Application of the DOC-DPF Integrated Exhaust Particle Treatment Device for New Marine Diesel Engines

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Abstract. Based on the analysis of the diesel engine post-processing technology line, a DOC-DPF tail gas treatment device is proposed. The exhaust system of marine diesel engine is reformed, the particulate matter purification test is carried out in the exhaust system installation DOC-DPF tail gas treatment device, and the exhaust particulate matter of the marine diesel engine is detected by the automatic smoke tester and other instruments. The results show that the new ship exhaust particulate disposal device can effectively reduce particulate emissions from ship exhaust and is suitable for ships.

1. Preface

Diesel engines are characterized by its excellent power, high efficiency, high compatibility, wide power band, and low fuel cost, which explain its wide applied in marine transportation. Diesel exhaust has lower contents of hydrocarbons (HC) and carbon monoxide (CO), generally around one tenth of that in gasoline exhaust. Although the emission of nitrogen oxides (NOx) in the diesel exhaust is nearly in the same order of magnitude as that of gasoline exhaust, its PM emission is far higher than that of gasoline exhaust, roughly 30 to 100 times of the gasoline engine [1]. The Ministry of Environmental Protection and the General Administration of Quality Supervision, Inspection and Quarantine jointly issued the GB15097-2016 national standards: Limits and Measurement Methods for Exhaust Pollutants from Marine Engines (CHINA I & II) on Aug. 22, 2016, wherein the emission limits for CO, HC, NOX, and PM are defined. As the first national standard stipulating the control of marine air pollutant emission issued in China, the standard fills the void for the standard for marine air pollutant emission. Following this, the implementation of the marine emission limit standards, the R&D and application of marine diesel exhaust purifying technology will be an important trend for future research.

On the basis of analyzing the DOC-DPF technical route, this paper modeled a DOC-DPF exhaust treatment device by installing a DOC-DPF exhaust treatment device on a ship to purify the exhaust of marine diesel engines. Meanwhile, exhaust emission tests were conducted before and after the device installation on the ship. Also, an automatic smoke tester was utilized to test the PMs of the marine
diesel exhaust. Finally, the treatment of PMs of the marine diesel exhaust using the test plant was examined.

2. DOC-DPF Technical Principle

PMs in the exhaust are filtered by DPF using its physical properties as a filter material, boasting an efficiency of up to 90%[2]. Nevertheless, DPF can only collect PMs rather than directly removing them. In that case, an additional regeneration system is required for PM treatment. DOC can effectively purify soluble organic components in the exhaust with the principle of oxidation catalysis. However, DOC is sensitive to sulfur in the fuel in that a high sulfur content might cause poisoning deterioration of the catalyst. Therefore, DOC is typically suitable for low sulfur diesel. POC is primarily applied to purify the soot in the PM, and it has the advantages of relatively low cost, low mass, small volume, and high simplicity for integration with the exhaust aftertreatment system. Yet, POC as a semi-permeable filter, is less efficient in terms of particle capturing relative to DPF, in addition to having a poor exhaust purification performance.

At present, the DOC-POC integration is well-recognized as a proven technique for lowering the quantity of PMs using its continuous regeneration method, with purification efficiency ranging between 30% to 80% [3]. For this reason, it is primarily applied in small diesel engines, such as those used in automobiles.

On the basis of DOC-POC integration, a DOC-DPF integrated exhaust treatment device was proposed against the complicated emission environment featuring high temperature, high mass flow, and high sulfur content of the marine diesel exhaust. The integrated exhaust treatment device is comprised of a DOC filter element and a DPF filter element. To be specific, the DOC and the DPF are installed adjacent to each other, at the front end and at the rear end of the exhaust treatment device[4]. The pressure testing sensors were set in point ① of the front end of the DOC and point ② of the rear end of the DPF. Exhaust back pressure values in the front and rear of the testing device were also set. When the exhaust back pressure value reaches the preset value, the bypass pipe will be opened, so that exhausts can be emitted to the atmosphere from the pipe, preventing the damage to the diesel engine from excessive exhaust back pressure[5]. The DOC-DPF exhaust treatment plant is presented in Fig. 1.

In order to apply the DOC-DPF integrated exhaust treatment device to larger or massive marine diesel engines, the device can be optimized as follows:

1) Rare earth elements such as cerium (Ce) can be added on the porous walls of the DOC filter element apart from the coating of precious metal catalysts mainly consisting of γ-Al2O3, Pd and Pt. The poisoning deterioration of the catalyst can be mitigated thanks to the addition of rare earth elements, allowing the DOC filter element to work continuously, even in the marine exhaust environment that contains high sulfur content.

2) Optimizing the structure of the DOC filter element in the DOC-DPF integrated exhaust treatment device. Appropriately decreasing the pore density can avoid clogging, while increasing the length of the filter element can improve the reaction effect, allowing the DOC filter element to better fit the marine exhaust treatment environment.

3) Appropriately reducing the wall thickness of the DPF and lowering the front-rear pressure drop of DPF can maintain the pressure drop of the plant within the range of the predetermined safety index under the high-concentration exhaust, ensuring the normal operation of the marine diesel. By finding a balance between exhaust back pressure and the collection efficiency, the improved DPF can be matched with the diesel engine. The DPF pore density is enlarged to ensure the DPF collection efficiency, allowing the plant to reach the expected filtering effect.

