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REMOVAL OF MARINE DIESEL PARTICULATE MATTER BY ELECTROSTATIC PRECIPITATOR

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ABSTRACT
Diesel particulate matter exhausted from marine diesel engine during the combustion process cause a various human health and environment impacts. Many methods were applied to control mass concentration of particulate matter from diesel exhaust gas. This research has been developed applying an electrostatic precipitator (ESP) to reduce marine diesel particulate matter. The objective is to investigate experimentally ESP's performance on reducing diesel particulate with variation of exhaust gas temperature. Using a single stage and wire-plate type of ESP, the diesel particulate characteristics, such as mass concentration, composition (SOF and DS), size distribution and mean diameter of the aggregate particulates, under different engine operating conditions, are analyzed. Effects of exhaust gas flow on ESP's performance and operating duration of ESP are also discussed. The results show that applied ESP can reduce particulate mass concentration. The particulate mass concentration that reduced depends on gas temperature and initial particulate mass concentration. ESP could reduce the Soluble Organic Fraction (SOF) greater than Dry Soot (DS), and the mean diameter of aggregate particulates decreases.

1. INTRODUCTION

Diesel engines are used widely as the power sources of ship and another marine power plant primarily due to their high thermal efficiency and durable performance. However, gaseous and particulate exhausted from diesel engine during combustion process results air pollution, especially around harbor regions. The diesel particulate consists of Soluble Organic Fraction (SOF) and Dry Soot (DS) include sulfate. The particle formation and concentration are affected by fuel composition, oil lubrication and engine operation [Ref. 1, 2, 3]. Beside that, diesel particulate properties also depend on exhaust gas cooling temperature [Ref. 4].

The diesel particulate causes health hazards to human beings, such as aggravated asthma, increases in respiratory dysfunction like coughing and hard or painful breathing, chronic bronchitis, decreased lung function and premature death. Therefore, decreasing of particulate matter concentration on diesel exhaust gas becomes serious attention from industrial societies and related researchers. Regulations on diesel emission standard also have been made more strict [Ref. 5]. The consequence, various methods to reduce marine diesel particulate matter developed continually. Lin [Ref. 6] used catalyzed particulate filter to reduce marine diesel particulate matter, Chae [Ref. 7] used non-thermal plasma for exhaust gas treatment, and Nishida [Ref. 8] developed wet scrubber and seawater electrolysis for suppressing marine diesel gaseous and particulate emissions.

Simultaneous, hence in this research have been developed usages of electrostatic precipitator (ESP) to reduce marine diesel particulate matter. The ESP is one of devices for removing dust particle that very effective having high collection efficiency. ESP not results backpressure of exhaust gas stream in tailpipe and can operate by low power. From other researches, gas temperature affects ESP efficiency. Ohyama [Ref. 9] has done numerical assessment to analyze the effect of gas temperature on ESP collection efficiency. The result showed that the collection efficiency decreases by increasing gas temperature, especially for 0.1 ~ 1.0 μm particle diameters. While, Bapat [Ref. 10] explained the experiment result which minimum collection efficiency reached at temperature 150^0C on application of ESP for

