Onboard particulate and gaseous emission measurements from slow speed marine engine equipped with open-loop scrubber under real world operation

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ABSTRACT

Particulate and gaseous emissions were studied from 2-stroke engine equipped with an open-loop scrubber, installed on a 78200-DWT containership, under real-world operation. This paper presents the on-board emission measurements conducted upstream and downstream of the scrubber with utilization of HFO and an ULSFO. Particle emissions were examined under various dilution ratios and temperature conditions, as well as two thermal treatment setups, involving a Thermodenuder and a Catalytic Stripper. Results revealed 75% SO_2 reduction downstream of the scrubber with HFO to emission compliant levels, while use of ULSFO further decreased SO_2 levels. Scrubber operation produced higher Particle Number emission levels compared to engine-out, mostly attributed to condensational growth of nanometre particle cores, induced by scrubber. The results of this study contribute to the generally limited understanding of particulate and gaseous emission performance of scrubbers in marine vessels and can feed air quality models on estimating marine pollution impacts.

KEYWORDS

Keywords: On-board measurements, Exhaust gas cleaning system, PN, Particle size distribution

1. INTRODUCTION

Ships emit high quantities of harmful pollutants, such as Sulphur Oxides (SOx), Nitrogen Oxides (NO_X) (Lehtoranta et al., 2019b) and Particulate Matter (PM) (Viana et al., 2014). PM properties such as particle Number (PN) concentration and Particle Size Distribution (PSD) are also of significant importance, due to severe consequences of PM on human health, since most of the emitted particles by combustion in ships are found in the ultrafine region, below 100 nm (Kuittinen et al., 2020).

An alternative of using low sulphur fuels enabled by IMO and often adopted is utilization of high-sulphur HFO in combination with exhaust gas cleaning systems, so-called scrubbers. Scrubbers can decrease exhaust SO_2 emissions, typically by up to 99% (Lehtoranta et al., 2019b), so to equivalently meet low sulphur fuel criteria. Three types of scrubbers are technically feasible and most often installed in ships: open and closed loop scrubbers and hybrid. Open-loop scrubbers use the natural alkalinity of seawater to clean the exhaust, while closed-loop ones utilize fresh water with an added alkaline chemical. Hybrid scrubbers can operate on both configurations, depending on the restrictions imposed over different sailing areas.

Number of scrubber installations on ships have increased dramatically since the introduction of 0.5% global sulphur cap (Comer et al., 2020), which results in increasing number of ships using high-sulphur HFO in combination with scrubber operate in ports and near populated areas. Hence, the imperative to characterize the emission performance of these emission controls is steadily rising. Shipping exhaust particle emissions, and especially those from scrubber outlets, have not been thoroughly investigated, in comparison to particles from other sources, such as automotive. Understanding emission performance downstream of scrubbers is of importance, in order to evaluate the effect of shipping on air quality and human health, in particular near populated areas.

Given the ongoing discussions on fuel change to low-sulphur or alternative fuels, and the increasing utilization of scrubber on retrofit or newbuild ships, understanding the scrubber and fuel impact on emissions and especially those of PM becomes crucial. This paper intends to present the particulate and gaseous emissions of an actual vessel equipped with a slow speed 2-stroke engine and an open-

loop scrubber during real-world operation over a 7-day measurement campaign. The objective is to collect real performance data in order to feed emission and air pollution modelling tools with emission factors (EF) downstream of a scrubber both for open seas operation but especially for operation near inhabited port regions.

