

## The effects of gas cooling on removal of SOF and sulphate by electrostatic precipitator for marine diesel

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### Abstract

Particulate matters (PM), SO<sub>x</sub> and NO<sub>x</sub> in exhaust gases emitted from marine diesel engines may cause serious problems in human health and coastal environments. Therefore, their emissions have been regulated in MARPOL Treaty 73/78 Annex VI of IMO Air Pollution Control since 2005. In this paper, the reduction of PM for marine engines was investigated using an electrostatic precipitator (ESP) with a heat exchanger. Experiments were carried out to confirm the reduction of PM, which were Dry soot, Soluble Organic Fraction (SOF) and sulphate. The experimental system consisted of a diesel engine, a heat exchanger and an ESP. The exhaust gas at a temperature of 180°C was cooled to 20°C in the heat exchanger, whereby particles of SOF and sulfuric acid were generated due to condensation. These particles were collected in the ESP. The particle concentrations were measured using a low-volume air sampler, a soxhlet extractor and an ion chromatograph. As a result, the gaseous SOF was condensed to particulate matter due to gas cooling. This particulate matter was collected by ESP, whose removal efficiency exceeded 85%. The removal efficiency of sulphate was also improved.

*Keywords: marine diesel, electrostatic precipitator, particulate matter, soluble organic fraction, sulphate.*



## 1 Introduction

Particulate matters (PM), SO<sub>x</sub> and NO<sub>x</sub> in the exhaust gases emitted from marine diesel engines may cause serious problems in human health and coastal environments. Therefore, their emissions have been regulated in MARPOL Treaty 73/78 Annex VI of IMO Air Pollution Control since 2005. The regulation typically requires the use of low-sulfur fuel to reduce the sulphate portion of PM emissions and SO<sub>x</sub> emissions. To reduce PM and SO<sub>x</sub> emissions, the Annex stipulates that the global sulphur fuel limit should be lowered to 3.5% in 2012 and further down to 0.5% in 2020 or 2025. Alternatively, it is also permitted to use an exhaust gas cleaning aftertreatment system or similar machinery that can reduce emissions to the levels that should be achieved by using a low-sulfur fuel [1].

Seawater scrubbers for reduction of PM and SO<sub>x</sub> have begun to be installed on ships in Europe. However, there are still unsolved problems, such as the need for an extensive installation area on ships and a large amount of seawater. To improve the SO<sub>x</sub> removal efficiency, Nishida *et al.* investigated the technique of reducing SO<sub>x</sub> and NO<sub>x</sub> by alkali water and acid water generated by electrolysis of seawater [2]. Herrera *et al.* conducted research on waste water disposal by coffee-based powder activated carbon on seawater scrubbers [3]. On the other hand, the problem of PM compositions has also been reported. It is known that PM includes Dry soot, sulphate and soluble organic fraction (SOF) [4]. Electrostatic precipitators (ESP) have been developed for the removal of PM [5–7]. The reductions of PM, SO<sub>x</sub> and NO<sub>x</sub> using plasma and chemical technologies have been investigated [8, 9].

In this study, a novel PM removal system for marine engines is proposed. Experiments were carried out to reduce PM, which were Dry soot, sulphate and SOF, by a gas heat exchanger and the ESP. The particle concentrations were measured by using a low volume air sampler, a soxhlet extractor and an ion chromatograph. The reduction amount and efficiency of sulphate, SOF and Dry soot were investigated.

## 2 Principle of reduction of SOF and SO<sub>4</sub><sup>2-</sup>

The principle of reduction of SOF and SO<sub>4</sub><sup>2-</sup> is shown in Fig. 1. Sulphate and sulfuric acid concentration are estimated by amount of SO<sub>4</sub><sup>2-</sup>. The system consists of a heat exchanger and an ESP. The exhaust gas at a temperature between 160 and 240°C includes Dry soot as particulate matter and H<sub>2</sub>O, SOF, and SO<sub>2</sub> as a part of gas. It is cooled to 30°C in the heat exchanger, whereby H<sub>2</sub>O mist and SOF particles are generated due to condensation. Sulfuric acid (H<sub>2</sub>SO<sub>3</sub> or H<sub>2</sub>SO<sub>4</sub>) is generated due to reaction between H<sub>2</sub>O mist and SO<sub>2</sub>. The PMs including sulphate, SOF, Dry soot and sulfuric acid are charged by a corona discharge, and then these are collected by electrostatic force in the ESP.