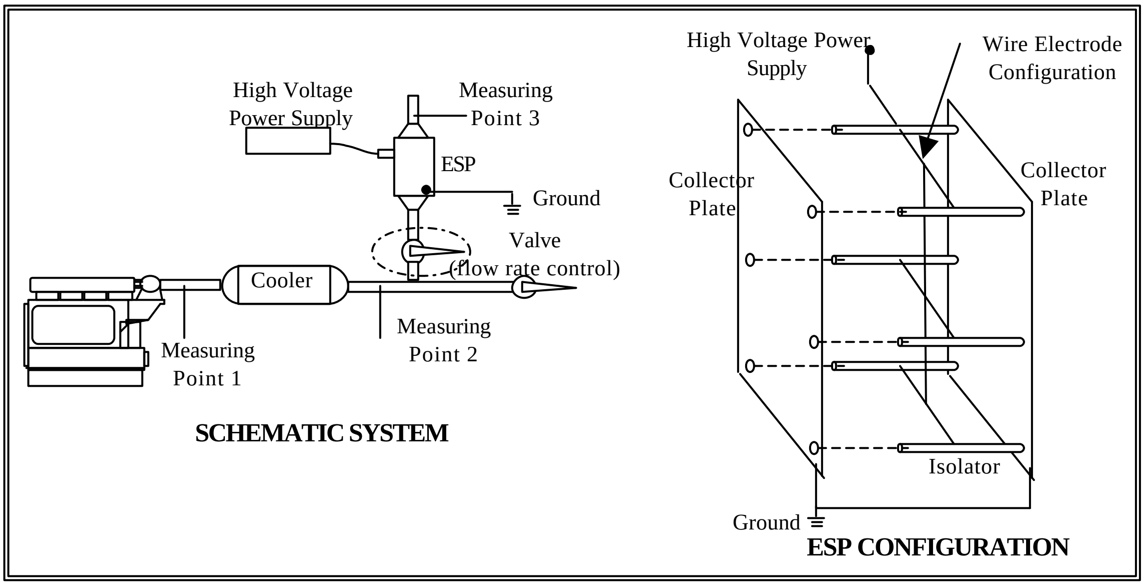

Figure 1: Experimental system schematic diagram

gas cleaning in cement industry. Then, the research focused on investigation of effect of particulate matter characteristic changing as effect by exhaust gas temperature cooling on ESP performance, and marine diesel particulate motion velocity in ESP.

2. EXPERIMENT

2.1. Experiment System

The experiment setup has been used to observe total particulate mass concentration, composition, and particulate size distribution caused by ESP, under various exhaust gas temperature and operating conditions of diesel engine. Fig. 1 shows the schematic of the experiments setup. The setup consists of a diesel engine, an exhaust gas cooler, ESP, and sampling apparatus. A 4-stroke single-cylinder direct injection diesel engine is used in the experiments with specific shown in table 1. The engine speed is kept constant at 2200 rpm for all operating conditions. Marine Diesel Oil is used to operate the diesel, and properties of the fuel are shown in table 2. For controlling exhaust gas temperature at the time entering ESP, the exhaust gas cooler is installed in the system. The Exhaust gas is cooled in 150^0C. Exhaust gas flow on ESP is controlled using manual control valve.

2.2. Electrostatic Precipitator Setup

A single stage and wire-plate type of ESP was used in this study. Two parallel collector plates, which made of aluminum, placed in distance 100 mm and connected to ground. Dimensions of each the plate are 300 mm (height), 200 mm (weight) and 0.5 mm (thickness). Wire Electrodes are made of aluminum with 0.5 mm diameter. Three wire electrodes placed on parallel with wire electrode distance 100 mm, and athwart to exhaust gas stream. An other wire electrode attached vertically at center position on the parallel wire electrodes, such as Fig. 1. 20 kV of Electric field and result electric current 0.5 mA from DC rectifier is supplied to wire electrode.

Table 1: Specification of Engine

Engine type	Horizontal Single cylinder 4-stroke diesel engine
Type and Model	YANMAR NF 19-SK
Cylinder Bore x Stroke	ϕ 110 x 106 mm
Swept volume	1007 cm^3
Clearance volume	61.78 cm^3
Compression Ratio	16.3
Effective Compression Ratio	14.5
Swirl Ratio	2.20
Maximum Power	14 kW / 2400 RPM
Rated continuous power	12.6 kW / 2200 RPM
Nozzle	0.33 mm in diameter, 4 holes
Nozzle injection angle	150^0
Injection timing	$19^0 \pm 1^0$ BTDC
Injection valve opening pressure	19.6 ~ 20.1 MPa

From previous research, exhaust gas flow rate into ESP correlates to surface area of collector plate. Ratio between the collector plate surface area and flow rate is termed ESP specific collection area.

In this study, value of the specific collection area is 7.6 m^2 / 1000m^3/h. In additional, we also investigate several value of specific collection area effect on ESP up to 4.0 m^2 / 1000m^3/h.