2. MATERIALS AND METHODS

2.1 MEASUREMENT CAMPAIGN

The on-board measurement campaign was performed on a 300 m long container vessel, between 16 and 24 November 2021, on a voyage from the port of Rotterdam, Netherlands to the port of Gebze, Turkey. The ship was built in 2002 and was equipped with a 2-stroke slow speed diesel (SSD) engine as a main engine (ME), with a nominal power of 62 MW at 98 rpm. The ship was travelling at an average speed of 18.4 knots during the cruising phase of the trip, similar to its indicated service speed, while the engine load at the same period was c.a 36.2%. The ship is equipped with an open-loop exhaust gas cleaning system, in order to comply with the global 0.5% FSC cap and the stricter 0.1% FSC limit inside SECAs and ports, when fuel with high sulphur content is used. Three types of fuels were used on the ship's ME during the on-board campaign. Two batches of HFO fuel (further called HFO1 and HFO2) were used, having FSCs of 2.64% and 2.45%, respectively, and one ULSFO (0.1% FSC).

2.2 TESTING AND SAMPLING

The emitted particles were examined with a variety of sampling systems and conditions. Two different units of the same dilution system (Dekati eDiluter Pro) were utilized for sampling of the exhaust gas from the stack through an L-shaped probe, and its dilution. The eDiluter Pro is a two-stage dilution system operating on cleaned pressurised air, where the first stage is heated (150 or 250°C) and the second non-heated stage. The total Dilution Ratio (DR) after the second stage ranged between 25 and 100, based on the measurement requirements.

PSDs and PN concentrations were measured with a Scanning Mobility Particle Sizer (TSI SMPS model 3080), comprising an impactor of 0.071 cm, a Differential Mobility Analyzer (TSI DMA model 3081) and a Condensation Particle Counter (TSI CPC model 3776), covering a particle range from 5.9 to 225 nm.

Three alternative sample conditioning schemes were studied to characterize total (volatile and non-volatile) and non-volatile particles alone, with two different thermal treatment configurations. The eDiluter Pro was used as the main dilution system for all three sampling schemes. In the first sampling scheme, the diluted sample was directly fed to the instruments after the second dilution stage of the eDiluter. That is denoted as "Fresh" sample. In the second scheme, a Dekati Thermodenuder (TD) (Amanatidis et al., 2018) was applied after the second dilution stage of the eDiluter. The TD comprises a heating stage at 300°C to vaporize semi-volatile particles and the vaporized material is then collected on activated carbon wall surfaces. Hence, only non-volatile particles at 300°C penetrate the TD. This is denoted as "Thermodenuder". The third dilution scheme utilized a commercially custom-made Catalytic Stripper (CS) with oxidation and sulphur storage capabilities, identical to the one that was used by Amanatidis et al., (2018). The CS was designed to operate along with an Ejector Diluter (ED) providing a DR of 12. The CS + ED was heated at 350°C, to evaporate volatile and semi-volatile particles. This scheme is denoted as "Catalytic Stripper + Ejector Diluter". The complete sampling scheme of the measurement campaign is demonstrated in Figure 1.

Gaseous emissions were measured in raw exhaust by a Horiba PG 350 E multi-gas analyzer and by a Bernath Atomic BA 3006 flame ionization detector (FID) for THC (Total Hydrocarbons), which both operate on 1-s time resolution. Non-dispersive infrared (NDIR) analyzer was utilized to measure SO_2, CO_2 and CO and a chemiluminescence analyzer (CLA) for NO_X in the Horiba system.

