sulphur Q	EN ISO 8754	mass %	0.100
Viscosity kinematic at 50°C Q	ASTM D 7042	mm²/s	79.99

Lab comments:

Q Accredited Analysis. Analysis marked with "Q" are part of the scope of the ISO 17025 accreditation number 1352 of SWEDAC.

Signed by: Almaz Meles - Laboratory Coordinator
Issued by: Saybolt Sweden
Place and date of issue: Göteborg - 2017-03-20

IVL Svenska Miljoinstitutet AB
FE 267
833 83, Stromsund
Sweden

Attention of : Mrs. H. Winnes

Analysis Report

Report number	: **11601/00043862.5/L/17**	Submitted date	: 2017-03-15
Main Object	: IVL samples	Sample submitted at	: Saybolt Sweden
Report Date	: 2017-03-27	Date received	: 2017-03-15
Date of issue	: 2017-03-27	Date completed	: 2017-03-24
Sample object	: IVL samples	Sample number	: 4906696
Sample type	: Submitted		
Sample submitted as	: Lub Oil		
Marked	: Received sample 4/2/17 , M.E. #4		

NAME	METHOD	UNIT	RESULT
Density at 15°C Q	ISO 12185	kg/m³	909.1
Ash Content Q	ISO 6245	mass %	1.636
Nitrogen	ASTM D 5762	mg/kg	520
Sulphur Q	EN ISO 8754	mass %	0.43
Viscosity kinematic at 50°C Q	ASTM D 7042	mm²/s	85.53
Elemental analysis	ASTM D 5291		
Carbon		mass %	84.3
Hydrogen		mass %	13.2
Oxygen	Calculated	mass %	0.4
Metals by ICP after ashing	ICP		
Aluminum (Al)		mg/kg	10
Barium (Ba)		mg/kg	<1.0
Cadmium (Cd)		mg/kg	<1
Calcium (Ca)		mg/kg	6100
Chromium (Cr)		mg/kg	<1
Copper (Cu)		mg/kg	<1
Iron (Fe)		mg/kg	7
Lead (Pb)		mg/kg	<1
Magnesium (Mg)		mg/kg	17
Nickel (Ni)		mg/kg	7
Posphorous (P)		mg/kg	495
Potassium (K)		mg/kg	<1
Silicon (Si)		mg/kg	<10
Sodium (Na)		mg/kg	7
Vanadium (V)		mg/kg	3
Zink (Zn)		mg/kg	500
Metals by ICP	ICP		
Arsenic (As)		mg/kg	<1.0
Mercury (Hg)		mg/kg	<1.0
Aromatic Hydrocarbon Types	EN 12916		

