Diesel Particulate Filter for Exhaust Gas from Marine Diesel Engines and Optimization of Its Regeneration System

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Abstract. The aftertreatment of the exhaust gas from marine diesel engines plays an important role in the protection of atmospheric and marine environment. For the soot particulate matter (PM) emitted from marine diesel engines, a mathematical model was established to optimize the cellular structure of the filter. Using the asymmetric cell technology (ACT) combined with a rotary microwave continuous regeneration structure, a novel device was designed to capture and filter the PM exhaust gas from marine diesel engines. It not only had the high ash volume and low exhaust gas resistance of ACT structure, but also featured the low energy consumption and continuous regeneration of rotary filter.

1.Introduction
Due to its high thermal efficiency, diesel has been widely used in the marine transportation industry. However, the huge total emissions of the large-sized marine diesel engines make the exhaust gas from marine diesel engines become one of the most serious sources of air pollution. The exhaust gas of diesel engines contains a lot of dangerous pollutants, including hydrocarbons, nitrogen oxides, carbon monoxide, and particulate matter (PM). Among them, the PM is one of the major pollutants in the exhaust gas from diesel engines.

Since the internal purification of diesel engines has reached a highly advanced level, little process can be made in the reduction of pollutant emissions by modifying the engine design alone, thereby necessitating the aftertreatment of the exhaust gas.

V. Bermúdez, J.R. Serrano et al presents a novel technique based on pre-DPF water injection to reduce the DPF pressure drop under soot loading conditions by disrupting its dependence on soot/ash loading[1]. Bin Zhang, Jiaqiang E et al. In order to improve the overall performance of this DPF, its multidisciplinary design optimization (MDO) model is established based on objective functions such as pressure drop, regeneration performance, microwave energy consumption, and thermal shock resistance[2]. Dieter Rothe, Markus Knauer et al studied the influence of active regeneration of a diesel particle filter (DPF) on the particle emission. Besides the gaseous emissions, particle number (PN), soot mass and particle size distributions were measured[3]. Jiaqiang E. Ming Liu et al. established a
DPF microwave regeneration model according to the laws of conservation of mass, momentum and energy[4]. Debora Fino, Samir Bensaid et al has reviewed current soot oxidation catalyst scenario, and the main factors that affect the activity of powder catalysts have been highlighted and kinetic soot oxidation models have been examined[5].

In this paper, the relationship between the capturing and filtering and the microwave regeneration of the wall-flow honeycomb ceramic DPF was explored, and the cellular structure of the filter was optimized, providing new ideas for the filter design of marine diesel engine particulate filtering devices.

2. Cellular Structure of Diesel Particulate Filter

The most effective purification methods for diesel PM is the diesel particulate filter, or DPF. The main working part of a diesel particulate filter is the filtering element, i.e., the filter. There is an urgent need to deliver a high filtering efficiency and a low exhaust gas resistance in the filter with an appropriate size, and to meet the requirements of continuous regeneration that operates simultaneously with the filter’s capturing. In this paper, a rotary filter design using the ACT channel structure was proposed to improve the filtering efficiency. The entire filter was divided into multiple zones, and each one of them could be rotated to a specific position for regeneration while the others continued to capture the soot particles, so as to achieve continuous regeneration.

A rotary wall-flow filter consists of eight cells, each of which is fan-shaped. The eight cell zones, which are separated by a steel plate and a coating, form a cylindrical entity, references to figures (Fig. 1). The airflow in the rotary filter flows along the axis, and its flow area is the sum of the wall areas of all the inlet channels across the entire filter. In contrast, the airflow in a conventional flow-through filter flows in the same way, but its flow area is merely the circular surface area. The channels in an ACT structure could not only ensure the filtering efficiency, but also further reduce the back pressure of the exhaust gas and expand the ash capacity, substantially extending the service life of the filter.

References to figures (Fig. 2), the filter structure is designed into eight module cells, which are separated by a metal plate that concentrates the microwave energy in the cell inside the regeneration chamber. For the filter regeneration system, a microwave radiating element needs to be installed at the inlet for heating regeneration. Each regeneration of the PM in a conventional filter needs to heat the microwave energy to the entire filter, consuming a lot of energy throughout the process. With the rotary filter, only one cell needs to be heated and regenerated at a time, and the next cell is heated and regenerated after the previous one is done. The filter adopts a stepper motor control to enable rotation at a certain angle, so as to heat and burn the particles in each cell at a time, achieving the continuous regeneration. The partial heating consumes much less energy, which is only 1/8 of the original.