Table 2: Specification of Fuel

Fuel type	Marine Diesel Oil (A-Heavy Oil)
Density (15^0C)	0.8528 g/cm^3
Flash point	65^0C
Kinetic Viscosity (50^0C)	2.42 mm^2/sec. (cSt)
Pour point	-22.5^0C
Residual Carbon	0.46 mass%
S	0.08 mass%
N	0.038 mass%
H2O	< 0.01 vol.%
Ash powder	< 0.001 mass%
Low Heating Value	42.7 MJ/kg

2.3. Measurement Technique

There are three positions to measure the diesel particulate on the experiment system, they are measuring point 1 (at engine exhaust manifold), measuring point 2 (at ESP inlet), and measuring point 3 (at ESP outlet). For each position of measuring, total mass concentration of the diesel particulates on composite filter paper is measured by a high precision electric balance. The filters, before and after collecting the samples, were weighed under strictly controlled temperature and relative humidity. Extraction of SOF from DS by dichloromethane, and the particle size is measured by Scanning Electron Microscope.

3. RESULT AND DISCUSSION

3.1 Effect of exhaust gas cooling

Gas temperature (T) having an effect on trapping particle by ESP. Decreasing of the gas temperature will decrease number of particle charge (q), as given in Eq. 1 [Ref. 11]:

$$q(t) = \frac{DkT}{2K_E e^2} \ln\left[1 + \frac{pK_E Dc_i e^2 N_i t}{2kT}\right] \quad \text{........... (1)}$$

Where D is particle diameter, k is Boltzmann's constant, K_E is electric constant, e is charge per electron, c_i is mean thermal velocity of the ions, N_i is ion concentration, and t is time.

Number of charge describe amount of ions accumulated in a particle. This is one of factors on affecting particle migration velocity (w). Particle migration velocity is affecting particle collection in ESP, and is expressed by

$$w = \frac{qeEC_c}{3pmD} = \frac{EC_c kT}{6pmK_E e} \ln\left[1 + \frac{pK_E Dc_i e^2 N_i t}{2kT}\right] \quad \text{........... (2)}$$

Where E is electric field strength in collection region, C_c is slip correction factor, and μ is gas viscosity. While, particle concentration in gas stream after precipitation process (N) is described in Eq. 3:

$$N = N_0 \exp^{-\left(w\frac{A}{Q}\right)} \qquad \text{........... (3)}$$

Where N_0 is initial particle concentration, A is collector plate area, and Q is exhaust gas flow rate. Therefore, ESP collection efficiency (η) can be written:

$$h = 1 - \exp^{-\left(w\frac{A}{Q}\right)} \qquad \text{........... (4)}$$

Decreasing of temperature also decreases gas viscosity. At the decreasing same temperature, gas viscosity decreases more rapidly than the number of charge. This means decreasing of temperature quickening particle migration, and finally increases collection efficiency as well.

In diesel engine, as shown in Fig. 2, exhaust gas cooling temperature increases particulate matter mass concentration, because volatile materials in exhaust gas are nucleated and condensed during cooling process. Exhaust gas cooling temperature also makes faster aggregation process of particulate matter. On the other case, cooling of exhaust gas temperature under 100^0C causes vapour in exhaust gas condensed form water droplet. The water droplet in exhaust gas can fasten particulate matter and hereinafter to become condensate.

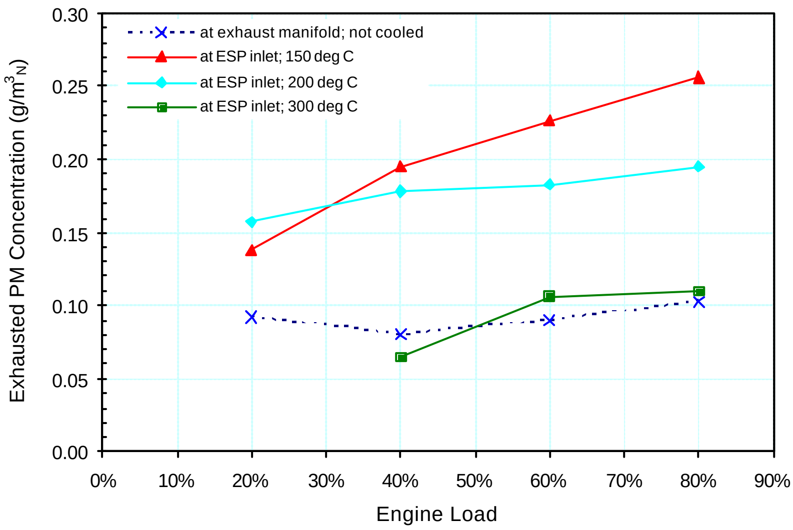

Figure 2: Exhaust Gas Temperature cooled effect on Diesel Particulate Concentration