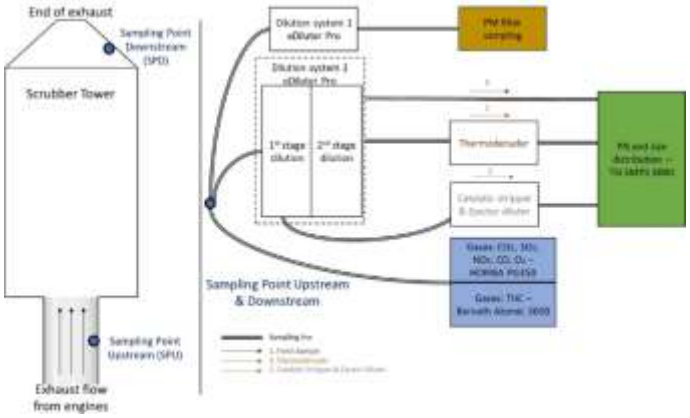

Figure 1: Layout of the measurement setup

Samples were extracted from two different locations, upstream and downstream of the scrubber tower, which are designated as Sampling Point Upstream (SPU) and Downstream (SPD), respectively, illustrated in Figure 1. The sampling method followed, dilution systems and instrumentation were the same for the two sampling points with exception of some modifications of the sample extraction: On SPU, raw exhaust from the engine was measured, while on SPD scrubbed exhaust was collected. Therefore, the effect of scrubber from the same engine with the use of HFO can be evaluated. Measurements were also performed at ULSFO operation at SPD but with the scrubber deactivated, so, in this case, we consider this to be an equivalent sampling condition to SPU used for HFO. Thus, the effect of fuel (HFO and ULSFO) from the same engine can be assessed, as well as an emissions comparison between ULSFO and HFO combined with scrubber can also be performed.

3. RESULTS AND DISCUSSION

3.1 OVERVIEW OF GASEOUS EMISSIONS

The mean SO_2, NO_X, CO and THC emission levels (in g/kgfuel) are displayed in Figure 2, where the fuel used, the sampling point and mean engine load are also depicted. The results, in Figure 2, present the mean of emission rate values, measured in 1-s resolution, for the sampling point (upstream and downstream scrubber and with ULSFO). Error bars in Figure 2 correspond to the standard deviation of the measurements per each sampling point.

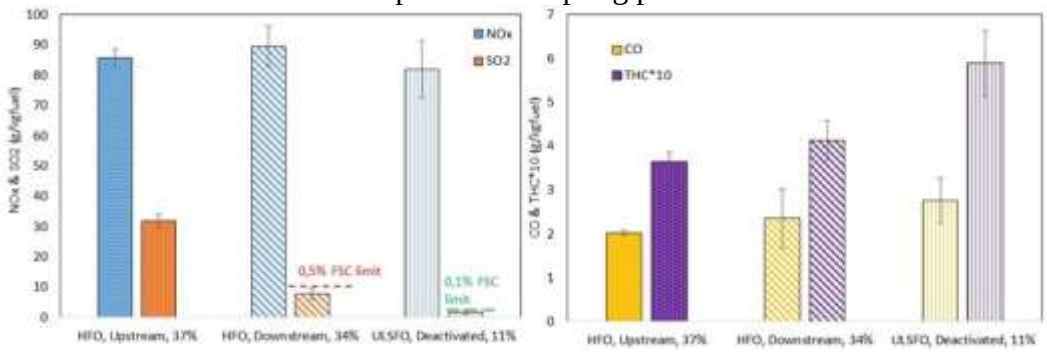

Figure 2: Layout of the measurement setup

As expected, much higher SO_2 was measured upstream of scrubber (31.8 g/kgfuel) than downstream (7.63 g/kgfuel), which decreased SO_2 emissions by 75%, to a level complying with the 0.5% global sulphur limit (10 g/kgfuel equivalent – red dashed line). Scrubber was not operated on its full capacity, since the actual seawater flow rate ranged between 640 - 725 m^3/h, during the cruising phase. ULSFO resulted to the lowest SO_2 levels, since this fuel actually had sulphur content similar to the stricter 0.1% limit (2 g/kgfuel equivalent – green dashed line). As a result, since regulation

compliance is accomplished, there is no need for the ship operator to further increase the scrubbing performance, which would in-line increase the energy and fuel consumption.

