SOx and PM removal using electrostatic precipitator with heat exchanger for marine diesel

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Abstract—**The reduction of SO_2 and PM for marine engines was investigated using the electrostatic precipitator (ESP) with the heat exchanger. The experiments were carried out to reduce SO_2 due to condensation of water in the exhausted gas. The experimental system consists of the diesel engine, the heat exchanger and the ESP. The exhausted gas at 180 ^{o}C of the temperature is cooled to 20 ^{o}C, and generated mist particles due to water condensation in the heat exchanger. The mist particles and PM are collected in the ESP. The particle concentrations were measured using the scanning mobility particle sizer and the low volume air sampler after hot dilution. SO_2 concentrations are also measured by the SO_2 monitor using UV fluorescence after hot dilution. As a result, the condensation water was sampled after the heat exchanger. SO_2 removal rate was 76 %, and the collection efficiency was 78% in ESP with the heat exchanger.**

I. INTRODUCTION

SOx, the particulate matter (PM) and NOx in the exhaust gases emitted from marine diesel engines may cause the serious problem of human health and the environment on the

coast. Therefore, it has been regulated in MARPOL Treaty 73/78 Annex VI of IMO Air Pollution Control since 2005. The regulation typically required the use of low sulfur fuel to reduce SOx emissions and the sulphate portion of PM emissions. To reduce SOx and PM emissions, the Annex introduces a reduction in the global sulphur fuel limit to 3.5 % from 2012 with a further global reduction to 0.5 % from 2020 or 2025. It is also permitted the use of new machinery designed to operate on an inherently low sulfur alternative fuel, such as an exhaust gas cleaning aftertreatment system [1].

Sea water scrubbers for reduction SOx and PM have been begun to install on many ships in Europe. However, there are still unsolved problems to need extensive installation area on ships and need a large amount of sea water. To improve the SOx removal efficiency, it is investigated to reduce SOx and NOx by the alkali water and the acid water generated by electrolysis of sea water [2]. It is also investigate that the waste water disposal by cof-fee-based powder activated carbon on sea water scrubber [3]. On the other hand, the components of PM were reported. It is known that PM includes soot, sulphate and soluble organic fraction (SOF) [4]. Electrostatic precipitators (ESP) have been developed for removal the PM [5 - 7]. The reductions of SOx, NOx and PM using plasma and chemical technologies have been investigated [8 - 9]

In this study, novel SO_2 and PM removal system for marine engines is suggested. The experiments were carried out to reduce SO_2 the water condensation and the corona discharge. And PM included mist particles generated by water condensation was collected by the ESP. The system consisted of the diesel engine, the gas heat exchanger and the ESP. The effects of removal efficiencies were obtained measuring the SO_2 and PM concentrations.

II. EXPERIMENTAL SETUP

A schematic diagram of experimental system is shown in Fig. 1. The experimental system consists of the diesel engine, the heat exchanger and the electrostatic precipitator (ESP). Emissions from a diesel engine generator (Denyo, DA-3100SS-IV, displacement volume of 400 cc) using residual fuel oil (ENEOS, LSA 01) with 100 % load were used. The exhausted gas at 180 ^{o}C of the temperature is cooled to 20 ^{o}C, and then mist particles are generated due to water condensation in the heat exchanger. The refrigerant of the heat exchanger is water. The PM included mist particles are collected in the ESP.

The structure of ESP is shown in Fig. 2. The ESP consists of the pre-charger and the collector. The pre-charger consists of high voltage spike-plate electrodes and grounded plate electrodes. The applied voltages were between DC -4.0 and -8.0 kV (corona currents were between 0.03 and 1.03 mA, current densities were between 0.08 and 2.8 mA/m^2) in the pre-charger. The collector has a parallel-plates configuration. The applied voltage was DC +10 kV. The spacing between the adjacent plates was 9mm, the grounded electrode lengths were 150 mm, and the high voltage electrode lengths were 130 mm in the pre-charger and the collector.

In order to determine the SO_2, particle number and particle mass concentration in the gas, it was diluted 10 times by the hot dilution system (KHG-2010, Palas) after sampling a part of the flue gas upstream and downstream the heat exchanger and downstream the ESP. The temperature of dilution air was adjusted to that of the flue gas. SO_2 concentrations were measured by the SO_2 monitor using UV fluorescence (HORIBA, APSA-370) after hot dilution.The particle size-dependent number concentrations were determined by the

Scanning Mobility Particle Sizer (SMPS, Model3936L76-N, TSI) for the particle-size range of $40 \sim 500$ nm. The particle mass concentrations were determined by the Low Volume Air Sampler (LVS, Model 2000, Tokyo Dylec).