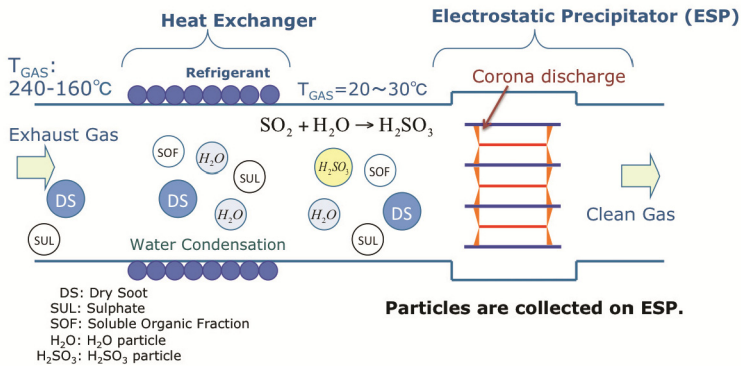


Figure 1: Principle of reduction of SOF and  $\text{SO}_4^{2-}$ .

### 3 Experimental setup

A schematic diagram of the experimental system is shown in Fig. 2. The 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 refrigerant of the heat exchanger is water.

The structure of the ESP is shown in Fig. 3. The ESP has high voltage spike-plate electrodes and grounded plate electrodes. The spacing between the adjacent plates was 9 mm, the grounded electrodes were 150 mm long, and the high voltage electrodes were 130 mm long. The applied voltages were between DC -4.0 and -10.5 kV (corona currents were between 0.0 and 4.3 mA, and current densities were between 0 and  $11.7 \text{ mA/m}^2$ ).

The PM concentrations in the gas were measured by a low volume air sampler. A part of the flue gas was sampled on the upstream and downstream sides of the ESP, and then PM was collected on Teflon filter (Tokyo Dylec, TX40HI20-WW) in the holder as shown in Fig. 2. The sampling tube was heated to the same temperature as the gas temperature by the tape heater to prevent condensation in the tube. The total PM concentration  $C_{PM}$  was calculated by equation (1):

$$C_{PM} = (M_{PM} - M_f) / (Q_L \cdot t) \quad (1)$$

where  $M_{PM}$  is a mass of the filter with the sampled PM,  $M_f$  is a mass of the filter before sampling PM,  $Q_L$  is the sampling gas flow rate (16.7 L/min) and  $t$  is the sampling time (1 min). The filter mass was measured after drying it for 2 hours at  $50^\circ\text{C}$ .

After measuring the total PM concentration, SOF and  $\text{SO}_4^{2-}$  concentrations were measured. SOF collected on the filter was separated by dichloromethane

using a soxhlet extractor, and then SOF concentration  $C_{SOF}$  was estimated from the measured mass of the filter as follows:

$$C_{SOF} = (M_{DPM} - M_{ext}) / (Q_L \cdot t) \tag{2}$$

where  $M_{ext}$  is a mass of the filter from which SOF was separated.

$SO_4^{2-}$  concentration was measured to estimate sulphate and sulfuric acid concentrations.  $SO_4^{2-}$  on the filter was separated into ultra pure water (electrical conductivity: 1.7 S/cm) by an ultrasonic cleaner after measuring the SOF concentration.  $SO_4^{2-}$  concentration  $C_{SO4}$  was estimated by measuring the  $SO_4^{2-}$  amount in the water with an ion chromatograph. The concentration of bound water  $C_{BW}$  with sulfuric acid was defined as equal to 1.3 times [10]  $SO_4^{2-}$  concentration  $C_{SO4}$ .

