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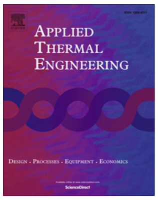

Research Paper

The influence of ash on soot deposition and regeneration processes in diesel particular filter

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HIGHLIGHTS

- Two new test benches were built to test the ash's effect on both deposition and regeneration processes.
- Ash is able to lower the pressure drop. 1 g/L reaches the lowest pressure drop.
- Small diameter ash has negative effect on deposition process, but positive effect on regeneration process.
- Mixed ash has positive effect on both deposition and regeneration processes.

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ABSTRACT

Particulate matter (PM) emissions from diesel engines are a major problem for the environment and human health. Diesel Particulate Filters (DPF) are widely used to remove PM to achieve strict regulatory emission standards for diesel engines. As the amount of PM deposition inside of the DPF increases, the back pressure of the engine rises, which reduces the engine output performance. A periodical heating to regenerate the DPF can effectively solve the above problem but a study of the effect of residual ash is needed. This paper discusses the influence of ash loading, ash particle size, and ash composition on filter performance due to deposition and regeneration processes on two different testing benches. The lowest pressure drop was obtained when the ash loading was 1 g/L in the soot deposition process. Larger ash loading was beneficial for reaching higher temperature and regeneration efficiency. The regeneration efficiency increased 47% when ash loading increased from 0 g/L to 10 g/L, but the regeneration efficiency only increased 4% when the ash loading increased from 10 g/L to 40 g/L. Smaller diameter ash particles resulted in lower pressure drop, and higher regeneration efficiency. Compared with pure Al_2O_3 ash, ash mixtures of $Al_2O_3 + SiO_2$ had lower pressure drop and higher regeneration efficiency.

1. Introduction

Diesel engines, compared with gasoline engines, have the advantages of lower fuel consumption and lower CO_2 emissions, and have the disadvantage of higher particulate matter (PM) emissions. PM emissions have negative effect on the environment and human health [1–3]. PM in diesel exhaust gases typically comprise of carbon, ash, organic compounds, and sulfate material [4]. The size of the PM ranges from microns down to nanometers in size [4]. Due to stringent national regulatory emission standards, engine manufacturers use diesel particulate filters (DPF) as one of the methods to reduce and control PM emissions. DPF are effective and reliable to capture PM and reduce emissions to the atmosphere [1,5–7]. DPF typically have filtration efficiencies as high as 95% [5,8–10]. DPF are designed with large surface areas to operate with acceptable pressure drop. However, accumulation of PM adds resistance to the gas flow and increases the pressure needed to maintain the flow, which reduces the engine fuel efficiency. The periodic regeneration of DPF by oxidizing the deposited PM reduces the gas flow resistance [11–13]. Other designs of DPF may incorporate catalysts to aid in the regeneration by enhancing the oxidation of the ash and by reducing the regeneration temperature, energy, and time for DPF regeneration [14–16].

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Ash in the DPF affects filtration efficiency, flow resistance, and regeneration efficiency [17–19]. Many experimental and numerical studies have been conducted to understand the chemical composition of ash and the ash's effect on filter performance. Liati et al. [4] presented a multi-scale analytical investigations of PM (soot and ash) from a truck and a passenger car. They concluded that ash formed the substrate for soot deposition along the filter walls and that Anhydrite ($CaSO_4$) was a common substance among the ash constituents. Tandon et al. [8] observed that ash improved the filtration efficiency on both bare and coated filters, because the ash layer served as a collector of the soot particles. Young et al. [17] found that an exchange between inlet and outlet cells was able to have more ash storage and improve overall filter performance. Iwata et al. [18] found that the ash aged DPF with filtration layer was no deep bed filtration phenomenon on the transient pressure loss and filtration efficiency was always over 99%. Sappok et al. [19] presented the processes controlling the formation, transport over a range of DPF regeneration conditions. Jiang et al. [20] applied a mathematical model of the filtration process for ash deposition. Their model showed the filtration efficiency decreased with the increase of ash loading. Zhu et al. [21] evaluated the effect of sulfated ash in different diesel engine lubricants on the performance of DPF. Liati et al. [22] applied scanning electron and transmission electron microscopes to observe the morphological and microstructural characteristics of ash particles. However, the effects of the ash loading on deposition and regeneration processes are not yet fully understood.

In this study, the influence of ash loading on soot deposition process was tested by a new single layer channel system. Regeneration tests were applied to investigate the effect of ash on regeneration process. The aim of this research is to provide detailed information on the effect of: (1) ash loading, (2) ash diameter, and (3) ash composition on deposition and regeneration processes.