The residence time of the gas in the heat exchanger was approximately 0.35 s, the gas velocity in the ESP was approximately 1 m/s.

The SO_2 removal rate η_{SO2}, the number collection efficiency η_{PMN} and the mass collection efficiency η_{PMM} were calculated by equation (1) and (2):

$$\eta_{SO_2} = (1 - \frac{N_{USO_2}}{N_{DSO_2}}) \times 100 \qquad (1)$$

$$\eta_{PMN} = (1 - \frac{N_{UPM}}{N_{DPM}}) \times 100 \qquad (2)$$

$$\eta_{PMM} = (1 - \frac{M_{UPM}}{M_{DPM}}) \times 100 \qquad (3)$$

where N_{USO2} and N_{DSO2} are the upstream and the downstream concentration [ppm] of the SO_2, N_{UPM} and N_{DPM} are the upstream and the downstream number concentration [part/m^3] of PM, M_{UPM} and M_{DPM} are the upstream and the downstream mass concentration [mg/m^3] of PM.
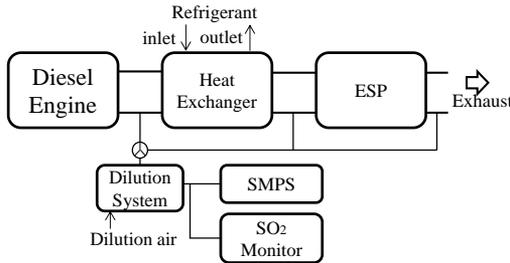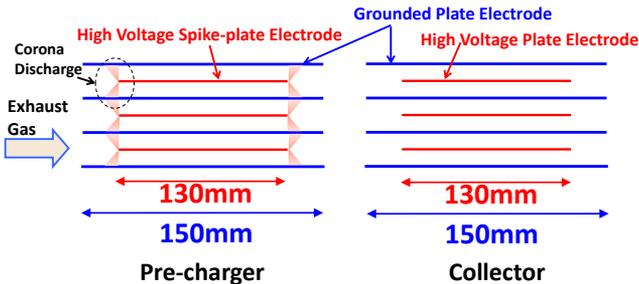

Fig. 1. Schematic diagram of experimental system.

Fig. 2. Structure of ESP

III. RESULT AND DISCUSSION

A. *Effect of Heat Exchanger on Water Condensation*

The purpose in this study is SO_2 reduction by water condensation in the heat exchanger. When the gas is cooled from 180 ^{o}C and 20 ^{o}C by the heat exchanger, the water content in the exhaust gas is condensed, and liquefied. It is considered that SO_2 is absorbed into the condensed water. The amount of the liquefied water in the heat exchanger was measured. The amount of condensed water as a function of the gas temperature is shown in Fig. 3. The condensed water was not confirmed between 180 ^{o}C to 50 ^{o}C of the gas temperature. However, the condensed water significantly increased less than 40 ^{o}C of the gas temperature. The pH of this condensed water was measured by pH meter (Toko Chemical Laboratories, TPX-999i), and the result was approximately pH 2.

The particle size distribution downstream the heat exchanger for various gas temperatures is shown in Fig.4. The maximum value of the distributions was at approximately 70 nm. Although the maximum values between 120 ^{o}C and 50 ^{o}C were almost same, which were significantly increased less than 40 ^{o}C. It is clear that the water content in the exhaust gas condenses less than 40 ^{o}C, and particle concentration increases in this experimental condition due to generating acid water mist. The SO_2 and Sulfate may be absorbed into the condensed water.

B. *Effect on removal SO_2*

It was investigated the effect of the water condensation and the ESP on removal SO_2. The SO_2 concentrations downstream the heat exchanger and the ESP as a function of the gas temperature are shown in Fig. 5. The gas temperature was adjusted by the heat exchanger. The DC -8.0 kV was applied to the pre-charger, and the DC 10 kV was applied to the collector. SO_2 concentration upstream the heat exchanger was 11.1 ppm. SO_2 concentration downstream the heat exchanger decreases with decreasing the gas temperature. Although SO_2 concentration was 10.5 ppm at 120 ^{o}C of the gas temperature, that was 8.0 ppm less than 40 ^{o}C. On the other hand, SO_2 concentration downstream the ESP significantly decreased comparison with that downstream the heat exchanger. Although SO_2 concentration downstream the heat exchanger was 10.2 ppm at 100 ^{o}C of the gas temperature, that downstream the ESP was 4.3 ppm. This cause is that SO_2 will be oxidized by corona discharge to form SO_3 and is highly soluble with water to form H_2SO_3 and H_2SO_4 [9]. SO_2 concentration downstream ESP decreases with decreasing the gas temperature due to the effect of the heat exchanger.