IVL Svenska Miljoinstitutet AB
FE 267
833 83, Stromsund
Sweden

Attention of : Mrs. H. Winnes

Analysis Report

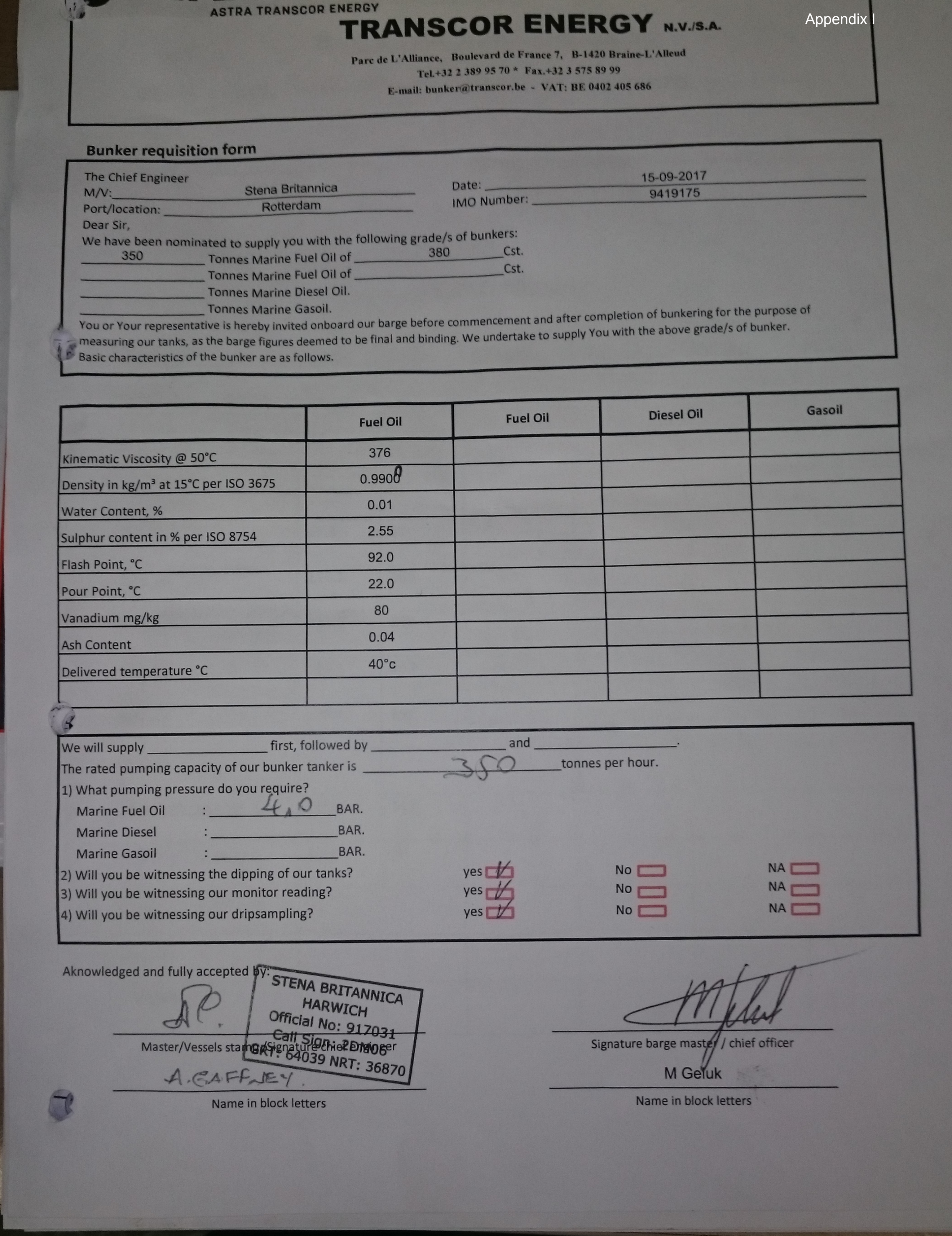
Report number	: **11601/00043862.5/L/17**	Submitted date	: 2017-03-15
Main Object	: IVL samples	Sample submitted at	: Saybolt Sweden
Report Date	: 2017-03-27	Date received	: 2017-03-15
Date of issue	: 2017-03-27	Date completed	: 2017-03-24
Sample object	: IVL samples	Sample number	: 4906696
Sample type	: Submitted		
Sample submitted as	: Lub Oil		
Marked	: Received sample 4/2/17 , M.E. #4		

NAME	METHOD	UNIT	RESULT
Total aromatics		mass %	25.5

Lab comments:

Q Accredited Analysis. Analysis marked with "Q" are part of the scope of the ISO 17025 accreditation number 1352 of SWEDAC.

Signed by: Almaz Meles - Laboratory Coordinator
Issued by: Saybolt Sweden
Place and date of issue: Göteborg - 2017-03-27



ASTRA TRANSCOR ENERGY
TRANSCOR ENERGY N.V./S.A.
Parc de L'Alliance, Boulevard de France 7, B-1420 Braine-L'Alleud
Tel.+32 2 389 95 70 * Fax.+32 3 575 89 99
E-mail: bunker@transcor.be - VAT: BE 0402 405 686

Bunker requisition form

The Chief Engineer
M/V: Stena Britannica
Port/location: Rotterdam
Date: 15-09-2017
IMO Number: 9419175

Dear Sir,

We have been nominated to supply you with the following grade/s of bunkers:

350 Tonnes Marine Fuel Oil of 380 Cst.
______ Tonnes Marine Fuel Oil of ______ Cst.
______ Tonnes Marine Diesel Oil.
______ Tonnes Marine Gasoil.