Microwave heating regeneration uses microwave to selectively heat the soot particles, so as to oxidize, burn and regenerate the DPF. The particles can absorb microwaves at a frequency of 2 to 10GHz with an efficiency of 60% to 70%. The ceramic materials have a poor absorption capacity for microwaves, while PM has a strong absorption capacity for microwaves, which is 100 times that of ceramics. Therefore, the energy can be concentrated on the PM in the filter and consume much less energy in the regeneration process, thereby extending the service life and improving the regeneration efficiency. Microwave has a strong penetrability, and its energy can be easily dissipated if not constrained. The separators in between the rotary filter cells function exactly to constrain the microwave energy, which will be reflected back once it encounters a metal surface larger than the wavelength. So the soot particles can absorb the energy and get heated and burnt to realize the efficient use of microwave energy.
3. Overall Design of Filter Structure

The overall structure of the filter can be divided into three parts: metal separators, regeneration zone end caps, and fixing components. The metal separators constrain the microwave to prevent it from dissipating. They also combine the filter cells into a whole structure. The metal separator are surrounded by thermal insulation mats resistant to high temperature, so as to enable airtightness and heat loss prevention. The separators are also installed with fixing and sealing components such as a snap ring. The filter structure and the microwave reaction chamber is separated by an annular gap as a seal. The left end cap of the regeneration zone is welded to the outer casing, and its right end cap is screwed to the sealing plate. The intermediate shaft and the metal separator are connected to the high temperature bearing, and the diameter of the shaft hole is 40mm.

The structure specifications are shown in Table 1:

| Support material | Thickness of metal plate | Gaps between end caps and outer casing | Airtight cushion |
|------------------|--------------------------|---------------------------------------|-----------------|
| Q235             | 1mm                      | 2mm                                   | 2mm             |

In practice, the size of the particulate filter is related to amount of the exhaust gas emissions from diesel engines. In this paper, the emissions of two 350kw marine Dalian Cummins generator sets (KTA19-G3M-50Hz) were taken as research objects.

3.1 Determining the Length-To-Diameter Ratio of the Filter

Studies have shown that as the ratio of length to diameter changes, the filtering efficiency and airflow resistance also change. However, the filtering efficiency is not sensitive to the diameter and the length and changes insignificantly. On the other hand, the airflow resistance decreases as the ratio of length to diameter increases. Given the spatial limitation of installation and the need for better regeneration, the ratio of length to diameter should be no greater than 1.

The flow of the exhaust gas calculated from the previous equations was 1.15 m³/s. And the value for the filter was set to 1.2 m³/s at the exhaust gas temperature of 528°C. This is because when the flow of the exhaust gas was 1.15 m³/s, which was lower than 2 m³/s, the corresponding specification of the exhaust gas flow for the filter was 1.2 m³/s. According to the Corning’s specifications of the filter, the filter could be selected by the length-to-diameter ratio based on the air flow. At this point, filter with the exhaust gas flow of 1.5 m³/s could be selected, and its length-to-diameter ratio was 1.

3.2 Determining the Size of the Filter

The airflow of the exhaust gas passes through the wall-flow filter, and the particles are intercepted and deposited on the channel wall. In this way, the capture of the soot particles is completed. The flow of the exhaust gas on the channel wall is a key factor affecting the filtering efficiency and airflow...
resistance. The maximum gas wall-flow speed in the channel is usually used to calculate the right filter volume. Considering the contradiction between airflow resistance and filtering efficiency, the maximum back pressure of the exhaust gas airflow should be controlled at 10kPa. Because the smaller the percolation velocity, the higher the filtering efficiency, the maximum percolation velocity of the exhaust gas the airflow should be no greater than 0.4m/s. For this reason, the percolation velocity could be set to 0.1m/s, with a filtering efficiency of more than 95%.

The calculated data are shown in Table 2:

| Maximum seepage flow (m³/s) | Length-to-diameter ratio | Volume (L) | Filter size (mm×mm) |
|-----------------------------|--------------------------|------------|---------------------|
| 1.2                         | 1.0                      | 16         | 274×274             |

To make the filter structure meet the design requirements of the project, the above calculated results were substituted into the overall structure, so that the volume of each cell in the eight filtering zones was 2L during filtration. The end surface of each zone where the exhaust gas airflow passed was 7366.83mm², and the outer diameter of the filter was calculated to be 314mm.

3.3 Optimizing the Structure Parameter of the Filter

The structure parameters that can be optimized in the filter include porosity, wall thickness, channel size, width ratio of the inlet and outlet channels, and pore diameter. Among them, wall thickness and channel size can be modified by adjusting the molds and processes, while porosity and pore diameter can be optimized by improving the filter composition, manufacturing processes, and sintering processes.

The pressure drop in filter with an ACT structure will decrease first and then increase with the increase of the pore density. When the diameter ratio of the inlet and outlet channels was 1, the pore density was 46.5cm⁻², which was the optimal value. But as the ratio of inlet and outlet channels increased, the optimal pore density became lower, so did the back pressure of the exhaust gas in DPF. However, when the ratio of inlet and outlet channels was 1.4, the back pressure of the exhaust gas did not change significantly. Meanwhile, in the generation process of the filter, each increment in the ratio of inlet and outlet channels could make the production more difficult.

