

Microscopic Visualization of PM Trapping and Regeneration in Micro-Structural Pores of a DPF Wall

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ABSTRACT

Trapping and regeneration processes in a SiC wall-flow diesel particulate filter (DPF) without a catalyst were investigated in detail through microscopic visualization. By microscopic observation of the cross section and surface, the transition from depth filtration to surface filtration could be observed clearly. The open pores on the wall surface were strongly related to the filtration depth of diesel particulate matter (PM). During the regeneration process, after the soot cake was burnt out, the particulates trapped inside the surface pores were oxidized. As a result, the particulate trapping and oxidation behaviors were strongly dependent on the microstructural surface pores.

INTRODUCTION

High efficiency power sources must be developed and widely implemented, as the threat of fossil fuel exhaustion that is threatening globally. Among the heat engines, diesel engine has the highest thermal efficiency for a given output power; however, particulates and NO_x must be removed from exhaust gases emitted from diesel engines to protect the global environment and human health. Achieving an environmental-friendly power source for next-generation diesel engines requires high efficiency emission controls. These could use complex assemblies of, for example, NO oxidation, particulate trap/oxidation, and DeNO_x reactors. Of these, a diesel particulate filter (DPF) plays an important role in particulate trapping and oxidation. Although these processes involve the most complex behavior of particulates and reaction phenomena, less information is available for understanding of such phenomena.

A DPF is generally made of ceramic materials, such as cordierite or silicon carbide [1], consisting of many rectangular channels with alternate channels blocked with cement at each end. The exhaust gas is forced to flow through a channel wall having numerous micron-scale pores that trap the diesel particulate matter. Further, the collected particulate matter must be oxidized to regenerate the DPF and reduce the back pressure on the diesel engine.

There are two methods of DPF regeneration. An active system (periodical regeneration) [2] that ignites the particles trapped in the filter with burners or electric heaters. In this system, the temperature of the DPF should be controlled between the DPF destruction point and a soot cake oxidation temperature, higher than 600 °C. The other is a passive system (continuous regeneration) [3], in which catalytic additives, such as Cu [4] and Ce [5] reduce the overall activation energy required for particulate oxidation; oxidation occurs at a lower temperature than with active regeneration.

Recently, using the lattice Boltzmann method (LBM), particulate trapping and chemical reactions were simulated for the inside of an artificial computer aided designed DPF wall [6], and a computer aided reconstructed DPF wall [7]. The numerical results and SEM images of trapped particulates were compared [7], to provide valuable information for the DPF design made of various types of materials, such as SiC, cordierite, mullite [8] and metals. Furthermore, a new concept was proposed for low backpressure filtration [9].

The current research group previously reported on the particulate trapping behavior of surface filtration and its active regeneration phenomena inside the DPF [10, 11]. These DPF operations are observed using an ordinary

video camera and a half-cylindrical wall flow DPF, covered by a quartz glass plate. Moreover, the micro-structural phenomena inside the DPF wall was observed through a digital microscope, using a small rectangular wall flow DPF covered by a quartz-glass plate [12]. Particulate trapping and oxidation reaction were investigated successfully for better understanding, modeling, and future design of ideal DPF configurations. However, these visualization methods cannot focus on the surface and deeper areas of the DPF surface simultaneously. In the current study, further modification in DPF design, as well as the microscope, was essential to achieve a higher DPF filtration efficiency [13]. This report used a new All-In-Focus microscope.

EXPERIMENTAL SETUP AND METHOD

MICROSCOPIC VISUALIZATION SETUP

Figure 1 shows a schematic diagram of the microscopic visualization setup. The wall flow DPF, made of SiC, is cut into cross sections of 8×8 and $7.5 \times 7.5 \text{ mm}^2$ with a length of 15 mm, in which a 4×4 and a 5×5 channel matrix is made, and alternate channels are blocked with cement at each end for Type-A and B DPFs, respectively. After removing the top horizontal wall, the edges of the remaining vertical walls of the channels were polished with 2.5 micron silicon-carbide sandpaper. The open flow channels were covered with a 0.5 mm thick quartz-glass plate. A small DPF was installed in an insulated flow duct. The trapping phenomena and regeneration processes inside the DPF (cross-sectional view) were observed through the glass plate using the All-In-Focus microscope (Photron Focuscope FV-100C), providing a focal range up to 100 microns, and a real-time video at 30 frames per second.

The phenomena on the surface (surface view) was observed using a long-focus lens microscope. The DPF temperature was monitored with a K-type sheathed thermocouple in the flow exit channel. During the regenerative process, an infrared thermal camera (Avio TVS-850) conducted 2D thermography measurements inside the DPF wall with a space resolution of 10 microns. In this case, the window was sapphire glass.

