Ceramic Filter for Ship Diesel Engines
— PM (black carbon) removal technology using the CERALLEC® system (Ver. 2*)

○ Masami Nonokawa,** Takao Katsuki,** Shunsuke Noshiro**

1. Introduction

The primary hazardous substances contained in exhaust gas from ship diesel engines are nitrogen oxide (NOx), sulfur oxide (SOx), and particulate matter (PM). Emissions of these substances have been regulated by the International Maritime Organization (IMO). (Most PM emitted by ships is derived from SOx. Regulations that limit the sulfur content [concentration] in fuel oil are regarded as PM regulations.) These regulations will be further tightened in the future.

PM has been reported to cause respiratory and cardiovascular diseases, among others.[1)] Recently, health damage caused by PM2.5 has been reported in China. The adverse impact of PM on the human body cannot be overlooked.

PM (black carbon) also has an adverse economic impact in that it contaminates cargo transported by ships and causes loss of product value.

Our CERALLEC® system is equipped with a built-in ceramic filter and is designed to remove PM (black carbon). The system has a track record in its application to the exhaust line of ship auxiliary engines (generators) to prevent damage to cargo caused by PM (black carbon). It has also been used in many on-shore diesel generators to remove PM (black carbon) in exhaust gas. The system has been demonstrated to be highly effective in reducing PM (black carbon) from funnels based on comparisons before and after installation (see Fig. 1).

Before installation

After installation

Fig. 1 PM emissions before and after installation of the CERALLEC® system

This paper introduces the mechanism of our CERALLEC® system for removing PM (black carbon). It is worth noting that a development project is underway to remove PM (black carbon) in exhaust gas from main engines during navigation. The development status of this project is also presented here.

* Paper accepted on February 24, 2016
** NGK Insulators, Ltd. (2-56 Suda-cho, Mizuho, Nagoya 467-8530, Japan)

2. Overview of the CERALLEC® system

2.1 Structure of the system

The basic structure of our CERALLEC® system is shown in Fig. 2. This system consists of a ceramic filter that collects and separates PM (black carbon) in exhaust gas, the main unit case which houses a filter, a backwashing valve which is used for washing out PM (black carbon) collected by the filter using compressed air, and a dust collection box which stores PM (black carbon) washed out by the backwashing air.

The ceramic filter has a honeycomb-shape (see Fig. 3), which enables compact system design, because the filtration area per unit volume is large. The size and shape of the main unit case and dust collection box can be determined based on the specifications of the target diesel engine and the status of the installation location for designing and fabricating the optimal system.

The features of our CERALLEC® system are indicated below.

(1) Use of a ceramic filter prevents fires from starting.
(Heat-resistant temperature: 900°C)

(2) Use of a honeycomb-shaped filter helps to achieve a compact system design.
(Required space is only one fourth to half that of a bag filter.)

(3) The filter has a long service life because of ceramics products.

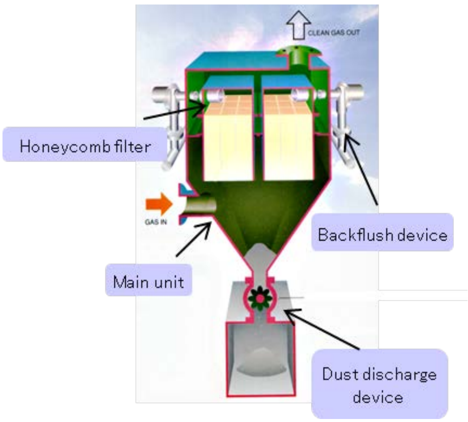


Fig. 2 Basic structure of the CERALLEC® system

Fig. 3 Ceramic filter

2.2 Mechanism of PM (black carbon) removal

Figure 4 shows the PM (black carbon) removal mechanism of the CERALLEC® system. The ceramic filter has a two-layer structure consisting of the support layer (which has numerous relatively large pores) and the coating layer (which has small pores) (see Fig. 5). PM (black carbon) in the exhaust gas is collected on the surface of the coating layer. When PM (black carbon) is collected over a long period of time, it forms a thick accumulation on the filter surface and increases pressure loss when the gas is fed. The PM (black carbon) accumulated on the filter surface is washed out (backwashing) periodically and automatically using compressed air. This function enables continuous removal of PM (black carbon) in exhaust gas during operation of a diesel engine. Changes in the filter's differential pressure during the general backwashing operation are shown in Fig. 6. The backwashing interval is determined based on the rising speed of the filter's differential pressure. Backwashing is performed periodically to restore the differential pressure. If the PM concentration of the exhaust gas is high, the backwashing interval is shortened to keep the filter's differential pressure constant and prevent the adverse impact attributed to the increased back pressure on the engine.

