Characterization of Advanced Aluminum Titanate Ceramic Filter Having Hexagonal Cell Geometry

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ABSTRACT: Aluminum titanate (AT)-based Diesel Particulate Filter (DPF) with hexagonal cell geometry has previously been presented as a promising media showing extremely lower pressure drop, coming from its specific hexagonal channels of DPF. In addition these AT characteristics, the investigation on an engine bench verified that AT filter with the hexagonal cell structure exhibited different combustion behavior from the one with the standard cell structure. To understand this behavior, direct observation inside the filter on its microscopic scale was carried out. It was found that the hexagonal channels induced multiple steps on particulate matter accumulation.

KEY WORDS: heat engine, particulate filter, measurement/diagnosis/evaluation, aluminum titanate [A1]

1. Introduction

Emission after-treatment technology is a promising factor for CO₂ restriction in the automobile industry based on the background of global warming problems, and has recently been in progress on wide range of the application. While a Diesel Particulate Filter (DPF) is a functional soot–filtration media and a powerful device for the after-treatment system, it still maintains open issues of higher fuel penalty on the vehicle based on the source to lead higher backpressure inside the exhaust pipe, and on the need to make the post fuel injection for removing the soot accumulated inside DPF on the driving. Especially on latter issue of reducing the post fuel, the thermal shock performance called as robustness to own a specified capability to accumulate much larger amount of soot particles and to maintain the structure stable after the soot particles were combusted by fuel injection is highly required for DPF indicating that higher robustness of DPF induces lower fuel injection since its frequency is less. Much of interests in the countermeasure for robustness issues are focused on the increase of the DPF weight since it depends effectively on the heat capacity, enabling thermal shock performance higher (1). However, the heavier weight of DPF simultaneously makes the disadvantage of higher backpressure, and such concept is not able to accelerate the improvement of fuel penalty as a total system. Also, this strategy is not considered as a proper way by considering the trend that weight saving on the total vehicle system is quite a meaningful for CO₂ reduction.

A novel conceptual DPF with aluminum titanate (AT) material and with hexagonal (HEX) cell design has recently been presented (2). The main characteristic is the lower backpressure coming from higher filtration area for soot, and higher inlet volume to provide ash accumulation based on the hexagonal cell design. Furthermore, due to the material properties of AT, thermal performance has been proved to be more comparable than conventional materials because it shows lower thermal expansion and higher heat capacity, enabling the increase in the limited temperature to make cracks inside DPF. In this paper, the temperature behavior on soot-combustion called as regeneration process was also noted. The main point to be interested is a big difference behavior on temperature peak during regeneration process. HEX design shows milder regeneration behavior than square (SQ) design and it means higher robustness. It is also mentioned that as filter weight gets lighter, regeneration gets milder at HEX design.

The main characteristic of HEX is to own two different types of wall, inlet/outlet wall, and inlet/inlet wall. Compared to conventional design such as square design, the inlet/inlet wall makes some unique possibility on the gas flow investigation. It is quite a meaning to analyze the detail mechanism inside the DPF on practical usage in order to develop DPF with higher performance. The relationship between HEX structure and DPF performance is discussed through the understanding of the structure function by directly observation method as microscopic visualization, where the soot-loading behavior inside HEX design was focused especially on the difference between inlet/outlet wall...
and inlet/inlet wall for the prediction for the flow direction of target gas. It was found that the HEX channels induced multiple steps on particulate matter accumulation, and dependent on the regeneration behavior.

2. Experimental

The direct observation was performed along the previous report
(1) (4). Fig.1 shows the schematic diagram for the direct observation of internal DPF under soot-loading process. A soot generation source is made of diesel fuel (conventional diesel fuel, JIS K2203 No.2) lamp such as an alcohol lamp to simulate soot emitted from recent diesel engines. The generated soot was almost dry one. The soot feed to DPF side was carried out with the suction probe on the rate of 0.75 litter/min. of the air flow, which is located to lower part in the lamp. The DPF sample used herein is aluminum titanate materials with HEX structure and cut some parts out in order to put it into a specified holder with quartz cell to be observed by microscope. The target shape on the measurement consists of 6 inlet channels and 1 outlet channel, and 1 inlet channel, which is connected to 3 inlet channels and 1 outlet channel, is selected as an object as shown in Fig.2. The focus was set on the surface of inlet/outlet wall ($w_s$) flow and inlet/inlet wall ($w_c$) flow of the channel. After the DPF part, the cross sectional wall of which is well-polished, was attached to the quartz-cell, it was surrounded by insulating materials, and fixed to the metal holder. The microscope located at the upper side of the holder was connected to the PC, where the movies and photos were taken in the soot-loading process inside DPF.

3. Results and Discussion

Fig.3 shows the direction of target parts for microscopic visualization, as mentioned above, the surface of inlet/outlet wall ($w_s$) flow and inlet/inlet wall ($w_c$) was observed at once. Fig.4 shows time history of soot deposition on individual wall substrates, where the status on the inlet/outlet wall ($w_s$) and inlet/inlet wall ($w_c$), are shown on upper side and down side as depicted, respectively. Black points indicate the soot particles on the walls. The target gas including soot-particles was kept introduced until all area was covered with soot. It can be seen that the procedure in the soot deposition is followed by 1st step on $w_c$, and 2nd step on $w_s$.