EXPERIMENTAL METHOD

Figure 2 shows a schematic diagram of the experimental setup for diesel particulate trapping. The diesel engine (Robin SDG2200, manufactured by SUBARU Co. Ltd.) possesses displacement of 230 cm^3 and a rated output of 2.8 kW. The fuel injection pressure was approximately 50 MPa. The engine was operated under a constant load of 2.1 kW at a constant speed of 3000 rpm throughout the experiment. Table 1 shows the engine specifications. A fraction of the exhaust gas was introduced into the small DPF through a bypass line maintained at a constant temperature of approximately 200°C . The exhaust gas flow velocity at the inlet of the small DPF was approximately 0.39 m/s, and the superficial velocity traveling through the DPF wall was approximately 2.31

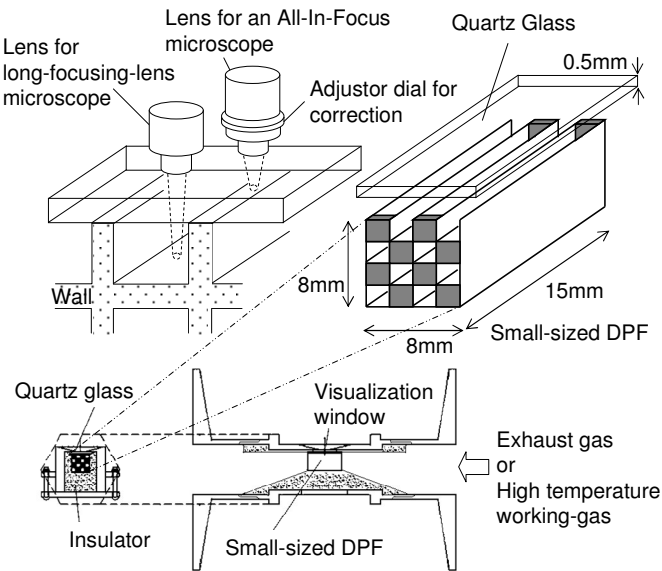


Figure 1 Setup for microscopic visualization of trapping and regeneration inside the DPF wall.

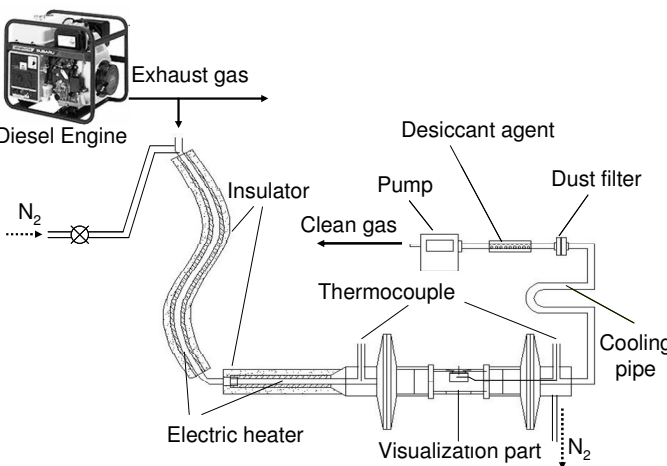


Figure 2 Experimental setup for particulate trapping.

Table1 Engine specifications	
System	4-strokes
Number of cylinders	1
Displacement	230 cc
Bore × Stroke	70mm × 60mm
Compression ratio	21:1
Injection pump pressure	~ 50MPa
Rated output power	2.8kW at 3000rpm
Maximum output power	3.3kW at 3000rpm
Maximum torque	10.8Nm at 2300rpm
Fuel	commercial light diesel

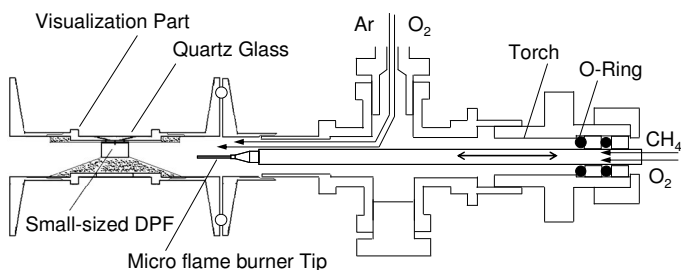


Figure 3 Experimental setup for DPF regeneration.

Table 2 SiC-DPF Specifications

Type	A	B
Filter Material	SiC	SiC
Catalyst	None	None
Cell Density	200 cpsi	300 cpsi
Wall Thickness	400 microns	380 microns
Porosity	58%	60%
Mean pore size	15 microns	50 microns

cm/s for SiC-DPF Type-A. For the DPF Type-B, the exhaust gas flow velocity at the inlet of the small DPF was approximately 0.44 m/s, and the superficial velocity traveling through the DPF wall was approximately 3.47 cm/s. The superficial velocity flowing through the DPF wall was similar to that of a real world DPF for both types.