3. Overview of the CERALLEC® system for auxiliary engines

3.1 System diagram

Since 2005, we have delivered 16 PM removal systems using the CERALLEC® system for auxiliary engines in pure car carriers (PCCs). The systems were installed primarily to prevent the fouling of cars due to PM (black carbon) emitted from auxiliary engines when loading and unloading cars at ports. A diagram of the CERALLEC® system in an actual use application is shown in Fig. 7.

The PM removal system consists of a CERALLEC® system (which removes PM [black carbon]) and an exhaust fan. The exhaust gas fan is installed to prevent pressure loss attributed to installation of the CERALLEC® system from affecting the engine. Installation may not be required depending on the permissible back pressure of the engine. A bypass pipe is installed by taking into account the scenario in which the dust collector is not used during navigation. The compressed air can be branched from the compressed air line installed in the ships because consumption of the compressed air is small.

3.2 Operation status

Table 1 shows the conditions of use for the CERALLEC® system installed in the auxiliary engine of a ship. The temperature of the exhaust gas is relatively high (about 350°C) since the gas comes from the auxiliary engine.

PM (black carbon) removal performance from the actual example (Table 1) is shown in Table 2. The exhaust gas from the auxiliary engine passes through the CERALLEC® system, which reduces the concentration of PM (black carbon) from 30 mg/Nm^3 to 1 mg/Nm^3 and removes 97% of PM (black carbon). These figures testify to the high performance of the CERALLEC® system. It should be noted that an accurate measurement method for PM (black carbon) concentration from diesel engines on ships fueled by heavy fuel oil C (MFO) has not been established.[2)] We defined the dust concentration measured based on JIS Z 8808-1995 (Methods of measuring dust concentration in flue gas) as the PM (black carbon) concentration.

The ship that was equipped with the CERALLEC® system (Table 1) is still in service, and the system is operating properly. Systems installed in other ships are also running smoothly. The CERALLEC® system has been demonstrated to be fully applicable to the removal of PM in exhaust gas from auxiliary engines.

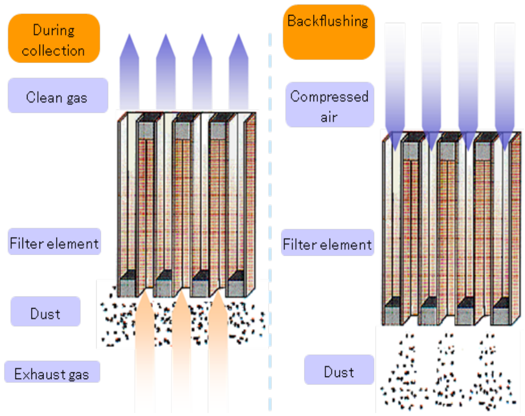


Fig. 4 PM removal mechanism of the CERALLEC® system

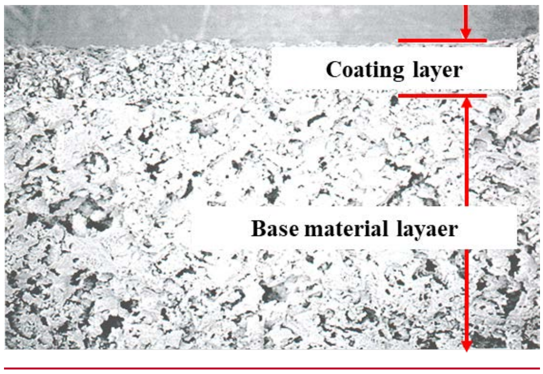


Fig. 5 Cross section of the ceramic filter (microscopic image)

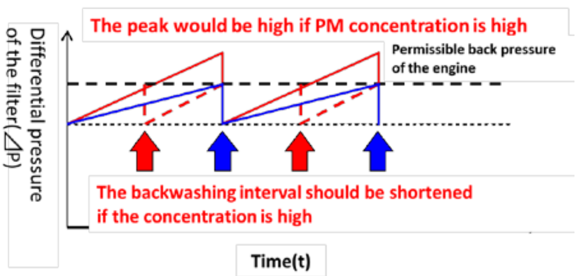


Fig. 6 Changes in the filter's differential pressure during the backwashing operation