NO_X levels vary slightly (approximately ±4% in average) between the different operating conditions. Specifically, based on results shown in Figure 2, scrubber operation seems to increase NO_X emission levels by 4.3% compared to upstream, while ULSFO decrease NO_X emissions by 4.3% compared to HFO. Grigoriadis et al., (2021) showed that lower engine load leads to higher NO_X emissions, while fuel does not play a critical role in influencing NO_X emissions, since NO_X formation is mainly determined by combustion setting parameters, rather than fuel properties for typical liquid marine fuels (residual and distillate). Lehtoranta et al., (2019b) showed a 5% decrease in NO_X emissions over the scrubber, supposing that probably NO_X are transferred into the effluent. Combining our emission observations with the existing knowledge from literature, scrubber impact on NO_X is not well established, but it is considered negligible for NO_X regulation compliance.

CO and THC emission levels appeared to rise with engine load decrease. Downstream of the scrubber and when using ULSFO, higher levels of CO and THC were found in comparison to the measurements taken upstream of the scrubber. Our approach is that these pollutants are mainly combustion related and therefore scrubber and fuel were not affecting their emissions performance. Engine load emerges as the dominant parameter affecting these pollutants, as evidenced by a substantial increase in CO and HC emission levels.

High error bars depicted in NO_X, CO and THC for measurements conducted downstream of the scrubber were most probably related to more measurements performed over different operating conditions, compared to upstream and ULSFO measurements. In total, 38 hourly downstream scrubber measurements have been performed, while this is only 5 hourly measurements upstream of the scrubber and 7 hourly ULSFO measurements, over the 7-day voyage.

3.2 PARTICULATE EMISSIONS

3.2 (a) Scrubber and fuel effects

The effect of scrubber and fuel on the PN levels and the corresponding PSDs are demonstrated in Figure **Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.**3. These measurements were conducted on the so-called "Fresh" sample conditions, and therefore total particles were obtained, including volatile and non-volatile ones. Mean PN levels and size distributions are presented in each case, together with the individual PSD along with the corresponding uncertainty range that corresponds to one standard deviation on each side of the mean value.

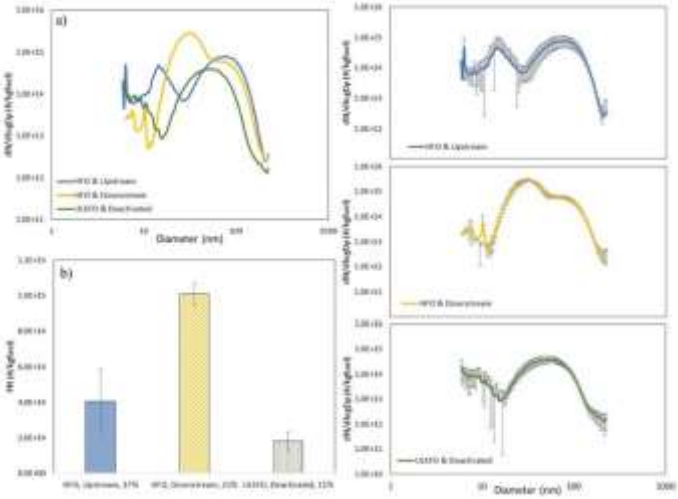

Figure 3: Mean PN size distribution (a) and PN emission levels (b) in (#/kgfuel) on "Fresh" sample, measured upstream and downstream of the scrubber with HFO and deactivated scrubber with ULSFO. Individual mean PN size distributions per each sampling point (right panels) are depicted along with error bars that correspond to standard deviation.

