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Technology for reducing emissions from marine diesel engines — Reduction of black carbon emission and suppression of wastewater pollution from scrubber —

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1. Introduction

The International Maritime Organization (IMO) has tightened the regulations on NO_x and SO_x emissions from marine engines in a stepwise manner. As measures for reducing NO_x emissions, selective catalytic reduction (SCR) and exhaust gas recirculation (EGR) have been adopted. As measures for reducing SO_x emissions, scrubbers have been intensively developed as well as a technology for reducing the sulfur content of fuel oil. On the other hand, particulate matter (PM) in exhaust gas has not yet been directly regulated. However, black carbon (BC) emitted from marine engines is considered to promote the melting of snow and ice in the Arctic region, leading to climate change, and international regulations for BC emissions have started to be discussed.1)

We clarified the emission situation of PM (e.g., PM mass concentration, PM number concentration) from marine diesel engines. At the same time, we developed an new PM reduction system (electrostatic precipitator (ESP) + cyclone precipitator (Cyclone); hereafter ESP-C system, or ESP-C) with the aim of establishing a technology for reducing PM emission. From the result of our research and development, the ESP-C system was found to be capable of removing PM from exhaust gases generated from diesel engines at a high collection efficiency. In addition, the ESP-C system was confirmed to exhibit a high PM collection performance for HFO (Heavy Fuel Oil), primarily used as a marine fuel, equivalent to that for LFO (Light Fuel Oil).2–4)

Wet scrubbers used to reduce SO_x emissions generate polluted wastewater and a large amount of wet sludge, which remains a serious problem.1) As a countermeasure, we recently developed an exhaust gas cleaning system (EGCS) by combining the ESP-C system with a new type scrubber and demonstrated that the wastewater pollution from the scrubber can be greatly suppressed by the new EGCS.5)

In this paper, we introduce the technologies that we have developed for reducing BC emission and suppressing the pollution of the wastewater from the scrubber as a response to the trend of the tightening of environmental regulations.

2. Newly developed EGCS

First, we review the structure of the EGCS as the overall image of the developed technologies (Fig. 1). The details of each technology used in the system are explained in the following sections.

2.1 ESP-C system

The ESP-C system consists of an ESP and a Cyclone. First of all PM is collected by the ESP and is finally collected in the dust hopper of the Cyclone. The PM collected in the dust hopper is intermittently subjected to combustion, and the combustion gas is returned into the inlet of the ESP. The final waste product of the ESP-C system is a small amount of dry ash and metal components that are present in the fuel.

2.2 SO_x scrubber

The exhaust gas, from which PM has been removed, is treated by the wet scrubber. The new type scrubber removes only SO_x, and the small amount of PM that was not collected by the ESP-C passes through the scrubber. Owing to this structure, the pollution of the wastewater from the scrubber is greatly suppressed, which may enable the realization of an open-loop system using seawater that requires no water treatment. In practical operation, various measures including the neutralization of wastewater are required.

3. Newly developed ESP-C system

The initial target of this work was the technology for reducing the amount of PM in the exhaust gas from diesel automobiles. To this end, we began developing a system that could easily be installed on automobiles, that is, a compact and maintenance-free system with a high collection efficiency. Meanwhile, environmental problems have recently been attracting attention and a measure for reducing the amounts of undesirable substances in the exhaust gas from marine engines has been increasingly demanded. In addition, the ESP-C system was found to be suitable for marine engines in the initial stage of the basic experiment. Therefore, we narrowed the applied target to marine engines and onshore power plants and carried out research and development on the system.

3.1 PM collection mechanism in ESP-C

Most of the PM emitted from diesel engines is composed of fine particles with diameter ≤ 0.5 μm. The relationship between the particle diameter and the collection performance of precipitators is roughly described as follows. The ESP can collect fine particles such as PM from diesel engines at a high collection efficiency, whereas the Cyclone is suitable for collecting large-diameter (at least 5 μm) particles and cannot collect fine particles such as PM from diesel engines.

For marine engines, which are required to operate continuously, particles deposited on the collection wall of the ESP must be removed. In our experiments, when the thickness of the PM layer deposited on the collection wall increased, the deposited PM layer naturally peeled off from the collection wall in the form of large agglomerates. While the PM agglomerates being repeatedly collected to and separated from the collection wall, the PM agglomerates moved downstream of the ESP; this process is known as the jumping phenomenon. As the thickness of the PM layer increases, the separation of the PM layer from collection wall occurs, because the peeling force by the high-speed flow of the exhaust gas becomes bigger than the electrical adhesive force.