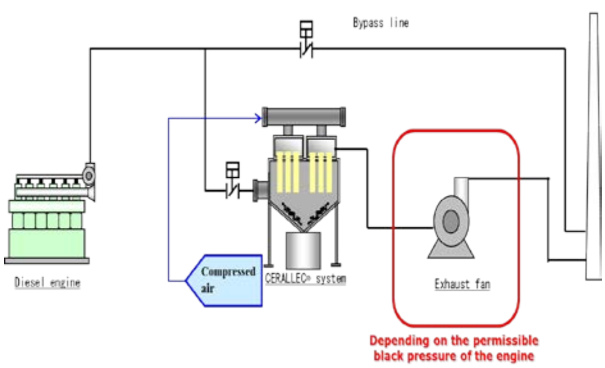


Fig. 7 Diagram of the CERALLEC® system for auxiliary engines

4. Development of the CERALLEC® system for main engines

4.1 Overview of development

Main engines emit a large amount of exhaust gas compared to auxiliary engines, and accordingly, they also emit a large amount of PM (black carbon). To reduce PM emissions from the entire shipping industry, it is important to remove PM (black carbon) in exhaust gas from main engines. In line with the commercialization of the CERALLEC® system for auxiliary engines, we commenced with development of a system for main engines in FY2012. We undertook a two-year development project from the "R&D program on soot filters for main engines" under the joint auspices of Daiichi Chuo Kisen Kaisha, the National Maritime Research Institute (NMRI), and Nippon Kaiji Kyokai (ClassNK). In FY2012, we used a four-cycle diesel engine owned by NMRI to clarify the conditions needed for applying the CERALLEC® system. In FY2013, we installed a small test system in an actual ship owned by Daiichi Chuo Kisen Kaisha to evaluate the performance on actual exhaust gas.

4.2 System diagram

A diagram of the CERALLEC® system for main engines is shown in Fig. 8. This system is different from that used with auxiliary engines in that a heater is installed to remove the clogging caused by the coagulating components in the exhaust gas because the exhaust gas temperature is low. An experimental system based on this diagram was used to verify the effectiveness of the CERALLEC® system in removing PM (black carbon) in exhaust gas from main engines.

4.3 Experimental method and conditions

Table 3 shows the specifications of the main engine on the actual ship that was used in the experiment. The engine was fueled by heavy fuel oil C, and the exhaust gas temperature was between 260 and 350°C.

The following points were verified and evaluated in the experiment.

(1) PM removal performance of the CERALLEC® system

(2) Establishment of a stable operation method for prolonged operation

4.4 Results of the experiment

(1) PM removal performance of the CERALLEC® system

The PM (black carbon) removal performance of the CERALLEC® system is shown in Table 4. The measurement was conducted based on two methods in accordance with JIS Z 8808.

The results revealed a significant difference in the dust removal rate.

Because the oil and sulfur content is high in exhaust gas from the main engine on the ship fueled by heavy fuel oil C, these components are considered to have affected the measurement results.

Table 1 CERALLEC® system for auxiliary engines: usage conditions

Engine output	Approx. 820–1,280 kW
Exhaust gas temperature	Around 350°C
Pressure loss attributed to the CERALLEC® system	Approx. 2.5 kPa

Table 2 CERALLEC® system for auxiliary engines: exhaust gas measurement results

	Unit	System inlet	System outlet
Q'ty of exhaust gas	Nm^3/h	3590	–
Exhaust gas temp.	℃	352	–
Dust conc.	mg/Nm^3	30	1
SOx conc.	volppm	730	–
NOx conc.	volppm	730	–

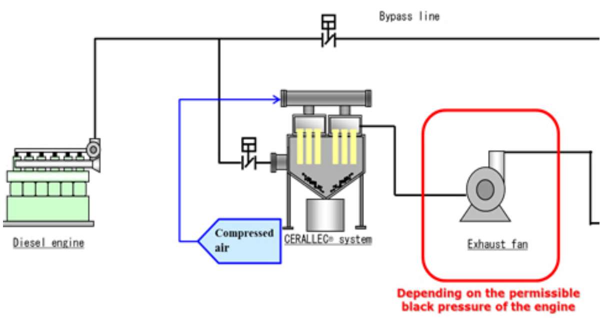


Fig. 8 CERALLEC® system for main engines: system diagram

Table 3 CERALLEC® system for main engines: specifications of the main engine on the actual ship used in the experiment

