Research on microwave heating of exhaust gas particles in marine diesel engine

W W Tang1,2,4, L H Wu1, A G Chen1,2, J X Zhou3 and Z H Lin1

1School of Naval Architecture and Ocean Engineering, Guangzhou Maritime College, Guangzhou, Guangdong, China
2Ship Energy Conservation and Emission Reduction and Safety Supervision Engineering Technology Development Center, Guangzhou Maritime College, Guangzhou, Guangdong, China
3College of Power and Energy Engineering, Harbin Engineering University, Haerbin, Heilongjiang, China, 150009

E-mail: tww110@qq.com

Abstract. The diesel engine is widely used in the ship transportation industry due to the inherent advantages of its high thermal efficiency. With the increasing awareness of environmental protection and higher requirements on exhaust emissions, the post-treatment of particulate matter from diesel engine emissions has become a research hotspot. In view of the application of particle catcher in China, an improved microwave heating regeneration device for particulate matter from ship exhaust is proposed, and its efficacy is demonstrated.

1. Introduction

For its inherent advantage of high thermal efficiency, diesel engine has been widely used in the ship transport industry. In return, for the huge volume and total emission of marine diesel engines, such emissions have become an important source of air pollution. Harmful emissions of diesel engines include Hydrocarbon (HC), Carbon Monoxide (CO), Nitrogen oxide (NOx), particulate matters, etc. Compared with petrol engines, diesel engines’ emission of particulate matters (PM) was about 30~100 times higher [1], making PM one of the chief exhaust pollutants from diesel engines. Therefore, PM has been regarded as one of the focuses of the control of exhaust pollutants from marine diesel engines.

Measures to reduce marine diesel engines’ PM emission mainly included previous treatment, in-engine purification and exhaust clean-up, whose respective characteristics were as follows: 1) previous oil treatment could bring down pollutant emissions and significantly increase the costs for vessel operation; 2) in-engine purification was mainly achieved by combustion improvement or the use of dual fuel, which required main engine replacement or huge transformation in the main engine and the vessel, both leading to large costs; 3) exhaust gas purification equipment that is added to the exhaust system required only small changes in the vessel without the need of making major changes to the main engine, hence the low costs of upgrade [2]. Therefore, exhaust clean-up devices, as the simplest and most economical alternative, would certainly be widely employed by vessel owners.

At present, a relatively mature exhaust purifier was the integrated DOC & POC, which could achieve the purifying efficiency of 30%~80% with continuous regeneration for particle cleaning. DOC (Diesel Oxidation Catalyst) worked under the oxidation catalytic principle. It could effectively clean
up soluble organic components in the exhaust. However, it was extremely sensitive to sulphur in fuels, whose high content could easily lead to catalyst’s poisoning deterioration. POC (Particulate Oxidation Catalyst) was for half-interchange filters. It captured particles with its multi-fold and unblocked channel and was found with poorer exhaust clearing capacity. Therefore, this technology was mainly used in diesel engines in automobiles and those of smaller volumes, for it could not adapt to the complex emission conditions including high exhaust temperature, large exhaust volume and high sulphur content of diesel engines on large or extra-large vessels. The existing relatively mature exhaust purification technology has failed to provide a satisfactory solution to the issue of marine diesel engine exhaust cleaning. Targeting the complex environment involved in marine diesel engine exhaust treatment, this paper proposed an improved microwave heating regeneration device for particulate matters in marine exhaust. The device employed DPF (Diesel particulate filter) to filter particulate matters and microwave heating to clean them up. DPF treated particulate matters in the exhaust with its own physical properties and could reach the efficiency of 90% and above.

DPF mainly consisted of two parts, particle capturing and particle regeneration, of which the latter posed the greatest challenges to DPFs. PMs trapped by the filter would pile up and block the exhaust passage, leading to the rising exhaust back pressure in the diesel engine, seriously affecting the engine performance. Exhaust particles can cause blockage of DPF filter element after the device is used for a period of time, so the particles deposited in DPF must be removed timely, that is, DPF is "regenerated".

By improving the existing exhaust gas recycling device adopting microwave heating, this paper upgraded the filter-regeneration process requiring the removal of the filter cartridge to the regeneration of the filter to be regenerated during the filtering process, thus reducing the inconvenience caused by removing the exhaust device and lowering, the pollution from the vessel exhaust to the environment. Such improvement was of high social and economic benefits.