The SO_2 removal rate as a function of the gas temperature is shown in Fig.6. This result was calculated from Fig.5 using equation (1). SO_2 removal rate of the system was calculated with SO_2 concentrations upstream the heat exchanger and downstream the ESP. Although SO_2 removal rate of the heat exchanger was 5.4 % at 120 ^{o}C, that was 27.9 % less than 40 ^{o}C. SO_2 removal rate of the system was significantly improved comparison with that of the gas heat exchanger, the removal rates were between 68 and 75.9 %.

These results indicate that SO_2 is absorbed into condensed water with decreasing the gas temperature, and is oxidized by corona discharge.
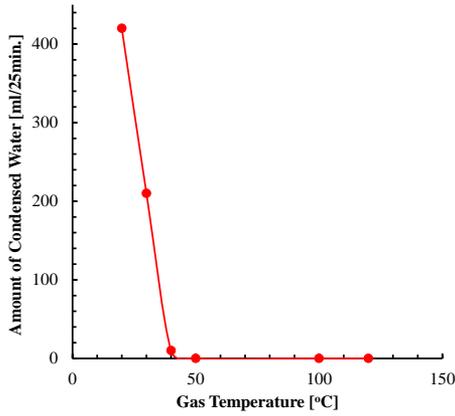
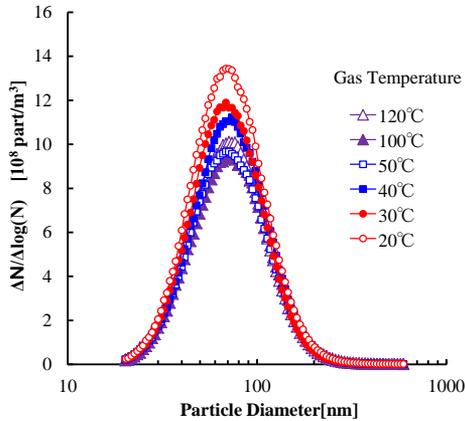Fig. 3. The amount of condensed water as a function of the gas temperature in the heat exchanger.

Fig. 4. The particle size distribution downstream the heat exchanger for various gas temperatures
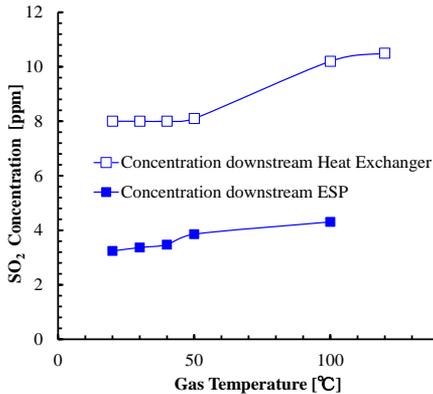

Fig. 5. SO_2 concentrations downstream the heat exchanger and the ESP as a function of the gas temperature. (DC-8.0 kV was applied to the pre-charger, DC 10 kV was applied to the collector. SO_2 concentration upstream the heat exchanger was 11.1ppm)
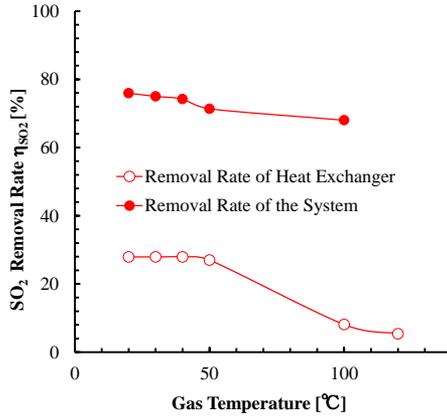
Fig. 6. SO$_2$ removal rate as a function of the gas temperature. (DC-8.0 kV was applied to the pre-charger, DC 10 kV was applied to the collector.SO$_2$ concentration upstream the heat exchanger was 11.1ppm)

C. PM Collection Efficiency

The PM collection efficiency was investigated so that the condensed water is needed to remove. The number collection efficiency as a function of the particle diameter for various applied voltages to the pre-charge in the ESP is shown in Fig.7. The gas temperature downstream the heat exchanger was 20 ^{o}C, DC 10 kV was applied to the collector. The collection efficiency was calculated by equation (2), which particle number concentrations were measured upstream and downstream the ESP. The collection efficiency at -4.0 kV of applied voltage is almost constant between 50 and 200 nm of the particle diameter. However, that larger than 200 nm decreases with increasing the particle diameter. It is known that this cause is the particle re-entrainment [10]. There are few examples in the literature describing the preventing particle re-entrainment [6, 7, 11]. The collection efficiency in Fig. 7 is improved with increasing applied voltage due to increasing particle charges, and the collection efficiency greater than -7.0 kV of applied voltage is almost same value. It is clear that PM included condensed water mist is removed in ESP.
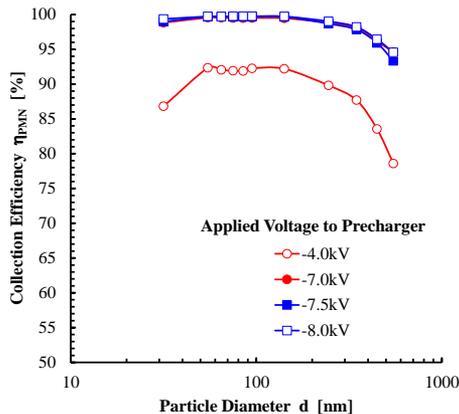