On the basis of the experimental results and this discussion, we developed the ESP-C system. Figure 2 shows the PM collection mechanism of the ESP-C system. (1) Fine PM is charged by corona electrons discharged from a discharge electrode. (2) The charged PM moves toward the collection wall by Coulomb force and is attracted to and deposited on the collection wall. (3) As the thickness of the deposited PM layer increases, the deposited PM layer naturally peels off and flows into the downstream Cyclone in the form of large PM agglomerates. (4) The large PM agglomerates are easily separated from the exhaust gas by the Cyclone, and the PM agglomerates are collected in the dust hopper. A purified exhaust gas, from which PM has been removed, is emitted from the ESP-C system into the atmosphere. Because both the ESP and the Cyclone have a structure that is free from clogging, the ESP-C system is maintenance-free and is capable of continuous operation.

3.2 Downsizing of ESP-C

The downsized Cyclone is introduced here. Figure 3 (b) shows the structure of a new ESP-C in which a branch route is built downstream in the ESP. In the downstream area of the ESP, the flow of the exhaust gas is split into a central part (main route) and a part in the vicinity of the collection wall (branch route). The exhaust gas flowing through the branch route has a high concentration of PM and is guided to the Cyclone. In the initial equipment (Fig. 3-a), all of the exhaust gas that passes through the ESP is treated by the Cyclone. In the improved equipment with the branch route (Fig. 3-b), however, the amount of exhaust gas treated by the Cyclone is greatly reduced, which enables the downsizing of the Cyclone.

Computational fluid dynamics (CFD) was used to evaluate the optimal shape of the branch route. Figure 4 shows an example of the result of steady-state analysis using an unstructured grid (about 800,000 meshes). The flow velocity counter and vector near the branch route are shown in the figure. The ratio of the flow velocity at the inlet of the branch route (U_s) to that inside the ESP (U_e) is defined as the flow velocity ratio α ($=U_s/U_e$). The optimal shape of the branch route was examined using the value of α. The results indicate that the gas with the high PM concentration near the surface of the collection wall can be unerringly guided to the branch route when α is set to 0.85–1.0. The size of the opening gap of the branch route is independent of the diameter of the cross section of the ESP and can be considered constant. Therefore, the effect of downsizing the Cyclone using the branch route becomes relatively significant for large ESPs.

3.3 Increasing of collection efficiency in ESP

Figure 5 shows a schematic of the electric field distribution and the behavior of the PM inside the ESP. The coulomb force that acts on the charged PM is strong in the region between the tip of the discharge electrode and the collection wall (strong-electric-field region, region A), and is weak inside the discharge electrode (weak-electric-field region, region B). To increase the PM collection efficiency, the region through which the PM flows should be the strong-electric-field region. To address this issue, we developed an ESP with a multistage collection wall, as shown in Fig. 6. In the multistage structure, the diameter of the main route increases in the downstream direction of the gas flow. This structure enables the PM in the exhaust gas to flow only in the strong-electric-field region in the ESP, achieving a high collection efficiency. As a result, the ESP can be downsized. In addition, the ESP with the multistage structure can maintain its high collection efficiency even in the ESP with a large aperture and high capacity.

3.4 Control system for ESP-C

The main control items of the ESP-C system are the applied voltage and the flow rate in the Cyclone. The higher the voltage applied to the discharge electrode, the higher the collection efficiency. Therefore, the optimal applied voltage should be set slightly lower than the sparking voltage. The sparking voltage depends on the conditions of the exhaust gas. In our control system, the optimal voltage is automatically determined. The flow rate in the Cyclone is adjusted by controlling the number of rotations of the blower in the Cyclone using α as an index. Figure 7 shows an example of the control panel of an ESP-C system. The actual data on the flow rate and temperature of the exhaust gas as well as various control data such as the applied voltage are displayed on the panel.

3.5 Experimental results on ESP-C

In this work, we carried out joint research experiments in collaboration with external institutions including the Tokyo University of Marine Science and Technology (low-speed two-stroke marine engine 3UEC37LA, 1103 kW; high-speed four-stroke marine engine 3L13AHS, 74 kW), the National Maritime Research Institute (mid-speed four-stroke marine engine MU323DGSC, 257 kW), and the National Fisheries University (training ship KOYO MARU; low-speed two-stroke marine engine 6L35MC, 3900 kW). Some of the experimental results are described here.