You or Your representative is hereby invited onboard our barge before commencement and after completion of bunkering for the purpose of measuring our tanks, as the barge figures deemed to be final and binding. We undertake to supply You with the above grade/s of bunker. Basic characteristics of the bunker are as follows.

	Fuel Oil	Fuel Oil	Diesel Oil	Gasoil
Kinematic Viscosity @ 50°C	376			
Density in kg/m³ at 15°C per ISO 3675	0.9900			
Water Content, %	0.01			
Sulphur content in % per ISO 8754	2.55			
Flash Point, °C	92.0			
Pour Point, °C	22.0			
Vanadium mg/kg	80			
Ash Content	0.04			
Delivered temperature °C	40°c			

We will supply ______ first, followed by ______ and ______.
The rated pumping capacity of our bunker tanker is 350 tonnes per hour.
1) What pumping pressure do you require?
Marine Fuel Oil : 4,0 BAR.
Marine Diesel : ______ BAR.
Marine Gasoil : ______ BAR.
2) Will you be witnessing the dipping of our tanks? yes ☑ No ☐ NA ☐
3) Will you be witnessing our monitor reading? yes ☑ No ☐ NA ☐
4) Will you be witnessing our dripsampling? yes ☑ No ☐ NA ☐

Aknowledged and fully accepted by:

STENA BRITANNICA
HARWICH
Official No: 917031
Call Sign: 2EMO6
GRT: 64039 NRT: 36870

Master/Vessels stamp/Signature chief Engineer

A. GAFFNEY.
Name in block letters

Signature barge master / chief officer

M Geluk
Name in block letters

IVL Svenska Miljoinstitutet AB
FE 267
833 83, Stromsund
Sweden

Attention of : Mrs. H. Winnes

Analysis Report

Report number	: **11601/00046530.2/L/17**	Submitted date	: 2017-10-13
Main Object	: IVL samples	Sample submitted at	: Saybolt Sweden
Report Date	: 2017-10-27	Date received	: 2017-10-13
Date of issue	: 2017-10-27	Date completed	: 2017-10-26
Sample object	: Stena Britanica	Sample number	: 5781788
Sample type	: Submitted		
Sample submitted as	: Fuel Oil		
Marked	: Received sample STENA BRITANICA Fuel Oil(Ro) - 17-09-2017		

NAME	METHOD	UNIT	RESULT
Density at 15°C Q	ISO 12185	kg/m³	989.5
Asphaltenes	IP 143 mod	mass %	8.9
Ash Content Q	ISO 6245	mass %	0.035
Heat of Combustion	ASTM D 240		
Gross Heat of Combustion		MJ/kg	42.19
Net Heat of Combustion		MJ/kg	39.97
Nitrogen	ASTM D 5762	mg/kg	4300
Sulphur Q	EN ISO 8754	mass %	2.77
Viscosity kinematic at 50°C Q	ASTM D 7042	mm²/s	420.0
Elemental analysis	ASTM D 5291		
Carbon		mass %	85.4
Hydrogen		mass %	10.5
Oxygen	Calculated	mass %	0.9
Metals by ICP after ashing	ICP		
Aluminum (Al)		mg/kg	<5
Cadmium (Cd)		mg/kg	<1
Calcium (Ca)		mg/kg	3
Chromium (Cr)		mg/kg	<1
Copper (Cu)		mg/kg	<1
Iron (Fe)		mg/kg	22
Lead (Pb)		mg/kg	<1
Magnesium (Mg)		mg/kg	<1
Nickel (Ni)		mg/kg	32
Posphorous (P)		mg/kg	<1
Potassium (K)		mg/kg	1
Silicon (Si)		mg/kg	<10
Sodium (Na)		mg/kg	14
Vanadium (V)		mg/kg	122
Zink (Zn)		mg/kg	1
Metals by ICP	ICP		
Arsenic (As)		mg/kg	<1
Mercury (Hg)	DMA 80	µg/kg	<2

Uncertainties, available on request, apply in the evaluation of the test results. Where available and for convenience purposes, the tested sample has been checked for compliance with supplied specifications, without accepting any liability. In case of dispute or concern, we refer to the interpretation of test results as defined in ASTM D3244, IP 367, ISO 4259 or GOST 33701.