Dry soot concentration  $C_{DS}$  was calculated as follows:

$$C_{DS} = C_{PM} - C_{SOF} - C_{SO4} - C_{BW} \tag{3}$$

The reduction amounts and the reduction rates of  $SO_4^{2-}$ , SOF, Dry soot and PM were estimated to investigate the effect of the gas-cooling on the efficiency of ESP.  $SO_4^{2-}$  reduction amount  $\Delta C_{SO4-V}$  and the reduction rate  $\eta_{SO4-V}$ , when the voltage of  $V$  kV was applied in the ESP, were calculated by equations (4) and (5):

$$\Delta C_{SO4-V} = C_{SO4-0} - C_{SO4-V} \quad [mg/m^3] \tag{4}$$

$$\eta_{SO4-V} = (\Delta C_{SO4-V} / C_{SO4-0}) \times 100 \quad [\%] \tag{5}$$

where  $C_{SO4-0}$  is  $SO_4^{2-}$  concentration on the downstream side of the ESP at the voltage of 0 kV, and  $C_{SO4-V}$  is the concentration at  $V$  kV.

The reduction amounts  $\Delta C_{SOF-V}$ ,  $\Delta C_{DS-V}$ ,  $\Delta C_{PM-V}$  and the reduction rates  $\eta_{SOF-V}$ ,  $\eta_{DS-V}$ ,  $\eta_{PM-V}$  of SOF, Dry soot and PM were also calculated similarly to (4) and (5). These concentrations were measured at the duct 3 as shown in Fig. 2.

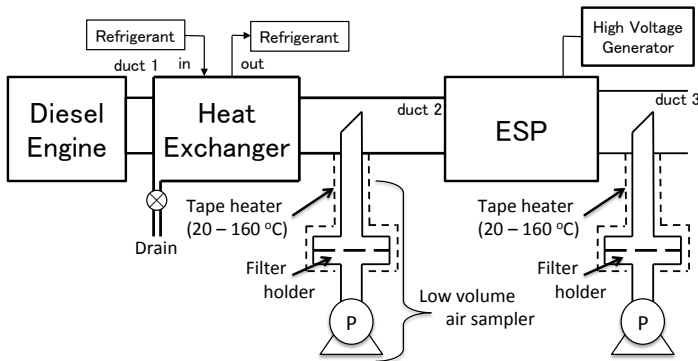


Figure 2: Schematic diagram of the experimental system.

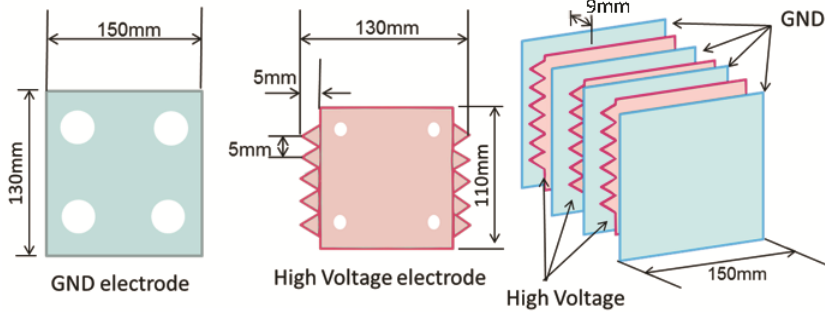


Figure 3: Structure of the ESP.

#### 4 Result and discussion

The relationship between the composition of PM and the gas temperature is shown in Fig. 4. These were measured at the duct 2 as shown in Fig. 2. The concentrations are expressed in weight per unit volume ( $1\text{m}^3$ ). The gas at  $160^\circ\text{C}$  had an  $\text{SO}_4^{2-}$  content of  $5.5\text{ mg/m}^3$ , bound  $\text{H}_2\text{O}$  content of  $7.2\text{ mg/m}^3$ , SOF content of  $3.3\text{ mg/m}^3$  and Dry-soot content of  $10.8\text{ mg/m}^3$ . The concentrations of  $\text{SO}_4^{2-}$ , bound  $\text{H}_2\text{O}$  and Dry soot did not significantly change with decreasing gas temperature. However, the SOF concentration significantly increased at  $70^\circ\text{C}$  or lower. This is probably because gaseous SOF forms particles due to