(1) Reduction of black smoke by ESP-C at engine startup

The low-speed two-stroke marine engine (Tokyo University of Marine Science and Technology, 3UEC37LA) was used in this experiment. At engine startup, thick black smoke is generated. Figure 8 shows the experimental results. When the applied voltage of the ESP is turned on, black smoke is significantly reduced and cannot be visually detected. The effect of the ESP is clear also from the particle number concentration measured with Dekati ELPI (Electrical Low Pressure

Impactor). At engine startup, the flow rate of the exhaust gas is low (i.e., the flow velocity of the exhaust gas in the ESP is low). Hence, PM can be easily collected by the ESP. Note that the output of the high-voltage power supply used in the experiment was 40 kV and the actual applied voltage was approximately 30-35 kV.

(2) Reduction of PM by ESP-C under steady-load operation

The low-speed two-stroke marine engine (3UEC37LA) was used in this experiment. Figures 9 and 10 show the experimental results. The PM collection efficiency η was calculated from the PM concentrations (the dilution tunnel method that complies with ISO 8178-1 or the number concentrations measured by the ELPI) at the inlet and outlet of the ESP. $\eta = \{1 - (\text{PM concentration at ESP outlet}) / (\text{PM concentration at ESP inlet})\} \times 100$. High PM collection efficiencies were achieved for both LFO (sulfur content, 0.07%) and HFO (sulfur content, 2.2%). The results of the particle size distribution measurements indicate that even nanoparticles (diameter <100 nm) can be efficiently collected by the ESP. Because BC is considered to be solid particles even in high-temperature exhaust gas, it is not affected by the temperature of the exhaust gas and can be efficiently collected by the ESP. Therefore, the ESP is suitable for reducing the amount of BC.

(3) Test of ESP-C on actual ship

A training ship KOYO MARU of the National Fisheries University was used in the experiment (Fig. 11) [6]. The experimental contents are as follows: low-speed two-stroke engine 6L35MC; LFO (sulfur content, 0.81%); course, Naha Port – East China Sea – Shimonoseki Port, January 2011. The PM collection efficiency was 90% for 75% load (the PM concentrations measured by ISO 8178-1). The ESP used in this experiment was vertically placed (i.e., the gas flowed in the vertical direction). Because PM in the exhaust gas is fine particles, the effect of gravity is very small and the PM collection performance of the ESP is to be independent of its direction (horizontal or vertical).

(4) Latest experimental results using improved ESP-C

Many improvements have been made through a series of studies. The latest experimental results using improved ESP-C are outlined here. The experiment was conducted in a 4-stroke medium speed engine. Figure 12 shows the prototype ESP-C used in this experiment.

The experimental conditions were as follows: the load was 75%; the exhaust gas was separated from the main exhaust pipe and was led to ESP; the gas temperature at the ESP inlet was about 300 ℃; the flow volume and velocity of the exhaust gas in the ESP were 4500 m^3/h and 10 m/s, respectively. Two types of fuel, LFO and HFO (sulfur content, 1%), were used. The PM collection performance was evaluated using Dekati ELPI+. The exhaust gas to be tested was suctioned through both the inlet and the outlet of the ESP, passed through the transfer tube maintained at 190 ℃ and after diluted by clean air heated at 250 ℃, and then supplied to the

ELPI+. Figure 13 shows the experimental results. The PM mass concentration was calculated from the particle number concentration corresponding to the particle size at each stage of the ELPI+ by assuming the density of particles of each size to be constant. Even when the flow velocity of the exhaust gas was as high as 10 m/s, high PM collection efficiencies were achieved for both LFO and HFO (PM collection efficiency about 80%). Figure 14 shows the amount of PM accumulated in the dust hopper of the Cyclone in about 10 hours of ESP operation using HFO.

(5) Pressure loss in ESP

The pressure loss of the prototype ESP was investigated at atmospheric pressure and a normal temperature condition. Figure 15 shows the relationship between the gas flow velocity U in the ESP and the pressure loss ΔP, which was experimentally obtained. Here, ΔP = (static pressure at ESP inlet) − (static pressure at ESP outlet). When U = 10 m/s, ΔP = about 280 Pa, indicating that the pressure loss in the ESP was small. Therefore, the ESP installed between the engine and a funnel has little effect on the engine.