IVL Svenska Miljoinstitutet AB
FE 267
833 83, Stromsund
Sweden

Attention of : Mrs. H. Winnes

Analysis Report

Report number	: **11601/00046530.2/L/17**	Submitted date	: 2017-10-13
Main Object	: IVL samples	Sample submitted at	: Saybolt Sweden
Report Date	: 2017-10-27	Date received	: 2017-10-13
Date of issue	: 2017-10-27	Date completed	: 2017-10-26
Sample object	: Stena Britanica	Sample number	: 5781788
Sample type	: Submitted		
Sample submitted as	: Fuel Oil		
Marked	: Received sample STENA BRITANICA Fuel Oil(Ro) - 17-09-2017		

NAME	METHOD	UNIT	RESULT
Aromatic Hydrocarbon Types	EN 12916		
Total aromatics		mass %	23.5

Lab comments:

Q Accredited Analysis. Analysis marked with "Q" are part of the scope of the ISO 17025 accreditation number 1352 of SWEDAC.

Signed by: Murat Can Ucar - Laboratory Coordinator
Issued by: Saybolt Sweden
Place and date of issue: Göteborg - 2017-10-27

IVL Svenska Miljoinstitutet AB
FE 267
833 83, Stromsund
Sweden

Attention of : Mrs. H. Winnes

Analysis Report

Report number	: **11601/00046530.3/L/17**	Submitted date	: 2017-10-13
Main Object	: IVL samples	Sample submitted at	: Saybolt Sweden
Report Date	: 2017-10-27	Date received	: 2017-10-13
Date of issue	: 2017-10-27	Date completed	: 2017-10-27
Sample object	: STENA BRITANNICA	Sample number	: 5781798
Sample type	: Submitted		
Sample submitted as	: Lub Oil		
Marked	: Received sample STENA BRITANNICA Lube Oil , 23-09-2017		

NAME	METHOD	UNIT	RESULT
Density at 15°C Q	ISO 12185	kg/m³	919.9
Ash Content Q	ISO 6245	mass %	>0.180
Nitrogen	ASTM D 5762	mg/kg	1200
Sulphur Q	EN ISO 8754	mass %	0.55
Elemental analysis	ASTM D 5291		
Carbon		mass %	83.4
Hydrogen		mass %	12.7
Oxygen	Calculated	mass %	<0.1
Metals by ICP after ashing	ICP		
Aluminum (Al)		mg/kg	11
Cadmium (Cd)		mg/kg	<1
Calcium (Ca)		mg/kg	7500
Chromium (Cr)		mg/kg	1
Copper (Cu)		mg/kg	<1
Iron (Fe)		mg/kg	40
Lead (Pb)		mg/kg	<1
Magnesium (Mg)		mg/kg	22
Nickel (Ni)		mg/kg	33
Posphorous (P)		mg/kg	450
Potassium (K)		mg/kg	5
Silicon (Si)		mg/kg	10
Sodium (Na)		mg/kg	12
Vanadium (V)		mg/kg	72
Zink (Zn)		mg/kg	510
Metals by ICP	ICP		
Arsenic (As)		mg/kg	<1
Mercury (Hg)	DMA 80	µg/kg	<2
Aromatic Hydrocarbon Types	EN 12916		

IVL Svenska Miljoinstitutet AB
FE 267
833 83, Stromsund
Sweden

Attention of : Mrs. H. Winnes

Analysis Report

Report number	: **11601/00046530.3/L/17**	Submitted date	: 2017-10-13
Main Object	: IVL samples	Sample submitted at	: Saybolt Sweden
Report Date	: 2017-10-27	Date received	: 2017-10-13
Date of issue	: 2017-10-27	Date completed	: 2017-10-27
Sample object	: STENA BRITANNICA	Sample number	: 5781798
Sample type	: Submitted		
Sample submitted as	: Lub Oil		
Marked	: Received sample STENA BRITANNICA Lube Oil , 23-09-2017		

NAME	METHOD	UNIT	RESULT
Total aromatics		mass %	24.9

Lab comments:

Q Accredited Analysis. Analysis marked with "Q" are part of the scope of the ISO 17025 accreditation number 1352 of SWEDAC.