4) Increasing the length of the DPF filter element, slowing down the flow velocity of the exhaust, and increasing the retention time of the exhaust in the pore passage can improve the filtering effect. Moreover, the filtering area of DPF is also extended with the increased length of the filter element, allowing the plant to contain more PMs.
3. Design of Test System

3.1. Design of Test System
In order to investigate the treatment effects of DOC-DPF tail gas treatment unit, a test is carried out in a civil waterway cleaning vessel, and the test results can truly reflect the performance of the device under complex environment. During the test, after the marine diesel engine exhaust system is transformed and DOC-DPF tail gas treatment unit is mounted on the marine diesel engine exhaust turbine, an automatic smoke tester and other instruments are used to analyze exhaust and test the change of exhaust PMs before and after the installation of DOC-DPF. The schematic diagram of the test system is shown in Figure 2.

3.2. Testing Scheme
This test is carried out in a real vessel to simulate real operation conditions of the vessel. A soot trapping test was applied to test the exhaust back pressure curve of DPF and DOC-DPF, and soot was trapped at 2100r/min and 75% load; then the tester and other instruments were mounted at the rear of DOC-DPF for exhaust analysis. The test point, test item and test frequency are shown in Table 1.

| Test Category          | Test Point                        | Test Item | Test Frequency                                      |
|------------------------|-----------------------------------|-----------|-----------------------------------------------------|
| Before exhaust         | Exhaust emission from marine      | CO, PMs,  | 3 samples were taken in equal intervals under various working conditions (instantaneous sampling) |
| treatment              | diesel engine                     | NMHC      |                                                     |
| After exhaust          | Emission from DOC-DPF             | CO, PMs,  |                                                     |
| treatment              |                                   | NMHC      |                                                     |
4. Test Results and Analysis

The main purpose of this test is to verify the efficiency in reducing PMs, CO and HC emissions. Through data comparison and analysis, it can be found that:

1) Seen from Figure 3 “Back pressure Curve”, the curves of DPF and DOC-DPF initially tended to be consistent, because the exhaust temperature did not reach the working temperature of DOC in the beginning and the PMs were accumulated in DPF, so that the back pressure sharps rose. Afterwards, the exhaust temperature reached the working temperature of DOC, and NO in exhaust was oxidized into NO₂ in DOC, so that the PMs were regenerated in DPF after oxidization and less PMs were accumulated in DPF; back pressure in DPF rose with the accumulation of PMs in the tendency of a parabola on the whole. DPF stopped capture when the back pressure reached 25Kpa. At this time, the full-load performance of the DPF diesel engine declined, and there was a need to regenerate PMs in DPF; the back pressure of DOC-DPF was stable at around 6Kpa. Within a reasonable range, the diesel engine had little performance impact and could continuously work;

2) Seen from Figures 4 and 5 (emission concentration and rate of PMs), the content of PMs in exhaust obviously dropped compared with that before exhaust treatment. The emission reduction efficiency reached 92%, and treatment effect reached the expected target;
3) Seen from Figures 6 and 7, with the increase of load, the content and concentration of CO and HC constantly dropped. After DOC-DPF was mounted, the CO and HC concentrations basically maintained a low level. This was because the diesel in the diesel engine was fully burned with the increase of load, and CO and HC concentrations constantly dropped. However, the diesel engine was under oxygen-enriched combustion, and the exhaust contained much oxygen. Under the action of DOC, CO and HC were fully oxidized.

4) Seen from Figures 8 and 9, by comparing two CO measurement results taken before and after exhaust treatment, the emission reduction effects were obvious, and the emission reduction efficiency reached about 90%. The HC emission reduction effects were significant compared with those before exhaust treatment, and the emission reduction efficiency reached 73%.
Figure 8. CO Comparison before and after Treatment

Figure 9. NMHC Comparison before and after Treatment

In the DOC-DPF exhaust treatment unit, CO and HC emission were reduced in exhaust through the oxidative catalytic reaction with catalyst in DOC. In the test process, optimized DOC was not blocked during the back pressure test, and better adapted to the vessel environment. According to CO and HC measurement data, extremely high conversion efficiency could be achieved, and the emission was significantly reduced;

DPF could intercept PMs on the filter for filtration, and the PMs purification efficiency ranged from 70% to 90%. During the test, the emission of PMs in the exhaust was significantly reduced after the mounting of this device, up to 92%. The actual treatment effects achieved the research expectations. During the back pressure test, the back pressure in DPF changed within 10Kpa, which did not lead to performance deterioration of the diesel engine. Hence, it could be continuously used in a vessel.

5. Conclusion

Unlike the previous tests of the exhaust treatment unit on the diesel engine frame, this test was carried out in a vessel which was really sailing. According to sea conditions where the vessel was sailing, the loss of the marine diesel engine for daily use and oil quality under navigation cost control, complex vessel emission conditions were simulated. During this test, it was found that, when the optimized DOC-DPF was used to treat marine diesel engine exhaust, the emissions of HC, CO and PMs were significantly reduced, the same as the results of the test in the automobile. It was proved that DOC-DPF could properly work. During the back pressure test of vessel exhaust, DOC-DPF could maintain low back pressure, caused little impact on diesel engine performance, and was rarely maintained in daily use. It met daily needs for exhaust treatment of the marine diesel engine, and provided a reasonable solution for controlling vessel emission pollution.

From a practical point of view, by reforming DOC catalyst, reducing the DOC cell density and increasing the DPF cell density and the filter length, DOC-DPF exhaust treatment unit could basically adapt to a marine diesel engine of 200kW level with certain use values. From the viewpoint of
research significance, although the test results were universally applicable to exhaust treatment of medium and small-sized marine diesel engines, there was also a need to further study the exhaust treatment pattern for large or super-large marine diesel engines, continuously improve the device and expand the scope of application.

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