3.6 Example of application of ESP-C system

Figure 16 shows an example of ESP-C unit and the system connected to a small power generator. By adopting a unit structure, the ESP-C system that can be easily connected to the existing engine and exhaust pipes will be possible. In addition, the ESP can be designed in accordance with required specifications, such as collection performance and area occupied.

3.7 Summary of development of ESP-C system

Conventional ESPs were evaluated as follows. The advantage of the ESPs is the high ability to collect PM in the exhaust gas generated when HFO or LFO are used. However, the existing ESPs were inevitably large because of the low velocity of the exhaust gas during ESP treatment and were evaluated to be impractical for marine engines.7) We have made various improvements as mentioned above and successfully developed a compact and maintenance-free ESP-C system that can be installed into marine engines.

4. Developed SO$_x$ Scrubber

4.1 Technical concept of new SO$_x$ scrubber

Conventional wet scrubbers simultaneously remove SO$_x$ and PM from exhaust gas. Therefore, the pollution of the scrubber wastewater by PM is serious and a large amount of wet sludge is generated, which is a major problem. With developed EGCS, the amount of PM in the exhaust gas is first reduced by the ESP and the subsequent new scrubber removes only SO$_x$. The small amount of PM that was not collected by the ESP passes through the scrubber and is emitted into the atmosphere. The new scrubber has multiple wet walls as its basic structure (Fig. 17). The principle of the scrubber is explained as follows. Water runs down along the walls of the plates in a membrane-like manner to allow the liquid to absorb the gas. It is important to avoid collisions between water droplets and the exhaust gas. The diffusion rate of the SO_2 gas is much higher than that of soot and oil mist in the PM, and SO_2 is highly soluble in water. Therefore, SO_2 easily reaches the wet walls and is absorbed. In contrast, a small amount of PM passes through the gap between the walls and is emitted into the atmosphere. As a result, the wastewater from the scrubber is less polluted by the PM. Thus, new EGCS is expected to be applicable as an open-loop cleaning system using seawater.

4.2 Experimental methods and results on new SO_x scrubber

SO_2 is highly soluble in water and seawater whose pH is appropriately controlled, and the techniques for absorbing SO_2 using a scrubber have been established. In this experiment, the main focus is to demonstrate that the treatment of the wastewater from the scrubber can be simplified by using the ESP in advance to reduce the amount of PM, which is a cause of pollution of the wastewater. In the experiment, commercially available oblique honeycomb filler was used to simulate the technical concept of new scrubber. For comparison, a commercially available random packing (rosette-type) was used for the conventional scrubber. The dimensions of the container for the filler were as follow: width 400 mm, height 400 mm, length 300 mm. The low-speed two-stroke engine (3UEC37LA) was used with HFO (sulfur content, 2.4%) at 50% load. Part of the exhaust gas from the ESP (PM collection efficiency in the ESP, 60%) was guided to the scrubber (gas temperature at scrubber inlet, 120 ℃; exhaust gas flow rate, 500 Nm3/h). To promote the pollution of the scrubber water, a small amount of tap water (50 L) was continuously circulated at a rate of 40 L/min for 180 min. At this time, the liquid-to-gas ratio was 4.8 L/Nm^3. After the start of the operation of the scrubber, the scrubber water was sampled at regular intervals to measure the items related to water quality, such as the pH, turbidity, the concentration of n-hexane extract, the concentration of metal elements, and the concentration of phenanthrene equivalence (PAHphe). In addition, the SO_2 concentration at the scrubber outlet was measured to investigate the ability to remove SO_2.

Figure 18 shows the relationship between the time elapsed and the turbidity of the scrubber water. The turbidity of the scrubber water after 180 min of circulation was greatly improved by the new scrubber (ESP-ON). As shown in Fig. 19, the concentration of metal elements was reduced by the new scrubber (ESP-ON). The reduction of the metal element concentration almost corresponds to the PM collection efficiency of ESP of 60%. In this way, the reduction of pollution of the wastewater from the scrubber is considered to be due to the synergetic effect of the ESP and the new scrubber. Figure 20 shows a change of the SO2 concentration at the scrubber outlet. For a pH of about 6 at the beginning of the experiment, the SO_2 concentration decreases to about 230 ppm (SO_2 reduction rate, about 50%). When the pH decreases with the circulation of the scrubber water, the solubility of SO_2 decreases, resulting in the increased SO_2 concentration. The ability of the new scrubber for removing SO_2 was equivalent to that of the conventional scrubber.