2. Description of experiments

2.1. Experiment material

The DPF tested in this work was purchased locally and used as supplied without modification. The DPF was made of Cordierite, without any catalytic coating. The DPF properties are summarized in Table 1. Carbon black (Printex-U), supplied by Evonik Industries AG, was used as a surrogate for diesel soot. Carbon black properties are summarized in Table 2. Several simulated ashes used in this work were purchased from Tianjin Longhua Company, and the properties are summarized in Table 3.

2.2. Experiment method

Fig. 1 shows a diagram of the filtration test bench. Pre-filtered house air, drawn by vacuum pump, flowed through a flow meter and into the single layer filtration channel. The body of the DPF sample holder was made of stainless steel (SS) and had an optical window made of Quartz glass. The DPF piece was cut to samples sizes 30 mm ∗ 60 mm ∗ 3 mm to fit into the sample holder.

To prepare the sample with a deposition of ash, the ash particles were mixed into alcohol to form a mixture to penetrate into the 30 mm ∗ 60 mm ∗ 3 mm DPF piece. The alcohol mixture concentration was determined by heating and evaporating the alcohol form a measured volume of mixture. From the concentration, the volume of mixture needed to deposit a specific mass of ash onto the DPF was determined. The required volume of alcohol mixture was poured onto the surface of the DPF sample and the alcohol was evaporated to leave a layer of ash.

For the filter performance tests, carbon black particles were generated by a particle dispersion device (Palas RBG1000) and deposited onto the DPF sample by the flow of the air through the DPF sample. In all of the experiments, the face velocity of the air through the sample was 0.02 m/s at room temperature. A 2-D laser displacement sensor (LJ-G080, Keyence) was applied to measure the thickness of the particle layer with accuracy of 1 μm. The pressure drop was measured between the inlet and outlet flow streams with an electronic pressure gauge (AZ8205, Taiwan HengXin).

Before the regeneration tests, the full scale DPF block was loaded with ash and carbon black, respectively, shown in Fig. 2. The particle loading system included particle generator, package device for DPF and vacuum cleaner three parts. The air from the compressor went through the pre-filter and air dryer to remove impurities and water, respectively. The air flow rated was controlled by rotameter and flowed into the particle generator. The ash particles in the particle generator were raised to form a stable ash particle aerosol. With the help of vacuum cleaner, the ash particles in particle generator flowed into the DPF channels. DPF was in axial position with respect to gas flow so that the gas had to flow through the porous inner walls because the channels were alternately plugged. After ash particles loading, the carbon black particles were loaded by the same method.

Fig. 3 shows the schematic of DPF regeneration testing bench with additional heating sources. The regeneration testing bench contained flow control, heating, replaceable DPF, and data sampling. The pre-filtered house air, which was provided by an air compressor, flowed through a mass flow meter, through the electrical heater (LE 10000 DF HT, LEISTER), and through the DPF. The pressure difference was measured by a pressure sensor between the inlet stream to the heater and the outlet from the DPF. Thermocouples were distributed inside of DPF as illustrated in Fig. 4, at five evenly spaced fractional locations along the axial length L of the DPF and at different fractional radial positions (indicated by fractions of the diameter, ϕ). The electrical heater was used to control the inlet temperatures at 500 °C, 525 °C and 550 °C. In the experiments, the DPF was heated to 200 °C first in order to achieve the stable temperature inside of the DPF. Then the DPF was heated to the desire experiment temperature. To reduce heat loss during the regeneration process, thermal insulation cloth was wrapped around the outside of the regeneration room housing the DPF. Ash and carbon black were loaded into the whole DPF block before regeneration testing respectively. In all of the regeneration tests, the carbon black loading, mass flow rate, and oxygen concentration were 5 g/L, 16.8 g/s, 21%, respectively.

2.3. Data analysis

T_{max} represents the maximum temperature of DPF, and $(dT/dx)_{max}$ represents maximum temperature gradient inside the filter.

η represents regeneration efficiency, and is calculated by

$$\eta = \frac{M_1 - M_2}{M_1 - M_0} \times 100\% \tag{1}$$

Table 1
Physical properties of full size DPF block.

Diameter (mm)	Length (mm)	Channel density (cpsi)	Channel size (mm)	Filter wall thickness (mm)	Pore diameter (μm)	Porosity (%)
144	152	100	2	0.35	7.6	27.9