Graphical analysis was employed to optimize the original filter parameters. The ranges of the optimized parameters are shown in Table 3:

| Porosity % | Channel width (mm) | Wall thickness (mm) | Pore diameter (mm) |
|------------|--------------------|---------------------|-------------------|
| 30~70      | 0.5~4.0            | 0.1~0.5             | 5~20              |

The calculated results of the boundary were divided into 16 zones for optimization, as shown in Table 4:

| Zone | Porosity ε | Channel width b/ (mm) | Wall thickness d/ (mm) | Pore diameter/ (μm) |
|------|------------|------------------------|------------------------|---------------------|
| 1    | 0.3~0.5    | 0.50~2.25              | 0.1~0.4                | 5~12                |
| 2    | 0.3~0.5    | 0.50~2.25              | 0.1~0.4                | 12~20               |
| 3    | 0.3~0.5    | 0.50~2.25              | 0.4~0.7                | 5~12                |
| 4    | 0.3~0.5    | 0.50~2.25              | 0.4~0.7                | 12~20               |
| 5    | 0.3~0.5    | 2.25~4.00              | 0.1~0.4                | 5~12                |
| 6    | 0.3~0.5    | 2.25~4.00              | 0.1~0.4                | 12~20               |
| 7    | 0.3~0.5    | 2.25~4.00              | 0.4~0.7                | 5~12                |
| 8    | 0.3~0.5    | 2.25~4.00              | 0.4~0.7                | 12~20               |
| 9    | 0.5~0.7    | 0.50~2.25              | 0.1~0.4                | 5~12                |
| 10   | 0.5~0.7    | 0.50~2.25              | 0.1~0.4                | 12~20               |
| 11   | 0.5~0.7    | 0.50~2.25              | 0.4~0.7                | 5~12                |
According to the analysis method, the frequency of occurrence of the optimal value distribution in each zone was calculated, and it was found that the channel widths of 1.2 to 1.5mm and 2.1 to 2.4mm were the most probable. Given the available process level, the optimal channel widths were 1.35mm and 2.25mm.

Similarly, wall thickness with the most optimal distributions was calculated to be 0.31 to 0.34mm and 0.61 to 0.64mm, and the optimal wall thickness was 0.325mm and 0.625mm.

In general, porosity and pore diameter should be selected differently for filters with various filtering efficiency. Those for the filtering efficiency of 80% and 90% are shown in Table 5.

Table 5. Optimized parameters of the filter structure with an exhaust gas flow of 1.15m³/s

| Filtering efficiency | Back pressure of exhaust gas (kPa) | Channel width (mm) | Wall thickness (mm) | Porosity ε | Optimal porosity ε | Pore diameter (μm) | Optimal pore diameter (μm) |
|----------------------|-----------------------------------|--------------------|--------------------|-----------|--------------------|--------------------|--------------------------|
| 80%                  | <5                                | 2.1~2.4            | 0.31~0.34          | 0.52~0.54 | 0.53               | 9.8~11.0           | 10.4                     |
| 80%                  | <5                                | 2.1~2.4            | 0.61~0.64          | 0.56~0.58 | 0.57               | 12.4~13.3          | 12.9                     |
| 90%                  | <10                               | 2.1~2.4            | 0.31~0.34          | 0.60~0.62 | 0.61               | 6.70~7.20          | 7.0                      |
| 90%                  | <10                               | 2.1~2.4            | 0.61~0.64          | 0.50~0.52 | 0.51               | 11.7~12.7          | 11.2                     |

The optimal ranges of porosity and pore diameter were calculated. When the filtering efficiency was 90%, the airflow resistance was less than 10kPa, the channel width was 2.25mm, the wall thickness was 0.325mm and 0.625mm, the porosity was 61% and 51%, and the pore diameter was 8.0μm and 11.2μm.

4. Conclusions

The filter element made of honeycomb ceramics employed the asymmetric cell technology (ACT) to increase the cross section and volume of the inlet channel and decrease the outlet channel volume. The designed structure could increase the storage capacity for the PM and ash, extend the regeneration cycle, and improve the cost efficiency of the diesel fuel. Through analysis, the filtering efficiency model and the airflow feature model were designed, and it was found that when the diameter ratio of the inlet and outlet channels was 1.4, the exhaust gas resistance could reach the lowest point. Finally, with an exhaust gas flow of 1.15m³/s, parameters about the size and structure of the designed filter were taken into account, and the model of graphical curve values was analyzed, so as to select the optimal parameters. The specific parameters of the filter were as follows: The ratio of length to diameter was 1.0, the porosity was 61% and 51%, the channel width was 2.25mm, the wall thickness was 0.325mm and 0.625mm, the diameter ratio of inlet and outlet channels was 1.4, and the pore diameter was 11.2μm and 8.0μm, respectively.

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