5. Conclusions

In a series of studies, the following findings on the cleaning of exhaust gas from marine diesel engines were obtained.

1) The PM emitted from marine diesel engines can be efficiently reduced by the ESP-C system. Because especially BC can be efficiently collected by the ESP without being affected by the temperature of the exhaust gas, the ESP is suitable for reducing BC emissions.
2) A compact, maintenance-free ESP-C system was realized by making the various improvements explained in this paper.
3) The new EGCS that combines the ESP-C and the new scrubber can greatly suppress the pollution of the wastewater from the scrubber. Therefore, the new EGCS is expected to realize the open-loop system using seawater.
4) Thus, the newly developed EGCS has high potential for enabling to satisfy the regulations on exhaust gas, which are projected to become stricter in the future.

When applying this technology to actual ships or power plants, it is necessary to deal with technical problems peculiar to each application. We will collaborate with those who are in related fields to address such problems. We will also disseminate Japan's technology to the world and contribute to the environmental conservation and the development of the marine industry.

Acknowledgment

These research and development were carried out in collaboration with Tokyo University of Marine Science and Technology (Tsukamoto Laboratory, Department of Marine Electronics and Mechanical Engineering), National Fisheries University (Maeda Laboratory, Department of Ocean Mechanical Engineering), National Maritime Research Institute (Marine Environment & Engine System Department), and JX Nippon Oil & Energy Corporation (Central Technical Research Laboratory). Some of the development funds were supported by the Technological Development Fund from the Ship & Ocean Foundation (currently, Ocean Policy Research Institute, Sasakawa Peace Foundation). We are grateful to those who are involved in our research and development for their instruction, cooperation, and support.

References

[1] Ocean Policy Research Foundation, "Survey research project report on black smoke from ships in Arctic sea route" (in Japanese), July, 2014.

[2] Xu, Z., Furugen, M., Makino, T., and Tsukamoto, T., Journal of JIME (in Japanese), 44-2(2009), 304-309.

[3] Sasaki, H., Tsukamoto, T., Furugen, M., and Makino, T., Trans. of JSME (in Japanese), 77-775, B (2010), 459-465.

[4] Furugen, M., Makino, T., Sasaki, T., Tsukamoto, T., CIMAC Congress 2013, Shanghai, Paper No. 137.

[5] Sasaki, H., Tsukamoto, T., Furugen, M., and Makino, T., Journal of JIME (in Japanese), 51-3 (2016-5), 294-299.

[6] Sasaki, H., T. Mochizuki, T. Tatsuro, M. Furugen, T. Makino, M. Tsuda, K. Maeda, ISME 2011, Kobe, Proc. No. C4-4.

[7] G. Hellen, J. Ristimaeki, CIMAC Congress 2007, Vienna, Paper No. 56.

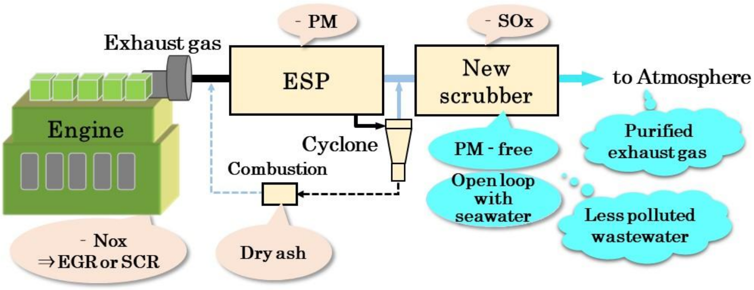


Figure 1. Schematic of developed EGCS

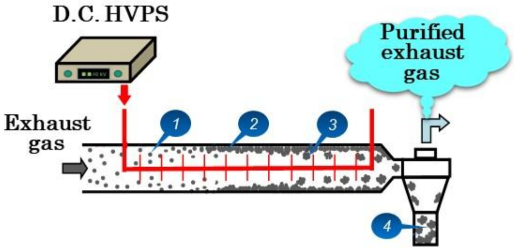


Figure 2. PM collection mechanism of ESP-C

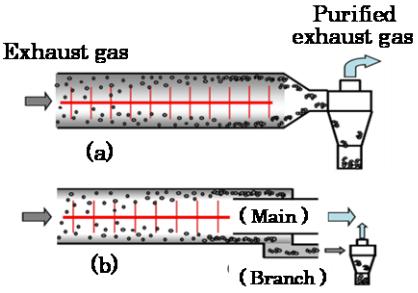


Figure 3. ESP-C with branch route at ESP outlet;
(a) Initial equipment, (b) Improved equipment