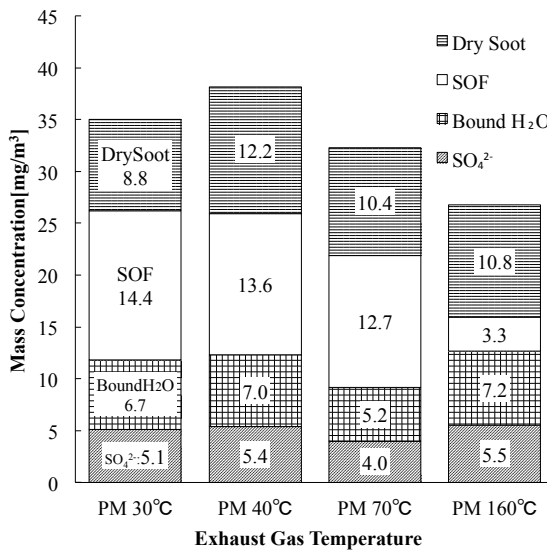


Figure 4: Relationship between the composition of PM and the gas temperature.

condensation. Although the gaseous SOF is difficult to reduce, particulate SOF is easily collected by ESP. Condensation of H<sub>2</sub>O mist into liquid water was also confirmed [11].

The voltage-current relationship for various gas temperatures in ESP is shown in Fig. 5. The corona onset voltages were approximately -4 kV. Although the corona current increased with increasing voltage, the current at the same voltage decreased at lower temperatures due to the decrease in electron energy.

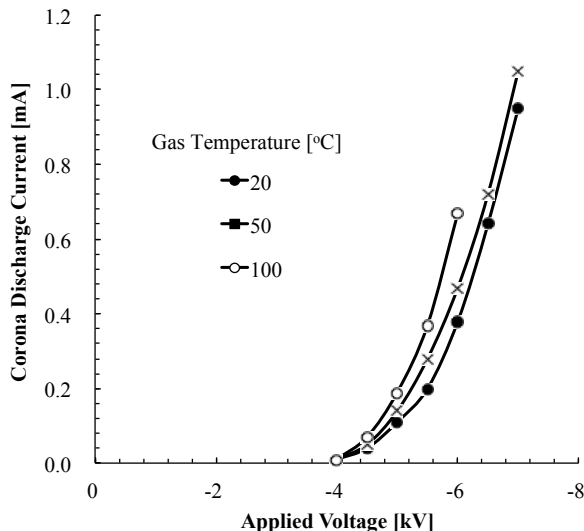


Figure 5: Voltage-current relationship for various gas temperatures.

The effect of reduction of PM in ESP was investigated.  $\text{SO}_4^{2-}$  reduction amount  $\Delta C_{\text{SO}_4}$  as a function of applied voltage in ESP is shown in Fig. 6.  $\text{SO}_4^{2-}$  was not reduced at 160°C. On the other hand, the amount increased as the voltage increased and reached 4.1 mg/m<sup>3</sup> at 30°C and -7 kV. The reduction rate  $\eta_{\text{SO}_4-V}$  as a function of the voltage is shown in Fig. 7.  $\text{SO}_4^{2-}$  reduction rate at 160°C was lower than 15% for any voltages. The rate exceeded 85% at 30°C, when the voltage at -7 kV was applied to the ESP. These results show that cooling the exhaust gas is effective for collecting sulphate by ESP. Negative amounts and rates means that the concentrations increase compared with the voltage of 0 kV. This cause is under investigation.

SOF reduction amount  $\Delta C_{\text{SOF}}$  as a function of applied voltage in ESP is shown in Fig. 8. SOF reduction amount at 160°C tended to increase as the voltage increased, and that was 2.4 mg/m<sup>3</sup> at -6.5 kV. However, the amount at 30°C increased with increasing voltage due to the charge, and that was 8.0 mg/m<sup>3</sup> at -6.5 kV or higher. This is because the SOF concentration increases due to condensation, as shown in Fig. 4. SOF reduction rate  $\eta_{\text{SOF}-V}$  as a function of applied voltage is shown in Fig. 9. SOF reduction rate increased with increasing voltage and decreasing temperature. This result shows that SOF particulate is easy to be charged at low temperatures.