PSD upstream of the scrubber appeared trimodal with one peak at 6 nm, a second at 14 nm and a third larger peak at 76 nm, while PSD downstream of the scrubber was quadrimodal with the first peak at 6 nm, a second peak at 10 nm, a third one at 31 nm and the fourth one at 66 nm (Figure 3a). ULSFO led to a bimodal PSD with a first peak at 6 nm and a second higher at 53 nm. PN levels downstream of the scrubber were found higher than upstream of the scrubber by 150%, while the lowest PN levels were observed for ULSFO use (Figure 3b). The soot mode, which represents the non-volatile carbonaceous part of particles (Amanatidis et al., 2018), was found at the same level, both in terms of PN level and PSD between SPU and SPD. Soot emissions are mainly attributed to engine performance, combustion quality and fuel type (Ntziachristos et al., 2016). Particles downstream of the scrubber were dominated by nanoparticles in the size range between 10 and 40 nm, that were formed from nucleation of volatized fuel ash species (Kasper et al., 2007; Ntziachristos et al., 2016), as seen in Figure 3a. Hot exhaust of c.a 300°C, containing high amounts of SO_2 and SO_3 was inserted into the scrubber, where high humidity conditions existed, and rapidly cooled down to 40°C, due to the presence of seawater. In such conditions, SO_3 reacted with water vapour molecules to form sulphuric acid nucleating into particles in the nucleation size range (d. Santos et al., 2022). These nuclei-sized sulphuric acid particles were not captured by coalescence with the seawater droplets and therefore a new high concentration particle mode was generated downstream of the scrubber. Thus, the increased PN downstream of the scrubber (Figure 3b) was probably to the enhanced nucleation mode that seems to be produced by scrubber, through nucleation or condensation on smaller particles than the measured size range upstream of the scrubber. The increased PN levels downstream of scrubber was also strengthened by the fact that scrubber was inefficient in removing soot mode particles.

On the right side of Figure, the mean PSDs of upstream and downstream of the scrubber, as well as with ULSFO use, of Figure 3a are separately demonstrated, along with the corresponding uncertainty ranges, expressed by one standard deviation. Deviations were emerged, due to utilization of the two HFO batches and variable DRs, for both upstream and downstream of the scrubber measurements, as well as different dilution temperature upstream of scrubber and variable engine load when downstream of scrubber. On the ULSFO case, ship was cruising at slow speed (about 12 knots) and engine load was at 10%, which created measurement uncertainties.

3.2 (b) Effects of sample conditioning

The effect of scrubber and fuel on the PN levels and the corresponding PSDs are demonstrated in Figure 4. These measurements were conducted on the so-called “Fresh” sample conditions, and therefore total particles were obtained, including volatile and non-volatile ones. Mean PN levels and size distributions are presented in each case, together with the individual PSD along with the corresponding uncertainty range that corresponds to one standard deviation on each side of the mean value.

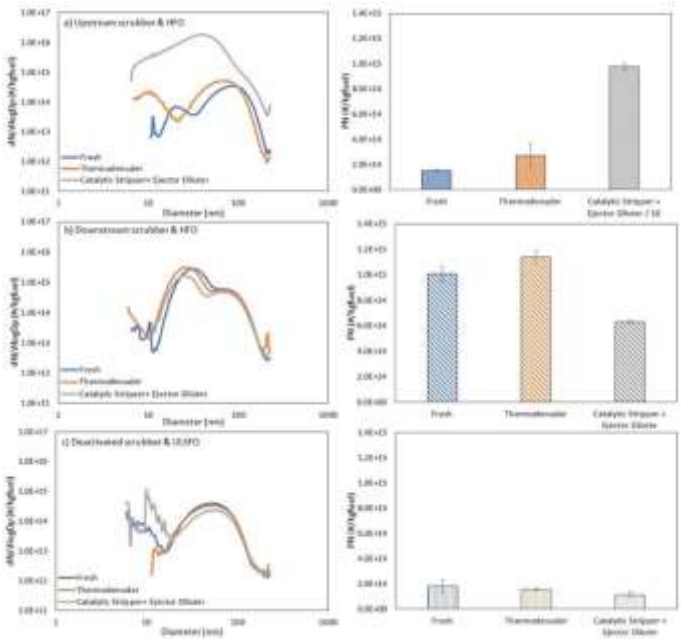

Figure 4: Mean PN size distributions (left panels) and mean PN emission levels (right panels) in (#/kgfuel) on "Fresh" sample, with "Thermodenuder" and with "Catalytic Stripper + Ejector Diluter", a) upstream scrubber with HFO, b) downstream scrubber with HFO and c) deactivated scrubber with ULSFO. Error bars correspond to standard deviation. PN upstream of scrubber with "Catalytic Stripper + Ejector Diluter" is presented as PN/10.