Fig. 7. Number collection efficiency as a function of the particle diameter for various applied voltage to the pre-charge in the ESP. (DC 10 kV was applied to the collector. The gas temperature was 20 ^{o}C)

The number collection efficiency as a function of particle diameter for various gas temperatures in the system is shown in Fig. 8. The particle number concentrations were measured upstream the heat exchanger and downstream the ESP. The particle size-dependent the collection efficiency is similar with Fig. 7. The collection efficiencies at 20 $^{\circ}$C and 30 $^{\circ}$C of the gas temperature are lower than that between 40 $^{\circ}$C and 120 $^{\circ}$C. This cause is that the particle number concentration increases due to water condensation as shown in Fig. 4. However, the collection efficiency at 30 $^{\circ}$C is achieved high value, which is between 71 % and 87 %.
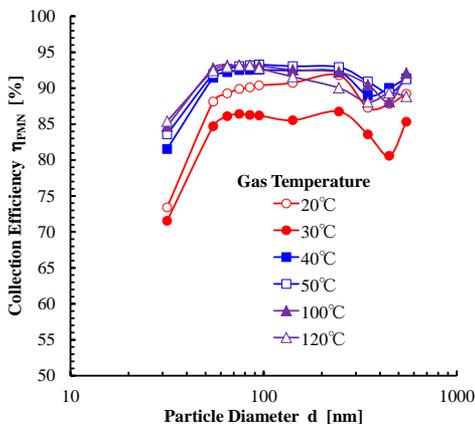

Fig. 8. Number collection efficiency as a function of particle diameter for various gas temperatures. (DC-8 kV was applied to pre-charger, DC 10 kV was applied to the collector.)

The mass concentration and the collection efficiency as a function of applied voltage to the pre-charger in the system are shown in Fig. 9. The gas temperature downstream the heat exchanger was 20 $^{\circ}$C, DC 10 kV was applied to the collector. The mass concentration upstream heat exchanger was 18.0 mg/m^3. The mass concentration downstream ESP is indicated in Fig. 9. The mass collection efficiency was calculated by the mass concentrations measured upstream the heat exchanger and downstream the ESP. The mass concentration downstream the ESP decreases with increasing the applied voltage to the pre-charger, it was 4.0 mg/m^3 at -8 kV. The mass collection efficiency increases with increasing the applied voltage, it is 77.8 % at -8 kV. It is clear that the number collection efficiency is not only achieved high value, but also the mass collection efficiency is achieved.

IV. CONCLUSION

In this study, a novel SO_2 and PM removal system for marine diesel engines was suggested. The effect of water condensation on removal SO_2 and the effect of the ESP on collecting PM were experimentally investigated. The results are follows:
1. The water content in the exhaust gas condenses less than 40 $^{\circ}$C of the gas temperature, and particle concentration increases in this experimental condition.
2. 27.9 % of SO_2 concentration is removed due to absorbing into condensed water.

3. 75.9 % of SO_2 concentration is removed due to the effect of condensed water and the oxidization by corona discharge.

4. Although the number concentration of PM increases due to the water condensation, the concentration greater than 71 % is removed by ESP. The number collection efficiency is not only achieved high value, but also the mass collection efficiency is achieved at 77.8 %.
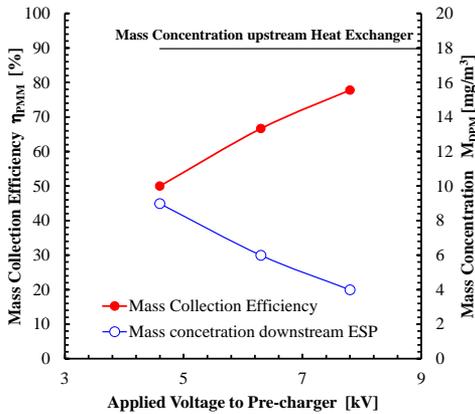
Fig. 9. Mass concentration and collection efficiency as a function of applied voltage to the pre-charger in the system. (DC 10 kV was applied to the collector. The gas temperature was 20 ºC.)

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