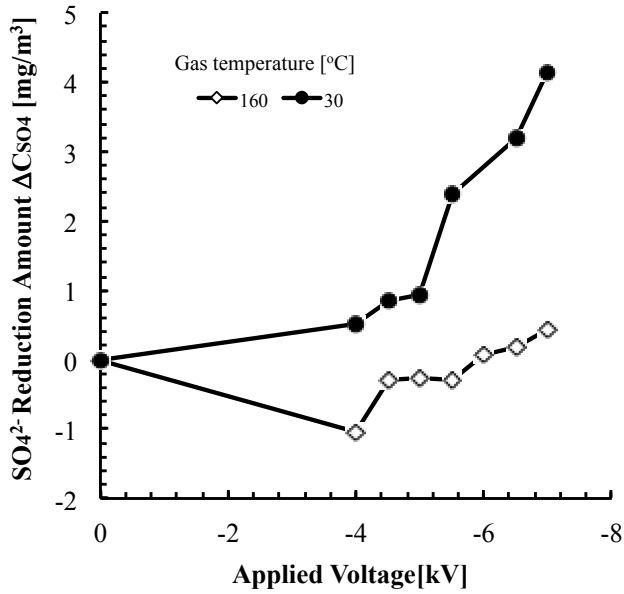


Figure 6:  $SO_4^{2-}$  reduction amount  $\Delta C_{SO_4}$  as a function of applied voltage in ESP.

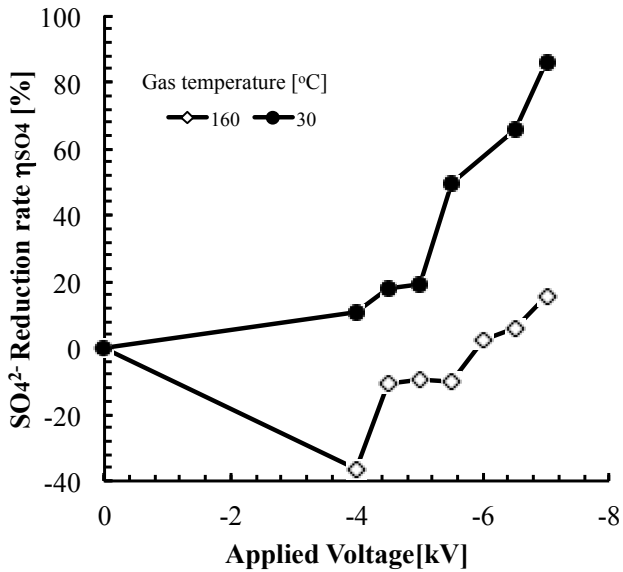


Figure 7: Reduction rate  $\eta_{SO_4}$  as a function of applied voltage in ESP.

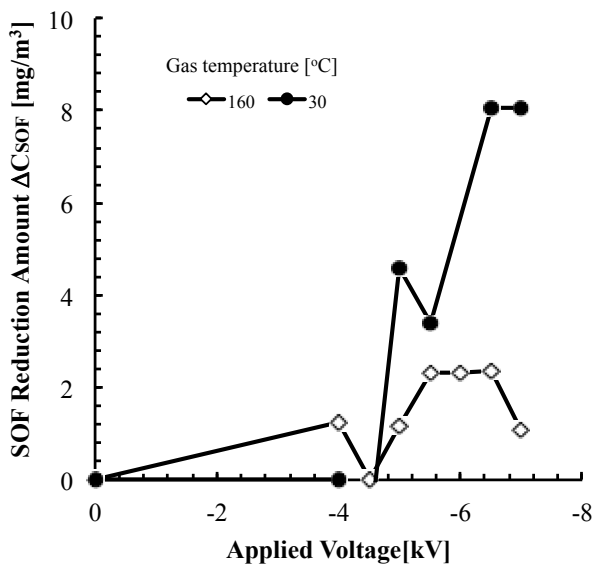


Figure 8: SOF reduction amount  $\Delta C_{SOF}$  as a function of applied voltage in ESP.