Use of a CS + ED to isolate non-volatile particles upstream of the scrubber had the opposite effects than this intention, as the resulting PN concentration was over 65-times fold higher than in the fresh sample. Amanatidis et al., (2013) showed that in presence of oxygen and high sulphur conditions, such as combustion of marine HFO, sulphur is stored in the form of sulphates in the CS's sulphur trap. They also observed generation of sulphate particles, which grow from 5 nm to 50 nm in a short time period, when exposed to high sulphur conditions. Particle generation also depends on the CS geometry, design and storage capabilities. In our case, the increased SO_2 concentration upstream of the scrubber, due to the utilization of fuels with high FSCs, accompanied by high quantities of NO_X (approximately 1500 ppm), reduced the adsorbent ability of CS and therefore sulphate and nitrate particles were generated.

Use of TD downstream of the scrubber produced a trimodal PSD, similar to the fresh sample, but with a slight shift of each mode to smaller particles. The TD PN was higher than fresh sample by 12%, mainly due to re-nucleation of particles in the size range between 10-30 nm, when exposed to high sulphur conditions (Amanatidis et al., 2018). Even downstream of the scrubber, sulphur was found in increased concentrations of various sulphur-based components (SO_2, SO_3, sulphates), compared to the use of low sulphur fuels, since the scrubber cannot completely abate sulphur particle species (Yang et al., 2021). Moreover, the high operating temperature of 300°C probably decreased the efficiency of TD and promoted the onset of re-nucleation, due to the reduction of residence time of species on low temperature, that permits adsorption in the denuding section (Amanatidis et al., 2018).

The PSD downstream of the scrubber using CS + ED displayed a bimodal pattern, with a higher first peak at 20 nm and lower second peak at 70 nm, shifting the PSD to smaller particles. The respective CS + ED PN emission level was 37% lower compared to fresh sample one, meaning that CS + ED eliminated the majority of volatile and semi-volatile particles downstream of the scrubber.

In the ULSFO & deactivated scrubber case (Figure 4c), TD presented bimodal PSD with a first peak 6 nm and a second one at 53 nm, while CS + ED was trimodal with a first peak at 6 nm, a second one at 10 nm and a third one at 51 nm. Even on the ULSFO with much less FSC (0.1%), CS induced

the generation of new artifact particles in the size range of 10 to 20 nm. The PN levels with TD and CS + ED were reduced by 14% and 38%, respectively, compared to fresh sample PN. This means that volatiles were diminished by the TD and were further eliminated by the CS + ED, due to the higher heated temperature (350°C).

4. CONCLUSIONS

This study provides the particulate and gaseous emission levels, along with the PSDs from a large 2-stroke SSD engine equipped with open-loop scrubber. This is the first time in worldwide literature that real sailing conditions measurements conducted on an open-loop scrubber used to abate emissions from such a large engine with maximum power output of 62 MW. Another special and unique element of this study is the first application of both TD and CS + ED on a marine engine environment during on-board testing.

Despite the notable rise in the installation of scrubbers on newbuilding and retrofit ships worldwide, scrubber emission performance is quite controversial, since they can effectively abate SO_2 emissions but their effect on particles is still bound to uncertainty. Therefore, more research is needed on this direction to comprehensively address the remaining challenges in scrubbers' emissions effectiveness. The developed EFs downstream of scrubbers can be fed to emission and air pollution models to identify their overall effect on the environment and human health, and thus to support in promoting new effective emission control policies and regulations. This study also highlights the importance of the appropriate particle testing conditions on marine engines under various DR, temperature and thermal treatment configurations, as well as the additional complexity induced by scrubber. This should be further investigated in future research as the necessity of creating a standardized marine measurement protocol is obvious for accurate shipping emissions estimation.

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