Research on two-channel diesel particulate filter electric heating regeneration technology assisted by marine diesel oxidation catalysis technology

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Abstract. A DPF two-channel tail gas treatment device was designed in this paper basing on the DPF regeneration technology of marine diesel engine, and the regeneration characteristics of the ordinary electric heating and DOC-assisted DPF electric heating are compared. Furthermore, the power and the regeneration rate of the regeneration unit. The results demonstrate that the DOC-assisted two-channel electric heating energy DPF could effectively reduce the regenerative power, increase the regeneration rate, so it is suitable for application in marine diesel engines.

1. Introduction

The diesel engine has a good economy and power performance, so it is widely used as the main power plant of boats and ships. At present, the problem of emission of particulate matter (PM) of the diesel engine is increasingly prominent. The potential harm to the atmosphere caused by harmful emissions from marine diesel engines has been paid more and more attention by some institutions and governments, which have formulated some strict emission measures to limit the air pollution caused by ships.

The main post-treatment technologies of diesel particulate matter include diesel oxidation catalysts (DOC) technology, diesel particulate filter (DPF) technology and particle oxidation catalyst (POC) technology[1]. Different particle post-processing technologies have different purifying effects on each component. The efficiency of DPF is up to 90% or more by filtration treatment of particulate matter in the exhaust by filter body. However, DPF itself can only collect particles and cannot remove them directly, so it is necessary to attach the regeneration system. DOC utilizes oxidation catalysis principle, and it can effectively purify soluble organic components in particulate matter, but it is especially sensitive to sulfur in fuel, which can easily lead to sulfur poisoning of catalysts. Therefore, DOC is generally suitable for diesel oil with low sulfur content. POC mainly purifies the soot in particulate matter, which has the advantages of low cost, light weight, small volume and easy to be integrated into the exhaust post-processing system. However, POC is a half-pass filter, and its capture ability is not enough, resulting in its slightly worse purification ability.
DPF is one of the most effective and promising post-processing technologies to control particulate emissions. However, DPF leads to increases of the exhaust back pressure of diesel engines due to its easy clogging and decreases of power, economy, and lack of mature regeneration methods for diesel engines, which limit the application of DPF[2].

According to the characteristics of the post-processing technology of diesel particulate matters, a DPF two-channel tail gas treatment device was designed in the present study, and the DOC auxiliary electric heater was used. The DOC-assisted DPF electric heating regeneration technology was investigated and its application in boats and ships was verified experimentally.

2. DOC-assisted DPF electric heating system

2.1. DOC auxiliary regeneration device

The working principle of the DOC-assisted regeneration unit is that NO and CO in the tail gas can be oxidized to NO$_2$ and CO$_2$ by catalysts. NO$_2$ has strong oxidation ability, and the particle matter in DPF can be oxidized and regenerated at a suitable temperature, thus reducing the energy consumption of electric heating. After the exhaust gas of diesel engine is discharged, it is pre-treated in the DOC auxiliary regeneration device, and then DOC oxidizes NO from tail gas to NO$_2$. NO$_2$ has strong oxidation ability, and it can react with the particle matter in DPF at a suitable temperature, thus reducing the energy consumption of electric heating[3].

The pre-treated tail gas enters the heating chamber from the tangential direction and rotates and flows along the wall of the heating chamber. After full heating with the spiral electric heater and achieving the regeneration temperature of the particle matter, it passes through DPF. The spiral electric heater is shown in figure 1. Side radial air intake method is employed, and exhaust gas is fully heated by a spiral electric heater to avoid uneven internal heating of DPF.

![Figure 1. The spiral electric heater.](image)

2.2. Two-Channel DOC-assisted DPF Regeneration Device

The schematic diagram of DPF two-channel tail gas treatment system for a marine diesel engine is shown in Figure 2.