Both exhaust gas temperature cooling effect, increasing of particulate matter mass concentration and particle motion velocity, influence final concentration of particulate matter in exhaust gas after treated by ESP. As shown in Fig. 3, even gas viscosity at temperature 300^0C higher than viscosity in lower temperature, particulate mass concentration on temperature 300^0C is lowest, because the initial particulate mass concentration is very less compared to the 150^0C and 200^0C condition (Fig. 2). Particulate mass concentration in temperature 150^0C less than in temperature 200^0C, yet the initial concentration more than in temperature 200^0C. It indicates that decreasing of temperature increases collection efficiency.

As show in the experiment result, the ESP could reduce particulate matter in marine diesel exhaust gas up to 85%, and the final particulate matter concentration is 18.4 mg/m^3_N on 80% engine load and 300^0C exhaust gas temperature. The particle mass concentration also decreases for low engine load. The minimum point of ESP performance on reducing marine diesel particulate matter is reached in temperature 200^0C.

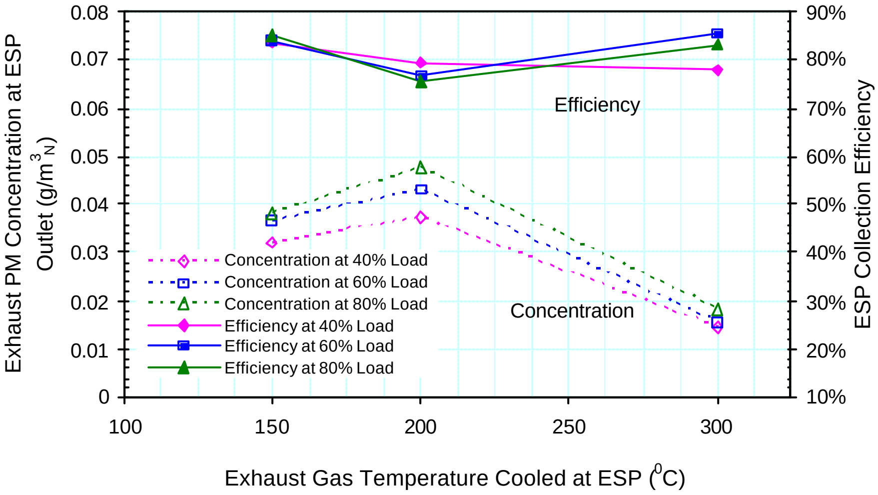

Figure 3: ESP Collection Efficiency on several of Exhaust Gas Temperature cooled

3.2 Particle composition and size distribution

The SOF in diesel particulate matter consists of aldehydes, alkenes and alkanes, hydrocarbon aliphatic, PAH and PAH-derivatives [Ref. 12]. The elements come from unburned fuel and oil lubricating, and from partially oxidized fuel and oil. DS that consist of small solid carbon particle, sulfate, and metal are formed during combustion process. In particulate matter aggregation, the SOF sticks on surface or inside of the aggregate.