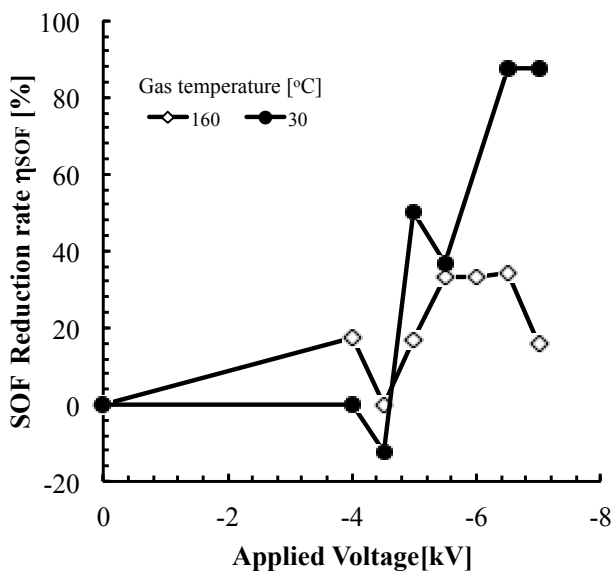


Figure 9: SOF reduction rate  $\eta_{SOF-V}$  as a function of applied voltage in ESP.



Dry soot reduction amount  $\Delta C_{DS-V}$  as a function of applied voltage is shown in Fig. 10. Dry soot reduction amount increased with increasing voltage. However, the effect of the gas cooling was not confirmed. This is because the Dry soot concentration is not influenced by the temperature, as shown in Fig. 4. The Dry soot reduction rate  $\eta_{DS-V}$  as a function of applied voltage is shown in Fig. 11. The efficiency was expressed in 100%, when the reduction amount was greater than the concentration in the gas. The Dry soot reduction rate increased with increasing voltage, and high efficiencies were achieved at both temperatures.

The total PM reduction amount  $\Delta C_{PM-V}$  as a function of applied voltage is shown in Fig. 12. The total PM reduction amount also increased with increasing voltage. The reduction amount at 160°C was lower than the amount at 30°C. The total PM reduction rate  $\eta_{PM-V}$  as a function of applied voltage is shown in Fig. 13. The rate at 160°C was no more than 57%, whereas the rate at 30°C reached 87%. These results indicate that the gas-cooling process helps improving the removal effect of harmful substances from marine diesel by ESP.

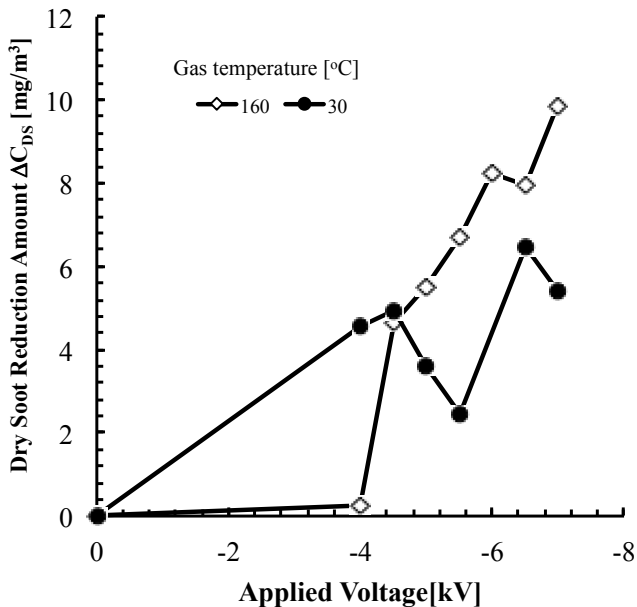


Figure 10: Dry soot reduction amount  $\Delta C_{DS-V}$  as a function of applied voltage in ESP.