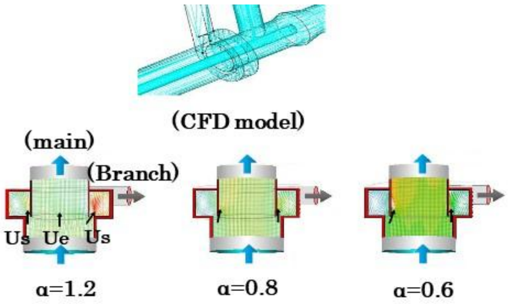


Figure 4. CFD analysis of branch route (α = Us/Ue)

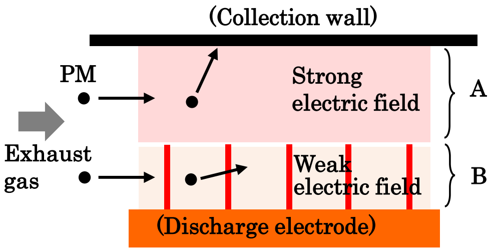


Figure 5. Electric field distribution and PM behavior inside ESP

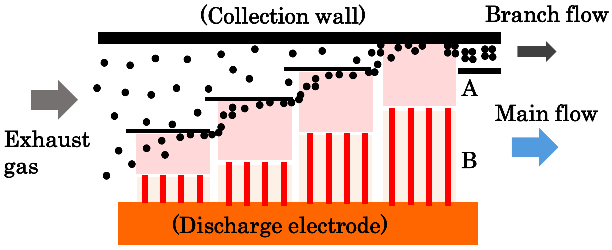
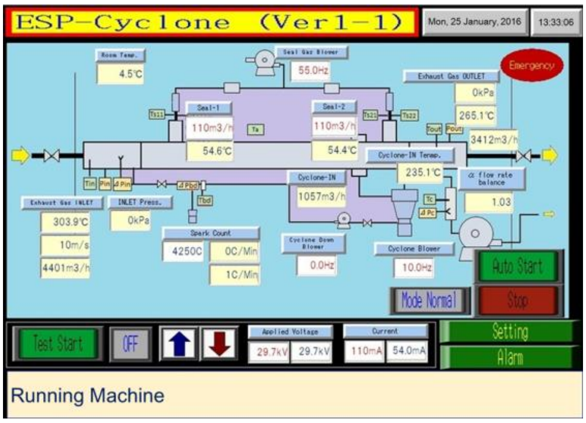


Figure 6. Multistage collection-wall structure of ESP



ESP−Cyclone (Ver1−1)

Mon, 25 January, 2016 13:33:06

Room Temp. 4.5℃

Seal Gas Blower 55.0Hz

Exhaust Gas OUTLET 0kPa 265.1℃ 3412m3/h

Seal-1 110m3/h 54.6℃

Seal-2 110m3/h 54.4℃

Cyclone-IN Temp. 235.1℃

Cyclone-IN 1057m3/h

α flow rate balance 1.03

Exhaust Gas INLET 303.9℃ 10m/s 4401m3/h

INLET Press. 0kPa

Spark Count 4250C 0C/Min 1C/Min

Cyclone Down Blower 0.0Hz

Cyclone Blower 10.0Hz

Mode Normal

Applied Voltage 29.7kV 29.7kV

Current 110mA 54.0mA

Running Machine

Figure 7. Control panel of ESP-C system

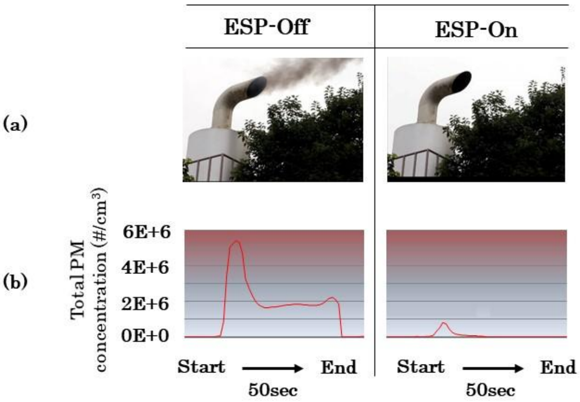


Figure 8. Effect of ESP on suppressing smoke at engine startup; (a) Black smoke, (b) PM number concentration measured by ELPI