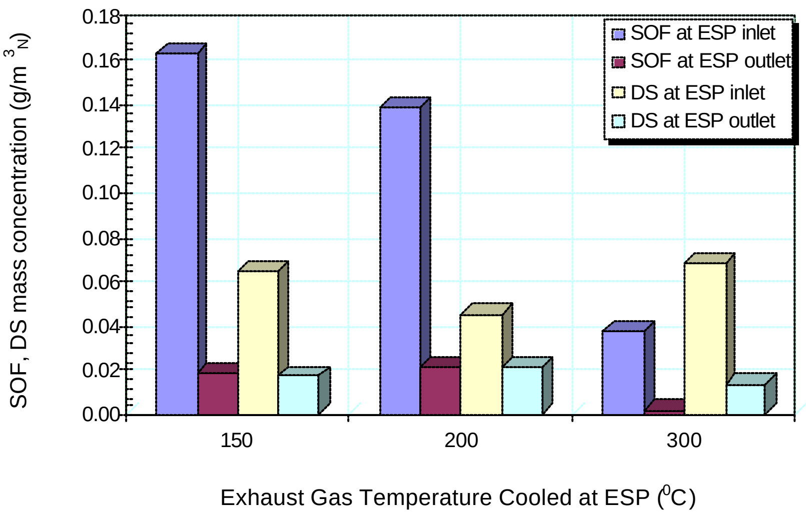

Figure 4: SOF, DS concentration by applying ESP at 60% Load

The resistivity is important parameter on collecting particle by ESP. Resistivity of SOF elements less than DS elements. At low resistivity, the particle motion velocity would be increasing. Adhesive of SOF effect on particle collision and surface plate also increase van der waals force. The reason why reducing the SOF higher than DS by ESP, shown in Fig. 4. The SOF is reduced until 95%, while DS is reduced up to 80% from each initial concentration at 60% engine load and 300^{0}C exhaust gas temperature.

Rapidly of aggregation process as resulted by exhaust gas cooling temperature also enlarge the mean aggregate diameter of particulate, as show in Fig. 5 and 6. Furthermore, usage of ESP on reducing particulate matter causes the mean diameter of particulate decreasing. In other words, ESP performance better collecting large particle than small particle. It caused by high particle charge process for large particle, and finally, particle motion which as main parameter on particle collection also quick.

Mean diameter of aggregate particulate in exhaust gas at ESP outlet decrease until 10.1 %, and size distribution curve shift to the left. Percentage of aggregate particulates number that has diameter smaller than 160 nm is increasing, but contrarily for aggregate particulates in diameter larger than 160 nm is decreasing.

