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Flow Analysis during Soot Trapping on Aluminum Titanate Ceramics Filter with Hexagonal Cell Geometry

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ABSTRACT: The phenomena of soot trapping and oxidation in a hexagonal cell geometry DPF made of aluminum titanium oxide were investigated through microscopic visualization experiment and a simple analysis based on Darcy's law through the wall and the deposited soot layer. There were two types of flow: one was a flow through a wall between inlet and outlet channels (inlet/outlet wall flow), and the other was a flow which was introduced into a wall between inlet and inlet channels, and was turned toward the direction parallel to the wall, and finally exited into the outlet channel (bypass flow). The flow rate of the bypass flow was increased with a thickness of soot layer deposited on the inlet/outlet wall. As a result, the soot was trapped even on the inlet/inlet wall surface. In the regeneration process, depending on the flow rate of the bypass flow, the maximum temperature for the hexagonal cell DPF became lower compared with that for the conventional DPF.

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

1. Introduction

The diesel engines have a thermal efficiency higher than that of gasoline engines, which results in reduction of CO₂ emission into the atmosphere. However, emission of particulate matters (PM) and nitrogen oxide (NO_x) from diesel engines becomes a significant issue from a point of view of human health and protection of environment in the world. Consequently, the emission should be reduced for future sustainable society ⁽¹⁾⁽²⁾⁽³⁾.

The diesel particulate filter (DPF) is very useful for reduction of emission of particulate matters. It is well known that most of all PMs can be trapped on the surface of the DPF wall, that is, the filtration efficiency is nearly equal to 100 %. As a result, an important issue for designing DPF is slightly shifted from filtration efficiency to reduction of pressure drop even in loading of PMs.

Recently, A novel hexagonally (HEX) designed DPF made of aluminum titanium oxide (AT) was proposed ⁽⁴⁾, for decreasing the pressure drop during trapping PMs using a higher inlet channel volume originated from its hexagonally designed cell. There are two types of walls between inlet and outlet channels and between inlet and inlet channels, as shown in Fig. 1. In this case, similar to the conventional square cell DPF, the soot was trapped on the surface of wall between inlet and outlet channels. On the other hand, it was expected that there was no soot deposition on the surface of wall between inlet and inlet channels since there was no pressure difference between inlet channels. However, in the previous experiment on soot loading by the

hexagonal cell DPF, it was clarified that the soot was trapped on the surface of the inlet/inlet wall ⁽⁵⁾.

In this study, the phenomena of soot trapping and oxidation in a hexagonal cell type DPF made of aluminum titanium oxide were investigated through microscopic visualization experiment and a simple analysis based on Darcy's law through the wall and the deposited soot layer.

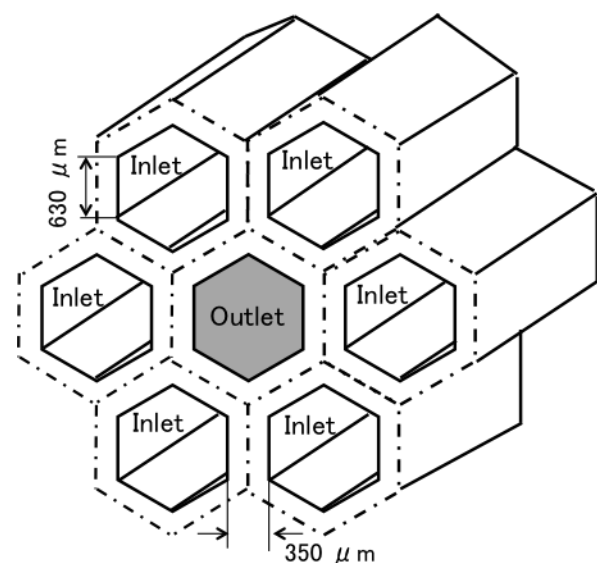


Fig. 1 Schematic illustration of hexagonal cell geometry DPF made of aluminum titanium oxide

2. Experimental set up

2.1. Microscopic visualization setup

Figure 2 shows a small-sized DPF made of aluminum and titanium oxide used in experiment. The cross sectional area and the length are $5 \times 5 \text{ mm}^2$ and 7 mm, respectively. The two inlet channels are opened for optical microscopic visualization. The end surfaces of vertical walls were polished using sandpaper including a few microns silicon carbide particles. The open channels were covered with a 0.5mm-thick quartz glass plate. The small DPF with the glass was installed in an insulated flow duct. Through the glass window, using an all-in-focus microscope (Photron Focuscope FV-100C: a $100\mu\text{m}$ focal range and a speed of 30 frames per second), the trapping and regeneration processes were observed⁽⁶⁾⁽⁷⁾ from both surface views: the one is the surface of the wall between inlet and outlet channels, and the other is between inlet and inlet channels. The DPF temperature was monitored using a K-type sheathed thermocouple in the flow exit channel.

Figure 3 shows an optical image of the polished surface of vertical wall with a thickness of $350 \mu\text{m}$. The white island shows a mirror-like polished surface of the AT oxide particle, while the dark and bright grey area show flowing pores. The ratio between the white and grey area results in the porosity at each horizontal location. The porosity distribution is also shown in Fig.3. The porosity around the middle is approximately 70% which is much higher than 42% measured by a mercury intrusion porosimetry, since some part of the wall might be broken during polishing.