On the basis of DOC-assisted DPF electric heating regeneration technology, the DPF two-channel tail gas treatment system model of the marine diesel engine is proposed to prevent the honeycomb ceramics used as catalyst carrier from being blocked by the dry carbon in tail gas of diesel engine. Two DPF devices are used in parallel. After DPF1 filtration, the clean tail gas enters the DOC-assisted DPF electric heating device and then the pre-treated tail gas enters DPF2. DPF2 is regenerated to avoid the effect of the dry carbon smoke on DOC.

3. Comparative experiment

In order to verify the feasibility of the tail gas filter on the ship, a comparative experiment was carried out. The regeneration with DOC-assisted DPF electric heater after DPF loading was conducted in the experimental group, and the regeneration time and power were measured in the experimental group. In
comparison, the control group was the loaded ordinary electric heater for DPF, and the regeneration time and power were measured.

Figure 2. The schematic diagram of DPF two-channel tail gas treatment system for a marine diesel engine.

The Test system of engine bench in the experimental group includes engine, brake dynamometer, test body, measurement system, filter regeneration system, exhaust system and so on. The diesel engine used in the experiment is an electrically controlled high pressure common-rail six-cylinder turbocharged engine, and the brake dynamometer adopted electric eddy current dynamometer with model GW250. The filter regeneration system includes a DOC auxiliary regeneration device and a spiral electric heater filter.

The test body consists of the DPF filter core and the heat insulation layer after the diesel engine tail gas loading. In order to make the performance of the diesel engine less volatile and exclude the influence of other factors, this test starts DPF regeneration when the back pressure is reduced to 13 KPa at both ends. The DPF filter core of the test body uses the cordierite as the filter material for the wall flow honeycomb ceramic filter. The insulation layer is mainly made of glass fiber material.

The measuring system consists of back pressure detection, temperature measurement, and regenerative power measurement. A pressure hole is arranged on the exhaust pipe in front of the filter body in the test section, which is connected to the U tube through the copper tube and conduit, which is used to measure the back pressure of the filter body and to monitor the pressure difference between the front and back of filter body in real time during regeneration process. The temperature detection consists of thermocouple and monitor. After a K type thermocouple is installed and the spiral regenerative device is installed, the regenerative power measurement is measured with a power meter due to the detection of exhaust gas temperature after regenerating device, and the power meter is connected to the circuit of the regenerative device for detecting the regenerative power of the device.

3.1. Test system in the experimental group

The exhaust pipe outside the exhaust gas turbine of a marine diesel engine is connected to the test pipe by means of a three-way valve. The test pipe is provided with a flowmeter and a thermocouple, which is employed to control the flux of the test exhaust gas and to measure the temperature of the test tail gas. The DPF filter in front of the DOC auxiliary regeneration device provides filtered tail gas for the test. The schematic diagram of the experiment group is shown in Figure 3.

The exhaust pipe of the diesel engine is connected to the outside world by switching the three-way valve. The diesel engine is started, and the throttle is adjusted to make the engine speed stably around 1800r/min and loading 80%. After the diesel engine is stabilized, the experiment is prepared to start.

The opening degree of the three-way valve is adjusted, and the test tail gas is put into the test device. The flux of test tail gas is controlled by Flowmeter and the temperature of the test tail gas is
measured and recorded. The electric heating disk and the spiral heater power supply are connected to start the regeneration test.

Figure 3. The schematic diagram of the experiment group.

The exhaust gas of the diesel engine is discharged from the exhaust pipe and filtered by DPF after the control of the flow through the three-way valve. The filtered tail gas is heated to 400°C by the electric heating plate. The heated tail gas enters the CuO/γ-Al₂O₃ filter and the DOC filter, and it then is heated to 450°C by a spiral heater. The back pressure difference before and after entering the filter body is detected in real time by back pressure detection. The temperature monitor can detect the temperature of the tail gas at the end of the spiral heater in real time. The power consumption of the electric heater is recorded by the dynamometer. When the back pressure of the filter is reduced from 13KPa before the experiment to 5KPa in the no-load state, the temperature, back pressure and power of the filter are calculated after finishing the experiment.