Manufacturer	Mitsubishi Heavy Industries, Ltd.
Type	Vertical two-cycle
Rated output	16,227 PS
Rated speed	127 rpm
Fuel used	Heavy fuel oil C (S content: 2.9%)

Table 4 PM removal performance of the system for main engines in the development experiment

Item	Unit	Type1 (circular)	Type2 (cylindrical)
Dust conc.at the inlet	mg/Nm^3	42	110
Dust conc.at the outlet	mg/Nm^3	2	54
Total dust removal rate	%	95	50.9
Conc. Of coagulating components at the inlet	mg/Nm^3	-	35
Conc. Of coagulating components at the outlet	mg/Nm^3	-	17
Coagulating components removal rate	%	-	51.4

Measurement method: JIS Z8808-1995

(2) Establishment of a stable operation method for prolonged operation

To demonstrate long-term stability in treating exhaust gas from the main engine, an experiment was conducted in which gas was fed for 1,100 hours based on optimal operation conditions established in an on-shore experiment.

Figure 9 shows the changes in the differential pressure of the ceramic filter during operation. Periodic backwashing and heating regeneration helped to achieve operation with a stable differential pressure.

After completion of the test, heating regeneration was terminated to determine if differential pressure could be restored by backwashing only. Differential pressure was seen to increase sharply, and stable operation could not be achieved.

5. Development of an exhaust gas treatment system using the CERALLEC® system

5.1 Overview of development

The “R&D program on soot filters for main engines” from FY2012 to FY2013 verified stable operation and high PM (black carbon) removal performance of the CERALLEC® system. Against this backdrop, a project was launched in FY2015 to develop an exhaust gas treatment system by combining the CERALLEC® system, a selective catalytic reduction denitration system (SCR system), and a scrubber. The system was installed on the downstream side of a four-cycle diesel engine owned by NMRI to verify the load reduction effect on the SCR system and scrubber (achieved by the filtering effect). Efforts have also been made to develop a catalyst deterioration evaluation system (using our own product, a zirconia-based NOx sensor) and a scrubber washwater treatment technology (also using own our product, a ceramic filtration membrane).

5.2 System diagram

A diagram of the exhaust gas treatment system is shown in Fig. 10. We conducted an experiment to verify the effect of downsizing the SCR system, extending the service life of the catalyst, and reducing impurities contained in the scrubber circulation water by taking advantage of the high PM (black carbon) removal effect of the CERALLEC® system.

5.3 Results of the experiment

(1) Effect on clogging of the SCR system

A high-density product with 85 cells (in contrast to the 45 cells of an ordinary product) was used in the experiment by taking into account the high PM (black carbon) removal effect of the CERALLEC® system.

As shown in Fig. 11, there was almost no increase in the differential pressure of the SCR system. No clogging attributed to PM (black carbon) was found on the surface of the unloaded catalyst (see Fig. 12).

(2) Effect on scrubber circulation water

We also investigated effects on the impurities in the scrubber circulation water by taking into account the high PM (black carbon) removal effect of the CERALLEC® system. As shown in Fig. 13, the turbidity decreased significantly, far below the 25 NTU specified in the IMO Guidelines. However, the concentration of polycyclic aromatic hydrocarbons (PAHs) increased when the CERALLEC® system was put in place. This is attributable to the characteristics of PM (black carbon) in the circulation water of adsorbing PAHs.