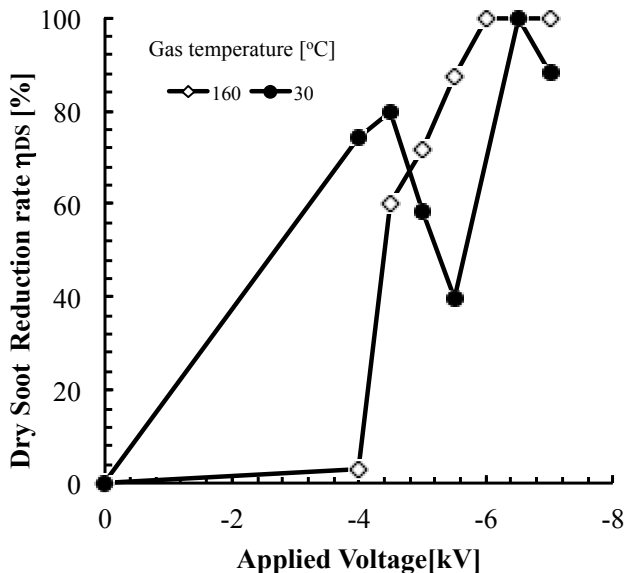


Figure 11: Dry soot reduction rate  $\eta_{DS-V}$  as a function of applied voltage in ESP.

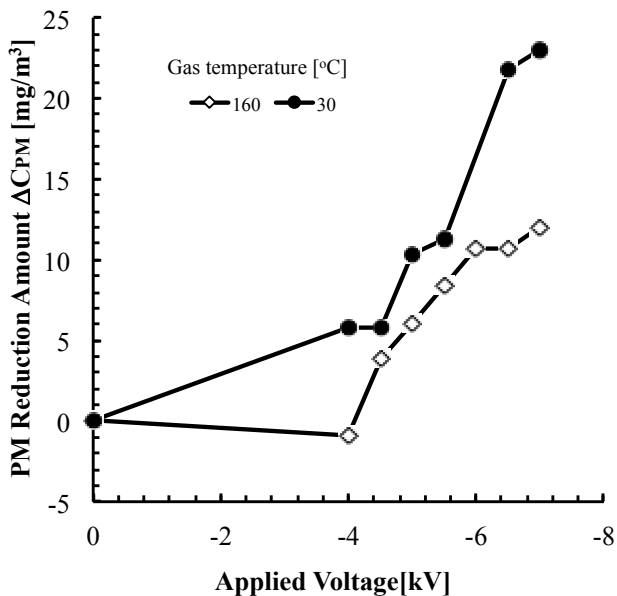


Figure 12: Total PM reduction amount  $\Delta C_{PM-V}$  as a function of applied voltage in ESP.



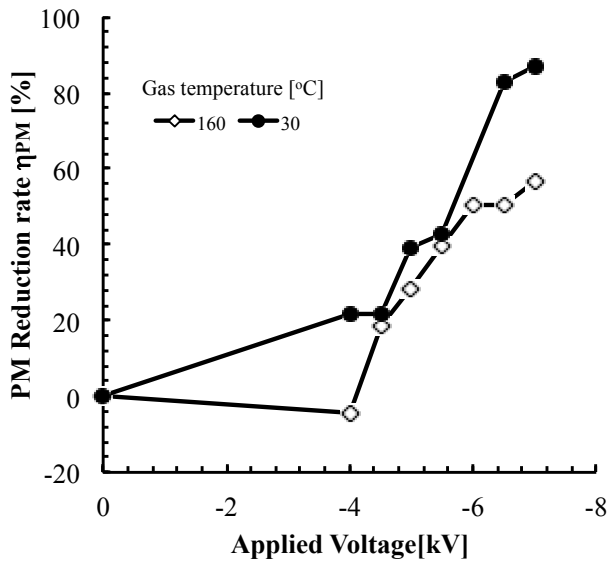


Figure 13: Total PM reduction rate  $\eta_{PM-V}$  as a function of applied voltage in ESP.

## 5 Conclusion

In this study, a novel PM removal system for marine engines has been proposed. Experiments were carried out to reduce PM, which were Dry soot, sulphate and SOF, by a gas heat exchanger and the ESP. Results are follows;

- 1) PM concentration in the exhaust gas increases, when the gas is cooled to 30°C from 160°C. This is because particulate SOF concentration increases due to condensation.
- 2) Cooling the exhaust gas is effective for collecting sulphate and SOF as part of particulate matter by ESP.
- 3) Dry soot is easy to collect at temperatures between 30°C and 160°C by ESP.

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