2. Limitations of diesel engine exhaust particulate matter regeneration technology at present

2.1. The filter
Wall-flow honeycomb ceramics was the filter of better overall performance at the moment. Its inner hole diameters were all in the micrometer scale and has been proven to be a filtering material that could effectively reduce soot particles by 90% or higher. It was also the most commonly used filter in developed countries at present, claiming high temperature-resistance and high mechanical strength [3]. Its main drawback, however, is the anisotropy in its physical parameters—its radial expansion coefficient was 2 times of the axial expansion coefficient. Since the PMs were all deposited in the inlet duct, thermal stress damages could easily occur in the regeneration process due to uneven heating. In addition, particles in plate-shaped structure in the honeycomb holes are unconducive for ignition and combustion.

2.2. Microwave heating regeneration technology
Considering the selective heating characteristic of microwaves in ceramic filters, microwaves would only heat soot particles, and not the ceramics; because of their volumetric heating characteristic, the spatial distribution of heat sources would be formed inside the filter [4]. Therefore, advantages of microwave heating include quick and even heating, and high regeneration efficiency (up to 85%). Filters using such a structure have two defects. First, a large external energy input is required in a relatively short time, which may result in the contradiction that the battery pack is difficult to meet the power required for filter regeneration. Secondly, the safety of microwave leakage should be paid attention to carefully. Nevertheless, it requires high attention to be given to safety issues such as microwave leakage.

2.3. DPF adopting microwave heating regeneration at the moment
A traditional cylindrical filter of microwave regeneration is shown in figure 1. In the same filter
regeneration and capturing cannot go concurrently, because if both these two operations run simultaneously the high air velocity would lower the PM temperature than the necessary ignition temperature.

![Figure 1. Overall diagram of microwave regeneration in the filter.](image)

Generally, marine diesel engines are heavy diesel engines, for which the DPFs are of large volume and are hard to replace. Exhaust gas inlet passage takes up part of the space in the filter setup and significantly reduces the space utilization. Moreover, the hollow part in the middle of the filter does not contribute to better space utilization. Therefore, based on the advantages of the traditional cylindrical filter and the partitioned microwave regeneration filter, the design of a small-sized DPF of high trapping efficiency could be conceived by lowering the requirements for exhaust resistance balance, filtering efficiency and radial dimensions.

3. The exhaust device capable of continuous microwave regeneration

Addressing the above problems of microwave regeneration in DPF at present, the authors propose a microwave heating regeneration device for PMs in marine diesel engine exhaust. The proposed design could resolve the problem of the traditional marine exhaust treatment device requiring removal of filter body for cleaning, no filtering of exhaust during the process, manpower requirement and pollution to the environment caused thereby, meeting the requirement of energy saving, emission reduction, and sustainable development in this age. The design illustration is as shown in figure 2.

![Figure 2. The structural illustration of the rotary continuous microwave regeneration DPF.](image)

1-Filter Body, 2-Exhaust Pipe, 3-Metal Partition, 4-Rotational Axis, 5-Heatproof Lagging, 6-Motor, 7-Quartz Glass Enclosure.

3.1. Filter optimization

Different from the traditional cylindrical filter, the filter body is designed into 6 module units by the microwave heating regeneration treatment device, and each unit is separated by a metal partition, as shown in figure 3.
Under the same filter body diameter, the filter body in this device has a bigger actual internal area and smaller flow resistance compared with the traditional cylindrical filter body. The actual internal area of the traditional cylindrical filter body \( S_C \) could be expressed as: \( S_C = \frac{\pi D^2}{4} \), where \( D \) is the diameter of the filter body. For the DPF featuring partitioned microwave regeneration, its actual internal area \( S_f \) could be expressed as: \( S_f = \pi D L \), where \( L \) is the length of the filter body. Therefore, under the same filter body diameter, the length-to-diameter ratio of DPF filter body, \( L/D \), is 0.8-2.5, for which the actual internal area of rotary partitioned microwave regeneration DPF becomes 3.2-10 times of that of the traditional cylindrical DPF. The percolation velocity formula can be expressed as: \( v_i = \frac{Q}{\phi A} \), where \( Q \) is the volume flow through the section, \( A \) is the section of the percolation, and \( \phi \) is the porosity. Therefore, DPF with zonal microwave regeneration can reduce the seepage velocity and flow resistance of the flow inside the filter body, but increase the filtration efficiency under the condition of the same exhaust flow rate and the same porosity of the filter body.

As a result, the design of partitioned microwave regeneration DPF can achieve a lower air seepage velocity and flow resistance in the filter, yet higher filtering efficiency under the same exhaust flow.