Signed by: Murat Can Ucar - Laboratory Coordinator
Issued by: Saybolt Sweden
Place and date of issue: Göteborg - 2017-10-27

APP 11. Pitot tube measurements and calculations of exhaust flow

Date/Test	**170921**	**170920-170921**	**170919-170920**			
Sulphur content of fuel (%)	2.77	2.77	2.77			
	Downstream scrubber					
MCR (100 % load), MCR of engine (brake kW) =	9600	9600	9600			
Load, Brake Load during test (%) =	76%	48%	41%			
P, Brake Power or effect during test (kW) =	7296	4640	3968			
Calculation of dry/wet correction factor as:						
No dry/wet correction factor was used						
Calculation of exhaust flow:						
Pitot tube, 1st point, pressure difference	163	130	93			
Pitot tube, 2nd point, pressure difference	281	133	130			
Pitot tube, 3rd point, pressure difference	296	132	126			
Pitot tube, 4th point, pressure difference	281	126	124			
Pitot tube, 5th point, pressure difference	271	116	115			
Pitot tube, 6th point, pressure difference	244	95	125			
Pitot tube, 7th point, pressure difference	209	107				
Pitot tube, 8th point, pressure difference	233					
Pitot tube, 9th point, pressure difference	256					
Pitot tube factor = 0.685						
Exhaust gas temperature during tests (°C)	29	28	26			
Density (kg/m^3)	1.17	1.17	1.18			
Diameter of Exhaust gas channel = 0.95 m						
Average velocity through exhaust gas channel (m/s)	14.1	9.8	9.7			
Average flow through exhaust gas channel (m3/h)	35907	24956	24771			
Exhaust mass flow wet (kg/h)	42011	29199	28982			
Calculation of NOx correction factor for ambient conditions:						
No NO_X correction factor was used						
Calculation of gaseous emissions:						
	76%	48%	41%			
Measured CO2 dry (%) =	5.7	5.9	6.2			
Measured O2 dry (%) =	13.6	13.4	12.9			

Measured CO dry (ppm) =	114.0	187.3	197.0			
Measured NOx dry (ppm) =	1019.0	1056.0	1265.0			
MEasured SO2 (ppm)	3.7	1.5	1.3			
Measured THC wet (ppm) =	45.4	63.4	n.a.			
Measured nmHC wet (ppm) =	44.2	62.8	n.a.			
Measured CH4 wet (ppm) =	1.1	0.6	n.a.			
P, Power or effect during test (kW) =	7296	4640	3968			
Constants used:						
KwCO2, factor for CO2 to convert % to g/nm3 wet = 19.64						
KwO2, factor for O2 to convert % to g/nm3 wet = 14.29						
KwCO, factor for CO to convert ppm to g/nm3 wet =0.00125						
KwNOx, factor for NOx to convert ppm to g/nm3 wet =0.002053						
KwSO2 factor for SO2 to convert ppm to g/nm3 wet = 0.00291						
KwHC, factor for HC to convert ppmC to gHC/nm3 wet =0.000619						
CO2, Mass flow (kg/hr) =	3990	2876	3006			
O2, Mass flow (kg/hr) =	6978	4779	4559			
CO, Mass flow (kg/hr) =	5.1	5.8	6.1			
NOx, Mass flow (kg/hr) =	75.1	54.1	64.3			
SO2, Mass flow (kg/hr) =	0.4	0.1	0.1			
THC, Mass flow (kg/hr) =	1.009	0.979				
nmHC, Mass flow (kg/hr) =	0.982	0.970				
CH4, Mass flow (kg/hr) =	0.023	0.008				
Calculated emission factors:						
CO2 Specific emission (g/KWh) =	547	620	758			
O2 Specific emission (g/KWh) =	956	1030	1149			
CO Specific emission (g/KWh) =	0.70	1.26	1.54			
NOx Specific emission (g/KWh) =	10.30	11.66	16.21			
SO2 Specific emission measured (g/KWh) =	0.05	0.02	0.02			
THC Specific emission (g/KWh) =	0.138	0.211				
nmHC Specific emission (g/kWh)=	0.135	0.209				
CH4 Specific emission (g/kWh)=	0.003	0.002				

IVL Swedish Environmental Research Institute Ltd.
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Phone +46-(0)10-7886500 // www.ivl.se