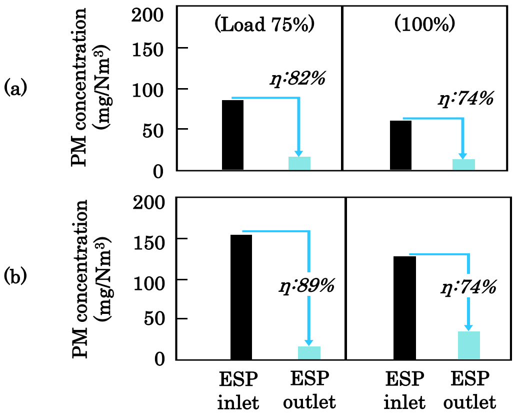


Figure 9. Effect of ESP on reducing PM concentration under steady loading (low-speed two-stroke engine, ISO8178-1); (a) LFO, (b) HFO

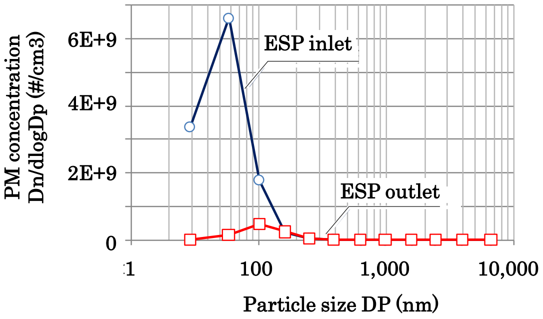


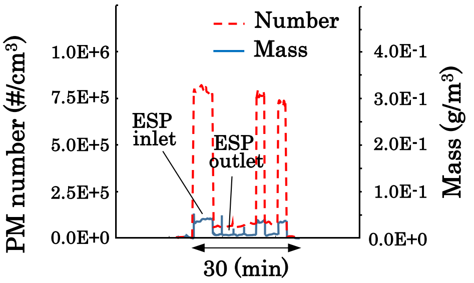
Figure 10. Effect of ESP on reducing PM number concentration (low-speed two-stroke engine, load 75%, LHO, ELPI)

(a) (b)

Figure 11. Test of ESP-C on actual ship;
(a) Training ship of National Fisheries University, KOYO MARU (2703 t),
(b) ESP-C placed vertically in engine room

Figure 12. Prototype ESP-C (ESP: 400 mm O.D., 4400 mm Length)

(a) LFO



(b) HFO

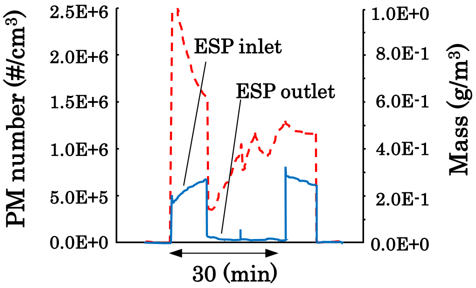


Figure 13. Effect of ESP on reducing PM number concentration under steady loading (mid-speed four-stroke engine, load 75%, gas velocity 10 m/s in ESP, ELPI+)

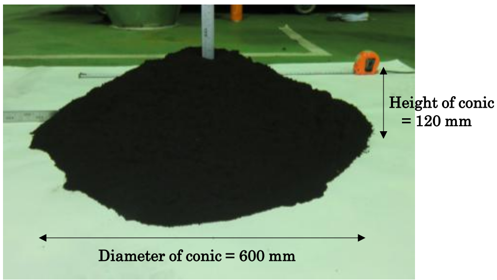


Figure 14. Amount of PM accumulated in the dust hopper of the Cyclone (data corresponding to Fig. 13 (b): mass of PM 1.8 kg, effective operation time of ESP-C about 10 hours)