This fact is explained by Darcy-law as expressed in Eq.(1),

$$\Delta p = \mu \frac{u}{k}$$

where $\Delta p$ is a pressure difference between inlet and outlet channel, $\mu$ is a gas viscosity, $u$ is a gas velocity through the wall, $t$ is a path length of the porous wall, and $k$ is a permeability of target, i.e., wall and soot layer. The gas flow through the walls is shown in Fig.5. As an initial step of non-soot generation, almost all of the working gas introduced penetrates through $w_s$ prior to $w_c$ since $w_c$ shows more effective path due to its quite shorter distance from inlet to outlet channel than $w_s$. Since it is considered that $\mu$ and $k$ are constantly stable due to its material properties under the experimental condition used, $u$ depends on the path length of $t$. Because path length in $w_s$ is shorter, the velocity going through $w_s$ is more than that going through $w_c$ as described in Fig.6. After the soot particles are deposited on $w_c$ with a specified region, the additional soot particles start to deposit on $w_s$ from a particular time when the velocity into soot-deposited $w_s$ is equal to the one into $w_c$. The fact is also interpreted by Eqs.(2) and (3).

$$\Delta p = \mu \frac{u_s}{k_{soot}} = \mu \frac{u_{c}}{k_0}$$

(2)

$$\frac{u_c}{k_{soot}} \cdot t_s = \frac{k_0}{k_s} \cdot t_c$$

(3)

Fig.3 Direction of target DPF parts for microscopic visualization
The soot-loading behavior onto the wall depends upon the rate. condition such as soot properties and gas components and flow and along the above-process since the gas velocity through both deposition on any wall, and once the soot is deposited on consists of euphemistic form through the actual wall thickness between inlet and outlet channel, shows longer path than deposition on any wall, and the soot deposition is considered to be conforming also on \( w_c \) [Fig.6 c]. Finally, the thickness of soot layers is taken into consideration to be higher on \( w_s \) than on \( w_c \) along the above-process since the gas velocity through both \( w_s \) and \( w_c \) is being comparable after the latter soot-deposition timing. The soot-loading behavior onto the wall depends upon the condition such as soot properties and gas components and flow rate.

As mentioned before, Iwasaki pointed out that the regeneration process is different between SQ and HEX design \( ^{15} \). Fig.7 shows the changes in temperature inside AT-DPF with different cell design, same size 5.66” diameter and 6” length , (a) Square (SQ) and (b) hexagonal (HEX) design under Drop-to-idle condition with soot-mass of 12 g/l, which is simulated to worst case regeneration as reported previously. In this figure, number indicates thermocouple position inside DPF as depicted in the upper side. Due to the lower gas flow, and the increase in oxygen concentration after the idle timing, internal temperature was increasing higher especially on downstream point, where combustion of soot located inside the DPF was accelerated. While a significant single peak appeared in SQ over 1000 deg.C after idling, a broad peak less than 1000 deg.C was shown in HEX. Since thermal shock performance depends effectively on the maximum temperature and thermal gradient, thus-obtained behavior on hexagonal design could be of advantage on the performance.

Fig.8 shows the temperature changes in the HEX structure with different filter weight (wall thickness) on regeneration testing under drop-to-idle condition at soot mass of 12g/l. The hexagonal design used is a specific type, different from one in the Fig.7. The thermocouple position is depicted on the upper side of the figure. It was observed that along lighter weight, temperature peak was getting broaden. As mentioned above, the conventional DPFs causes the lower thermal shock performance if the filter weight is lighter coming from the lower heat capacity as of the
unit of Jg⁻¹L⁻¹. However, HEX design is found to be independent of the filter weight on the thermal shock performance as shown in Table1. Thus HEX design shows quite unique performance and it seems to come from the cell design, that is the existence of inlet/inlet wall.

Considering this regeneration behavior in the gas flow aspect, the modeling obtained from direct observation inside cell, indicates the interpretation with regeneration behavior. The hot gas generated on the forced regeneration, similar to the gas including soot particles on the soot-loading step, penetrates two kind of wall (w₁ and w₂), and combusted the surface of soot layers. Since the thickness of soot layers on w₂ is lower than one on w₁, the deposited soot layers on w₂ disappear firstly and combustion area decreases. This indicates that regeneration process also consists of two steps as expressed in Fig.6 d-e. Therefore, it is considered that thus-multiple step makes broader temperature peak on the regeneration. Furthermore, as shown in Fig.2, the result that HEX with thinner wall thickness makes the broader peak on the regeneration process, is considered to be dependent on the gas flow thorough w₁ and w₂. Because thinner w₂ makes higher w₁, the thickness of soot layers on w₁ gets thicker and that on w₂ gets thinner than the case of thicker wall. This means combustion area decrease fast and combustion lasts longer and show milder regeneration process. The further quantitative investigation such as kinetic analysis on the generated reaction species like CO, and CO₂ detection under regeneration process could help thus-obtained modeling to be clarified.

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It has been found that unique cell structure of hexagonal design shows interesting combustion behavior of loaded soot inside DPF during the drop-to-idle condition in engine bench investigation. While square cell design shows sharp temperature peak on the regeneration process, hexagonal design shows broad peak. Furthermore, hexagonal design with thinner wall thickness makes broader temperature peak on the regeneration. The result indicated the relation to the different function on inlet/outlet wall and inlet/inlet wall. The microscopic visualization method revealed that soot-deposition starts firstly on inlet/outlet wall, and secondly on inlet/inlet wall based on Darcy’s law. This fact of multiple steps on the target gas flow leads that hot gas on the regeneration process makes the faster combustion of inlet/inlet wall than that of inlet/outlet wall due to its thinner soot-layers on the wall. Since the thinner wall thickness of the DPF makes the gas diffusion balance through inlet/inlet wall smaller, the combustion of soot inside the DPF with thinner wall is considered to be retarded. These studies are fruitful and promising for developing next-generated filter with higher robustness, and the design optimization of cell structure are highly desirable.

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