3.2. Optimization of microwave heating regeneration technology

Traditional microwave regeneration of filter needed the microwave-emitting component to be installed at the air inlet of the filter for heated regeneration. For every time of regeneration, a traditional filter was to transmit the microwave energy onto the entire filter, which needed huge energy load. The microwave regeneration with rotary filter, however, only heat-regenerated one filter unit at one time; after that, it started the heated regeneration of another region. In this way, it could well gather the microwave energy into the filter units in the regeneration chambers. The filter, with its rotation angle controlled by the step motor, heated each region for combustion and thereby made continued
regeneration possible. Since the heating of filter each time was completed by local microwave application, the energy load could be as small as 1/6 of the original as shown in figure 4.

Microwave featured strong penetrability. If not restrained, microwave energy could easily dissipate. The separators of rotary filter units served as restraints to microwave energy. After contacting metal surfaces greater than its wavelength, the microwave would be sent back and absorbed and heated by soot particles for combustion.

3.3. Particle trap optimization

The traditional ship exhaust gas treatment device can only be cleaned by disassembling the filter body, during which the exhaust gas cannot be filtered, resulting in the problem of human consumption and environmental pollution, which conforms to the requirements of the era of energy conservation, emission reduction and sustainable development.

To settle the above-mentioned technical problem, the device adopted the following technical solution: The said microwave heating regeneration device for the treatment of marine diesel engine exhaust PMs included the microwave heating regeneration system as well as the monitoring and control system, the latter of which monitored the data of the former in real time and realized the feedback control thereof as shown in figure 5.

Figure 5. The workflow of the logic control.
The microwave heating regeneration system included: the microwave emitter, back pressure tester, filter body, metal partition, rotational axis, heatproof lagging, motor, and the marine power grid; the metal partition is welded to the rotational axis; the insulating protective casing is connected mechanically to the rotational axis; the back pressure tester is connected to the rotational axis, the axis to the said motor, and the motor to the marine power grid; the microwave emitter is connected to the shell, and is electrically connected to the marine power grid, as shown in figure 6. The monitoring and control system comprises of the exhaust pressure sensor, exhaust temperature sensor, controller, alarm, and feedback system.

![Figure 6. The flow diagram of the connection principles of the microwave heating regeneration system.](image)

Thus, in this design the microwave heating regeneration system combined the filtering process and the regeneration process in the exhaust treatment in concert.

Specifically, the filter body is a honeycomb ceramic filter, with high-temperature-resistant and wear-resistant asbestos material filled between it and the shell. The microwave emitter is installed in the exhaust inlet pipe, which emitted microwave in order to evenly and rapidly heat up the honeycomb ceramic filter. The microwave emitter is the core of the microwave regeneration system, which is powered by the marine power grid. The emitted microwave is reflected in the filter to heat up the honeycomb ceramic filter cartridge evenly and rapidly, thus completing the regeneration of the exhaust PMs. The frequency and duration of the microwave emitted are precisely controlled by the data module as shown in figure 7.

![Figure 7. The flow diagram of the operational principles of the microwave heating regeneration system.](image)

The operational process of the device is as follows: after the marine exhaust entered the exhaust device, PMs therein would be filtered and absorbed by the filter body in certain areas; after the back pressure of the filter body in a certain areas reached the set value, the rotational axis would rotate to the set angle to the microwave regeneration zone, where the microwave emitter would emit microwave to heat and incinerate the PMs on the filter body so that the filter body of the area could again filter the PMs from the exhaust; the same process is repeated for the filter bodies of other areas.
after reaching the set back pressure, thus realizing filter regeneration without the removal of the filter bodies.

The DPF supported regeneration and filtering at the same time without the need to configure two sets of DPF devices as what needs to be done with the traditional DPF. Such a design simplifies the structure of the trapping system and reduces the space required for installation. In addition, the regeneration unit in the DPF only accounted for 1/6 of the entire filter volume, for which the microwave power required for regeneration become much lower as well (as shown in figure 8, so that the marine power grid is enough to meet the demand without the need of any special power conversion units, thus relieving the problem of large power consumption during microwave regeneration process.

![Diagram](image_url)

Figure 8. Power consumption comparison chart.

4. Conclusion
The microwave regeneration device for marine diesel engine exhaust PMs proposed herein is able to clean up diesel engine exhaust to meet the national emission standard, and could automatically regenerate the filter body without the need of removal, thus ensuring the device’s continued operation at high efficiency. This device has also eliminated such problems as huge environmental pollution caused by the consumption of fossil fuels in traditional marine diesel engines and agree with the requirement of the times for low-carbon, environmental protection, and sustainable development. It is very likely that the device will become the first choice for future vessel exhaust treatment equipment.

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