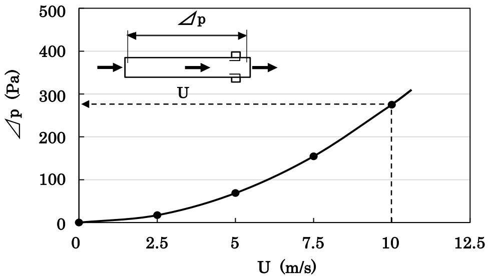


Figure 15. Pressure loss of ESP (air, 25 ℃, 1 bar)

(a) (b)

Figure 16. Example of application of ESP-C system (1400 kW diesel engine);
(a) ESP-C unit (2000 mm width, 2500 mm height, 3000 mm length),
(b) ESP-C system connected to small power generator

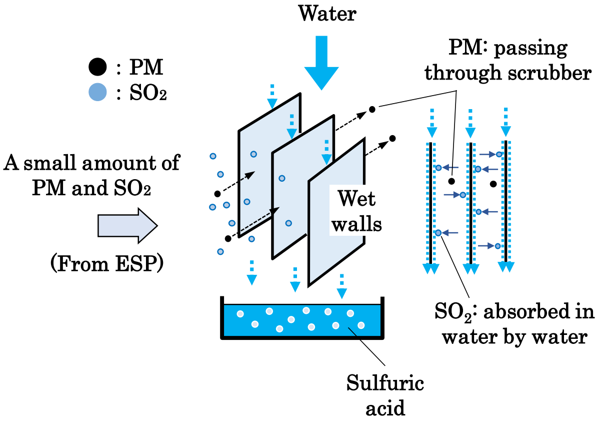
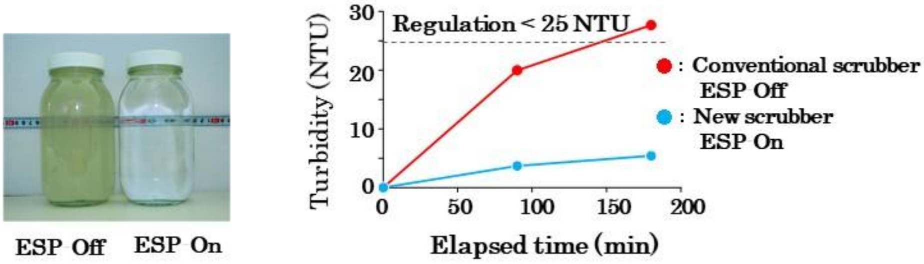


Figure 17. Technical concept of new SO_x scrubber



(a) (b)

Figure 18. Turbidity of scrubber water (HFO, exhaust gas 500 m³/h, tap water 40 L/min, circulation usage);

(a) Appearance of scrubber water
(b) Change in turbidity of scrubber water with elapsed time

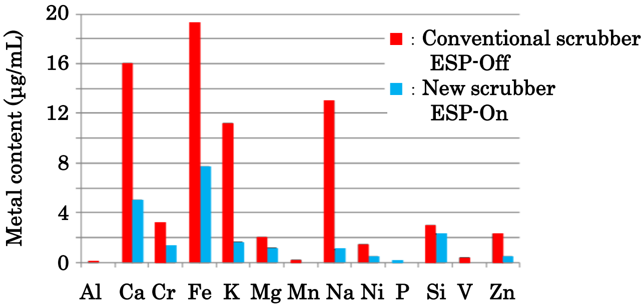


Figure 19. Concentration of metal elements in scrubber water (HFO, exhaust gas 500 m³/h, tap water 40 L/min, 180 min circulation usage)

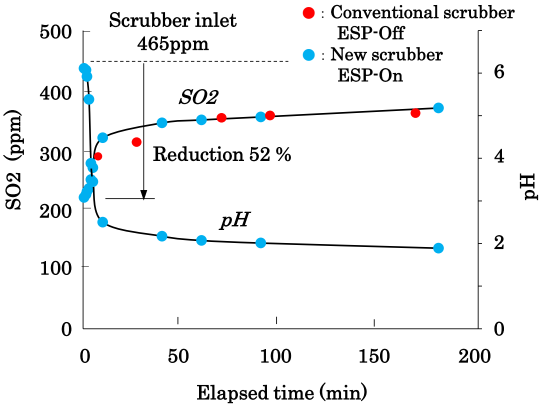


Fig20. Change of SO_2 concentration and pH at scrubber outlet (HFO, exhaust gas 500 m³/h, tap water 40 L/min, 180 min circulation usage)