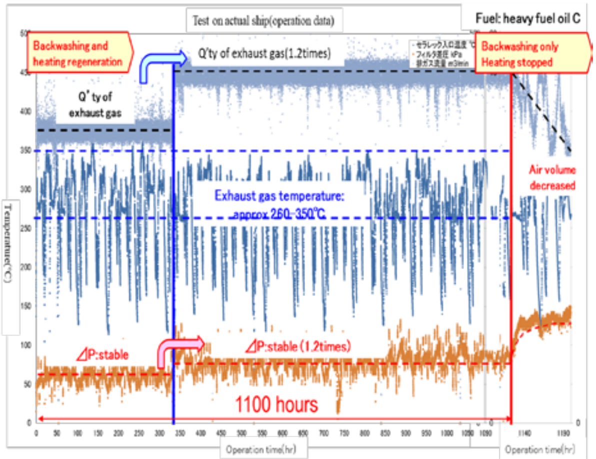


Fig. 9 Changes in differential pressure during prolonged operation

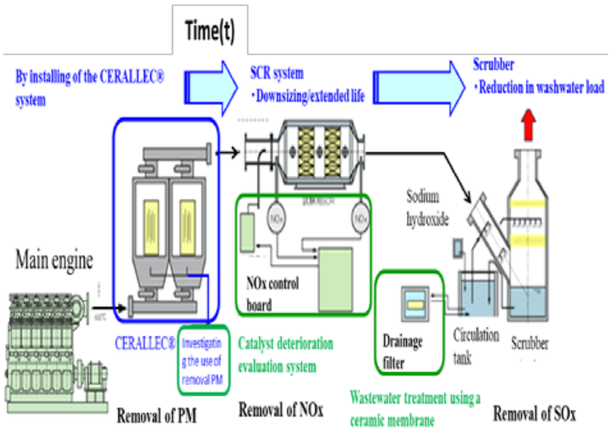


Fig. 10 Diagram of the exhaust gas treatment system

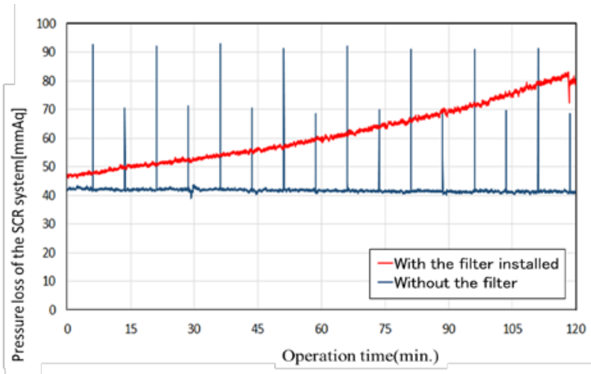
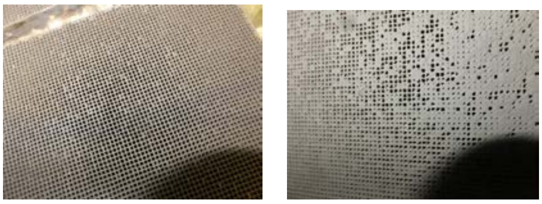


Fig. 11 Changes in pressure loss of the SCR system



With the CERALLEC® system Without the CERALLEC® system

Fig. 12 Photos of the catalyst surface after operation

Fig. 13 Changes in the turbidity of the scrubber circulation water

5.4 Future plans

Engine manufacturers have been developing selective catalytic reduction denitration systems (SCR systems) to comply with the IMO NOx Tier 3 regulations from 2016. An on-shore test is underway at NMRI. The test has revealed the possibility of downsizing the SCR system, extending the service life of the catalyst, and simplifying scrubber peripheral equipment by installing our CERALLEC® system on the upstream side of the SCR system.

A similar exhaust gas treatment system will be installed in the exhaust gas line of the main engine on an actual ship to ascertain the performance on exhaust gas and evaluate long-term stability.

At the same time, we will monitor developments in the method of measuring PM (black carbon) in exhaust gas from the main engines of ships. The PM (black carbon) removal performance of the CERALLEC® system will be reevaluated based on the specified measurement method.

6. Conclusion

Our CERALLEC® system represents an effective technology to reduce PM (black carbon) from diesel engines on ships. Notably, we have delivered 16 systems for auxiliary engines. These systems have been demonstrated to be fully operative.

We will evaluate the long-term stability on actual ships using exhaust gas from main engines and will design an exhaust gas treatment system on a trial basis to be installed in actual ships.

R&D conducted from FY2012 to FY2016 was supported by the Joint R&D for Industry Program under the auspices of ClassNK, with cooperation from Daiichi Chuo Kisen Kaisha and NMRI. We would like to express our deep appreciation for guidance and cooperation from the parties concerned.

References

1. Ocean Policy Research Foundation, “Investigation and Research Report on the Environmental Impact of Particulate Matter (PM) Generated by Ships,” pp.7–16.
2. Maeda, “Reducing PM Generated by Ships Using a Filter Type DPF,” Journal of the Japan Institution of Marine Engineering, 46-6 (2011-11), pp.38–45.
3. “Ceramic Filter for Diesel Engines on Ships — PM Removal Technology Using the CERALLEC® System,” Journal of the Japan Institution of Marine Engineering, 48-4 (2013-7), pp.82–86.