3.2. Test system in the control group
The exhaust pipe outside the exhaust gas turbine of a marine diesel engine is connected through a three-way valve. The simulating exhaust gas device is equipped with a Flowmeter flow controller and a heater, which is used to simulate the conditions of exhaust gas regeneration and to ensure the flow rate of the tail gas flowing into the electric heater and the temperature and other parameters are consistent with that of the test group. The control group test diagram is shown in Figure 4.

Figure 4. The control group test diagram.
The exhaust pipe of the diesel engine is connected to the outside world by switching the three-way valve. The diesel engine is started, and the throttle is adjusted to make the engine speed stably around 1800r/min and loading 80%. After the diesel engine is stabilized, the experiment is prepared to start.

The opening of the three-way valve is adjusted, and the test tail gas is passed into the simulation tail gas device. The treated tail gas is passed into the electric heater, and the tail gas is heated to 650°C by the electric heater to pass through the filter body. The back pressure difference before and after entering the filter body is detected in real time by back pressure detection. The temperature monitor detects the temperature of the tail gas at the end of the spiral heater in real time. The power consumption of the electric heater is recorded by the dynamometer. When the back pressure of the filter is reduced from 13KPa before the experiment to 5KPa in the no-load state, the temperature, back pressure and power of the filter are calculated after finishing the experiment.

4. Analysis of test results
The pressure difference before and after using DPF was used to calculate the regeneration efficiency, which is the PM particle conversion rate. Results imply that according to the pressure corresponding to the temperature measured in every minute before and after using DPF during the test, the back pressure curve is calculated and drawn. The back pressure curve is shown in Figure 5. DPF temperature measured by thermocouple was selected to calculate and draw the temperature time curve, as shown in figure 6. The regenerative power recorded by the power meter was used to draw the renewable energy consumption curve, as shown in figure 7.

![Figure 5. The back pressure curve.](image)

![Figure 6. The temperature time curve.](image)

![Figure 7. The renewable energy consumption curve.](image)
It can be seen from the back pressure curve that the curve of the conversion rate of the PM particle in the experimental group increased with the increase of temperature, and the transformation rate of PM particles reached the highest at 450°C. The reason is that the catalytic efficiency of DOC is increasing with the increase of temperature, and NO₂ produced by DOC catalyzing has high oxidizability. Particulate matter in DPF can be oxidized and regenerated at 450°C. However, the particulate matter in DPF decreased gradually with the increase of time, so the conversion rate of PM particles began to decrease.

The curve of the control group increased slightly with the temperature increase of PM particle conversion. The PM particle conversion at the temperature of above 500°C increased continuously and reached the highest at 650°C. The reason is that the exhaust temperature is generally at 250-500°C, and the ignition point of the particulate matter is generally 550-650°C. When the temperature is lower than the ignition point of the particulate matter, the conversion efficiency of PM particles is not high. When the temperature was close to the ignition point of the particulate matter, the particles were ignited and regenerated gradually, and the conversion rate of PM particles increased. However, the particulate matter in DPF decreased gradually with the increase of time, so the conversion rate of PM particles began to decrease.

The former DOC auxiliary regeneration device can provide a large amount of NO₂ for the latter stage DPF so that the filtered and deposited PM in the latter stage of DPF can be regenerated fully in time. DOC can make NO in tail gas be oxidized to NO₂, and the molecular bond of NO₂ breaks at the appropriate temperature (450°C). The produced oxygen atoms and the carbon atoms captured by DPF can combine and produce CO₂ so that the particles could be removed. At the same time, NO₂ is reduced to NO again and discharged into the atmosphere with tail gas.