Figure 3 shows the experimental setup for DPF regeneration testing. Further, the engine was stopped and the DPF was regenerated by a high temperature working-gas produced by a burner. DPF inlet temperature and the oxygen concentration were controlled by the engine load and excess air ratio.

MICROSTRUCTURE OF SiC-DPF

Figure 4 shows the SEM image of the SiC-DPF wall surfaces with a porosity of 58% and average pore size of 15 microns. Figures 5(a) and (b) show optical images of the polished cross sections of the SiC-DPF walls for Type-A and B, respectively. The average porosity distributions are also shown. The SiC-DPF walls are 400 and 380 microns thick. The specifications for each type of SiC-DPF are shown in Table 2. The top edges of the vertical walls were polished to a mirror-like flat surface. Since the collimated rays of visible-light from the microscope were incident on the surface in the normal direction, the reflected light was detected as white islands. The remaining dark or bright-gray region show flowing pores in the walls. Porosity increases drastically from average to 100% near the surface.

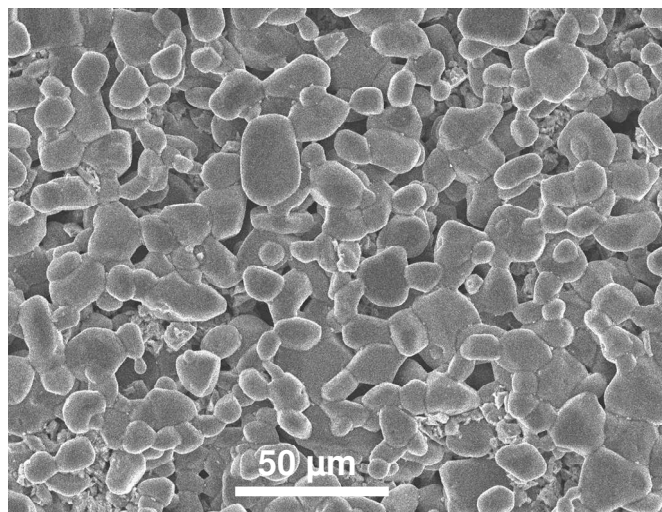
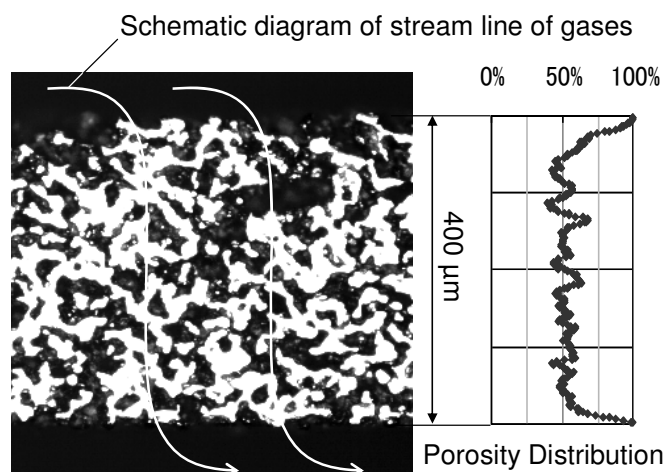
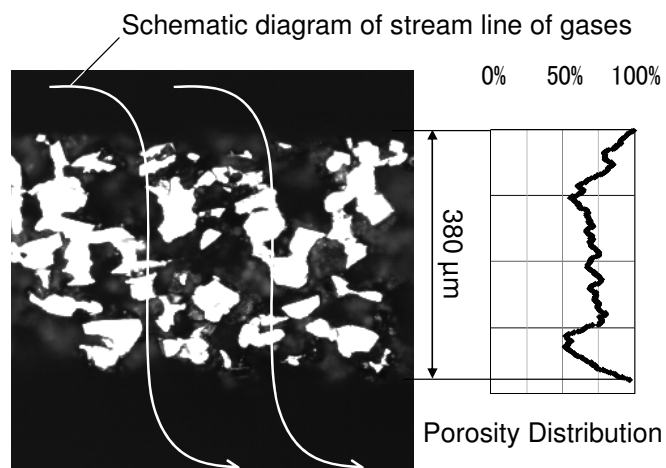


Figure 4 SEM image of the SiC-DPF wall surface, with a porosity of 58% and average pore size of 15 microns.



(a) Silicon Carbide (SiC), Type-A



(b) Silicon Carbide (SiC), Type-B

Figure 5 Optical images of the polished cross sections of SiC-DPF walls.