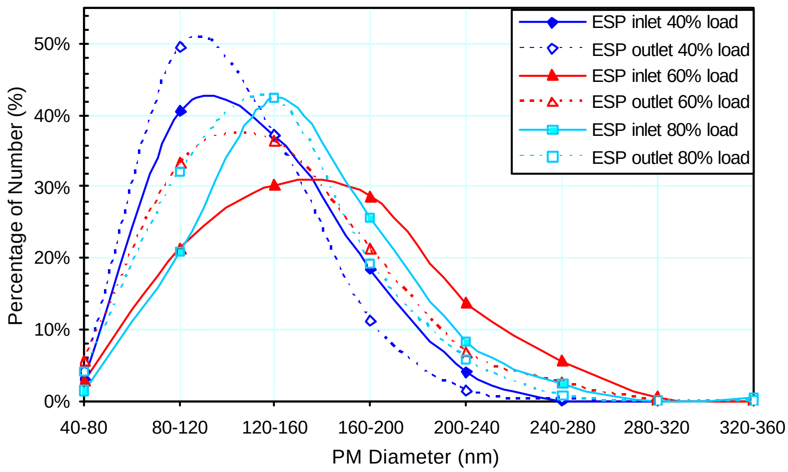

Figure 5: DPM size distribution

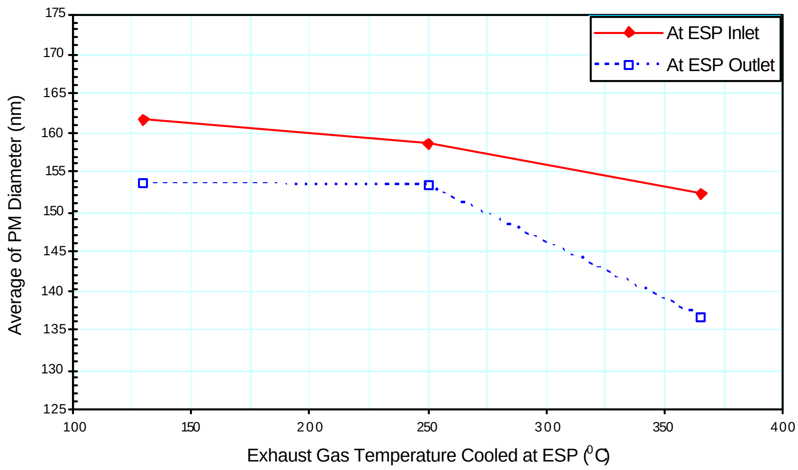

Figure 6: Mean diameter of PM Aggregate at 80% load

3.3. Particle Motion Velocity and Operating duration

ESP performance depends on gas flow capacity and plate collection area. Ratio of the parameters is termed as specific collection area of ESP. Effect of specific area on collecting of marine diesel particulate is shown in Fig. 7. Pursuant to the result and using the Eq. 4, particle motion velocity of marine diesel particulate is 9.5 cm/sec at 75% engine load and 400^0C exhaust gas temperature. While some typical particle velocity for various applications shown in table 3. Comparison of marine diesel particulate migration velocity and the others particle indicate that using of ESP to reduce marine diesel particulate could be applied because migration velocity of the particle more than average of the others particle migration on actual precipitator.

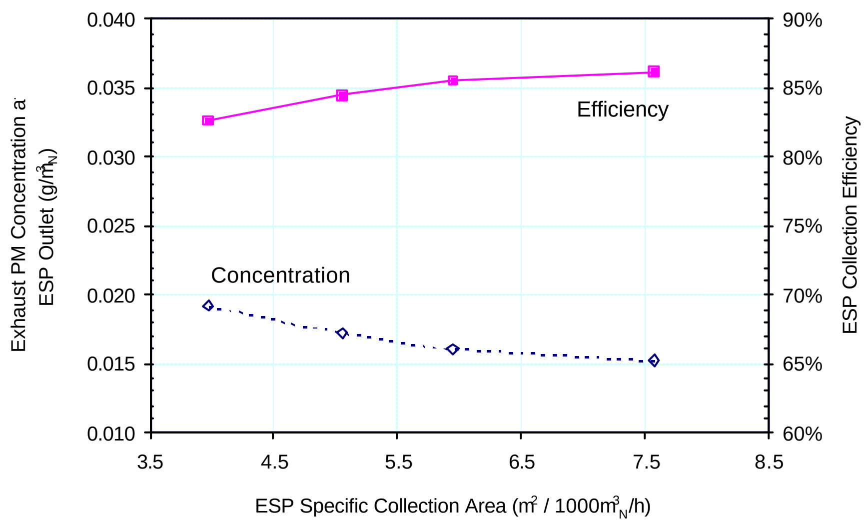

Figure 7: ESP specific collection area various at 75% load and gas temperature 400^0C

Table 3: Typical particle motion velocity for various applications determined from field measurement on actual precipitator [Ref. 13]

Application	Particle Motion Velocity (cm/sec)
Utility fly ash	4 – 20.4
Pulverized coal fly ash	10.1 – 13.4
Pulp and paper mills	6.4 – 9.5
Sulfuric acid mist	5.8 – 7.62
Cement (wet process)	10.1 – 11.3
Cement (dry process)	6.4 – 7
Gypsum	15.8 – 19.5
Smelter	1.8
Open-hearth furnace	4.9 – 5.8
Blast furnace	6.1 – 14.0
Hot phosphorous	2.7
Flash coaster	7.6

Beside trapped on collector plate, particulate matter also stuck on wire electrode because electrons attack the particulate on near wire electrode and together migrate to the wire. Heaping of the particle on wire disturbs electric field intensity, and then lessens ESP performance. Investigation of

6 hr ESP operation as shown in Fig. 8, there is no effect at 400^{0}C exhaust gas cooling temperature. While at 150^{0}C exhaust gas cooling temperature, the electric field intensity is disturbed since 5th hour. Nevertheless, in generally, the particle on wire electrode can be removed by rapping to wire electrode.