It can be seen from the temperature-time curve that there was a linear increase in the temperature of both the experimental group and the control group during the initial phase of the heating, with a greater incremental slope for the experimental group. The reason for this difference in slope was, during the initial stage of heating, the PM that deposited in the DPF could not be ignited at such a temperature, and hence the heating of DPF by the electric heater was characterized by a linear increase temperature. The exhaust from the experimental group flowed into the heating chamber from the tangential direction, rotating along the wall of the heating chamber and was well heated by the spiral electric heater. Compared with the control group, the exhaust flow pattern of the experimental group was spiral, and its flow rate was inversely proportional to the heating time, indicating that the heating of the experimental group was more effective than that of the control group, and hence the greater incremental slope for the experimental group.

During the intermediate phase of the heating, an abrupt temperature change occurred at about 450 °C in the experimental group, while the change occurred in the control group only after 500 °C. During the intermediate heating phase, the temperature reached the ignition point of the PM that was deposited in the DPF, burning the PM, during which a large amount of heat was released, causing a sudden change in temperature. In the experimental group, the DOC-assisted regeneration device in the previous stage could provide a large amount of NO₂ for the DPF in the latter stage. This supply of NO₂, in turn, facilitated the early ignition of the PM at 450 °C, which explains why in the control group, the PM deposited in the DPF only burned after 500 °C.

In the final phase of the heating, the experimental group experienced a temperature drop after 800 °C, which contrasts with the control group, whose temperature was still rising. The reason behind this early temperature drop was the better oxidation efficiency under the influence of the NO₂ experienced by the PM that was deposited in the DPF at the latter stage. This causes the DPF in the experimental group to complete its regeneration much faster than its counterpart in the control group, which explains the early drop in temperature. Whereas for the control group, the oxidation did not occur as fast as it did in the experimental group, which explains why the temperature of the control group was still rising even after that in the experimental group had begun to drop.

It can be seen from the regeneration energy consumption curve that in the experimental group, the experiment ended after the heater had already stopped working at $t = 325$ seconds, whereas for the
control group, it was at $t = 425$ seconds, and hence the total energy consumption is higher for the control group. Through the analysis of the regeneration energy consumption by the temperature-time curve, it was found that using total energy consumption parameter as a measure of the devices’ energy consumption may give rise to a certain degree of deviation. This is because in the temperature-time curve, the ignition point of the PM in the experimental group DPF has been reached at 250 seconds, during which the heat generated was enough to maintain the regeneration. At this instance, the regeneration energy consumption was the actual regeneration energy consumption for the experimental group. Similarly, for the control group, because the ignition point of the PM deposited in the DPF was only reached at 350 seconds, the regeneration energy consumption can only be considered as the actual regeneration energy consumption after this instance. Finally, excluding the errors, it could be concluded that the regeneration energy consumption in the experimental group is lesser than that of the control group.

5. Conclusions
It can be seen from the comparative experiments that compared with that of the traditional electric heating regeneration technology, the DOC-assisted DPF spiral heating regeneration technology has the advantages of low energy consumption and rapid regeneration rate for regeneration.

The theoretical basis of the DOC-assisted DPF spiral heating regeneration is that the oxidation rate of the soot particles with NO$_2$ is 10 times as fast as that without NO$_2$. The device includes a DOC auxiliary regeneration device and a spiral electric heater. The catalysts in the DOC auxiliary regeneration unit oxidize NO in the exhaust gas to NO$_2$, which is achieved by oxidizing PM by NO$_2$. However, the catalyst is very sensitive to the sulfur content of fuel oil, so it is necessary to use CuO/γ-Al$_2$O$_3$ desulphurizer for desulfidation before DOC. The reaction temperature of the DOC and CuO/γ-Al$_2$O$_3$ desulphurizer is required to a certain extent, so the energy consumption is saved by combining the two units and sharing one heater. The front stage electric heating plate is close to the rear stage spiral heater, and the exhaust gas temperature loss is small, so the whole energy consumption is superior to that of the traditional electric heating regeneration technology. It is possible to apply spiral electric heater to ship by setting the heating chamber wall rotating heating, slowing down the flow rate of tail gas, increasing heating area, increasing thermal efficiency and saving energy consumption.

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