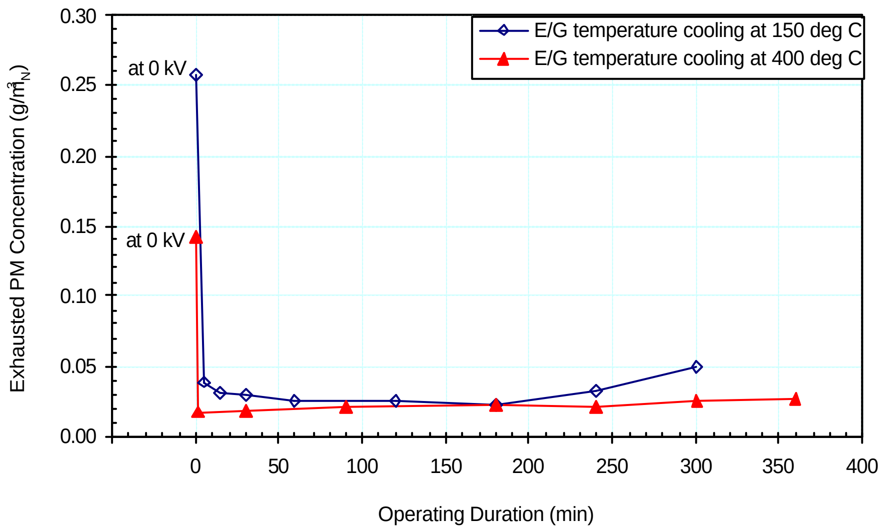

Figure 8: Operating duration on ESP at 75% load

4. CONCLUSION

Using of single stage and wire-plate ESP Type by 20 kV DC electric field to reduce marine diesel particulate matter is investigated. The results are summarized as follows:

1. Marine diesel particulate matter could be reduced until 85%, and the particulate mass concentration in ESP outlet for high temperature less than low exhaust gas cooling.
2. The ESP could reduce SOF more than DS, and the mean diameter of particle aggregate in exhaust gas would be decreases too.
3. Particle motion velocity of marine diesel particulate on ESP is about 9.5 cm/sec, and the velocity value is higher than average of particle motion velocity for various other applications.

5. REFERENCES

1) Opris C.N., Gratz L.D., Bagley S.T., Baumgard K.J., Leddy D.G., Johnson J.H. (1993), "The Effects of Fuel Sulfur Concentration on Regulated and Unregulated Heavy-Duty Diesel Emissions", SAE Technical Paper 930730
2) Baumgard K.J., Johnson J.H. (1996), "The Effect of Fuel and Engine Design on Diesel Exhaust Particle Size Distributions", SAE Technical Paper 960131.
3) Abdul-Khalek I.S., Kittelson D.B., Brear F. (1999), "The Influence of Dilution Conditions on Diesel Exhaust Particle Size Distribution Measurements", SAE Technical Paper 1999-01-1142.
4) Ning Z., Cheung C.S., Liu S.X. (2004), "Experimental investigation of the effect of exhaust gas cooling on diesel particulate", Journal of Aerosol Science, Vol. 35, pg. 333–345
5) Kyodo (2005). Gov't introduces world's strictest diesel exhaust regulations, Kyodo News, January http://home.kyodo.co.jp/all/display.jsp?an=20030325215

6) Lin, C.Y (2002) "Reduction of particulate matter and gaseous emission from marine diesel engines using a catalyzed particulate filter", Ocean Engineering Journal, Vol. 29, pg. 1327-1341
7) Chae, J.O (2003). "Non-thermal Plasma for diesel exhaust treatment", Journal of Electrostatics, Vol. 57, pg. 251-262
8) Nishida, O., Kawaji, T., Fujita, H., Harano, W. (2005) "Development for Perfect Suppression of Marine NOx, SOx and PM", in proceeding of ISME Conference, Tokyo
9) Ohyama, R., Urashima, K., and Chang, J.S. (2000). "Numerical modeling of wire-plate electrostatic precipitator for control of submicron and ultra fine particle", Journal of Aerosol Science, Vol. 31 Suppl, pg. S162-S163.
10) Bapat, J.D (2001). "Application of ESP for gas cleaning in cement industry—with reference to India", Journal of Hazardous Material, Vol. B81, 285-308
11) White, H.J. (1963). "Industrial Electrostatic Precipitator", Addison Wesley.
12) Johnson H.J., Bagley S.T., Gratz L.D. and D.G. Leddy, (1994), "A Review of Diesel Particulate Control Technology and Emission Effects", SAE Technical Paper No. 940233.
13) Theodore, L., and Buonicore, A. J, (1976) "Industrial Air Pollution Control Equipment for Particulates", Cleveland: CRC Press.