Figures 4(A) and 4(B) show SEM images of wall cross sectional area cut in the direction along the flow channel and perpendicular to the channel. The pore structure is almost homogeneous in both directions.

2.2. Experimental procedure

Figure 5 shows a schematic illustration of the experimental setup for the diesel particulate trapping. A diesel fuel lamp was used as a soot generation source to produce almost dry soot. The conventional diesel fuel (JIS L2203 No.2) was used for experiment. The soot was introduced into the small sized DPF with surrounding air using a suction pump. The superficial velocity of the wall flow for the DPF was set up at 0.12m/s.

Figure 6 shows the experimental setup for the DPF regeneration testing. After some amount of soot was deposited on the surface of the filter wall, the DPF was regenerated by a working-gas with a 7% oxygen concentration under the condition of DPF temperature of 550°C , where the DPF temperature increases with time and then reaches the maximum of 550°C . An infrared gas-analyzer was used to measure the CO and CO_2 concentration during regeneration, as shown in Fig. 6.

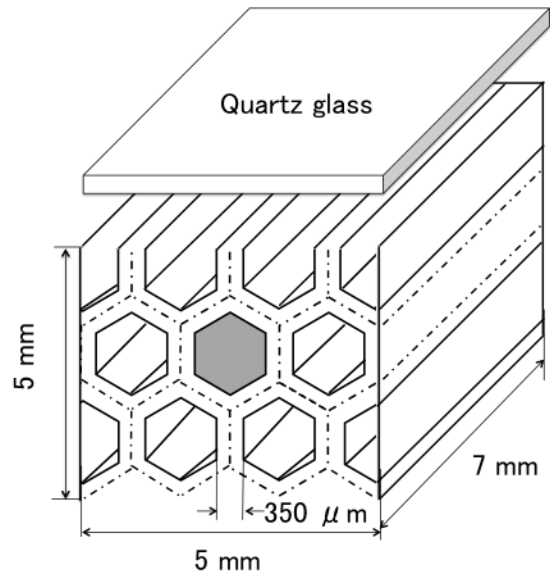


Fig. 2 Setup for microscopic visualization of diesel particulate trapping and oxidation inside a hexagonal cell DPF made of aluminum titanium oxide

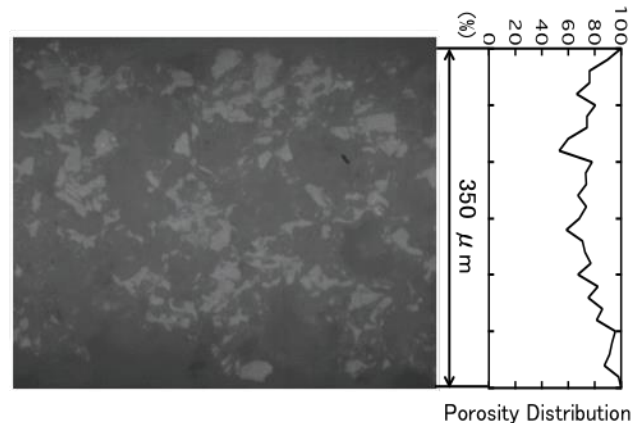


Fig. 3 The optical image of polished cross section of AT-DPF wall. The porosity distribution is also shown.

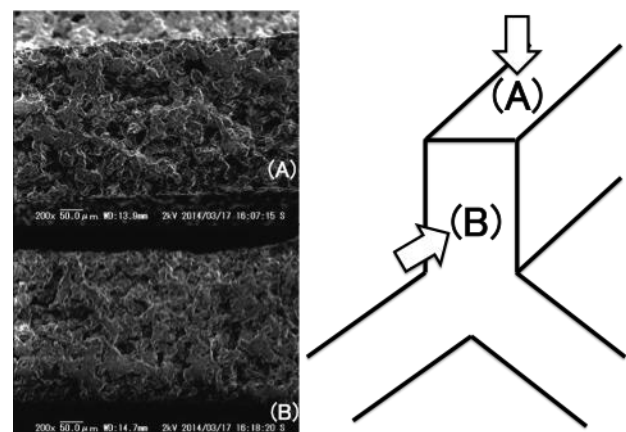


Fig. 4 The SEM images of cross section cut in the direction along the flow channel (A) and perpendicular to the channel (B)

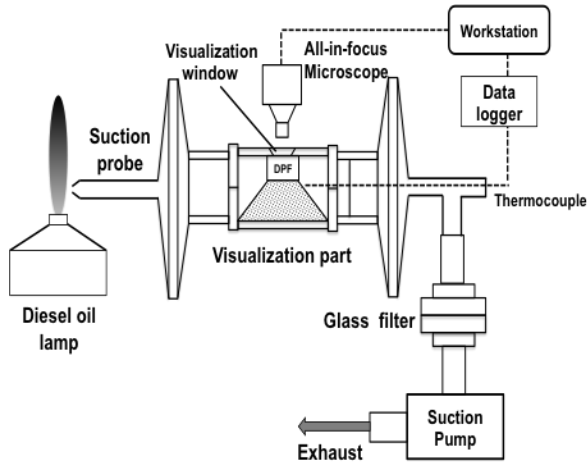


Fig. 5 Schematic illustration of the experimental setup for the diesel particulate trapping.

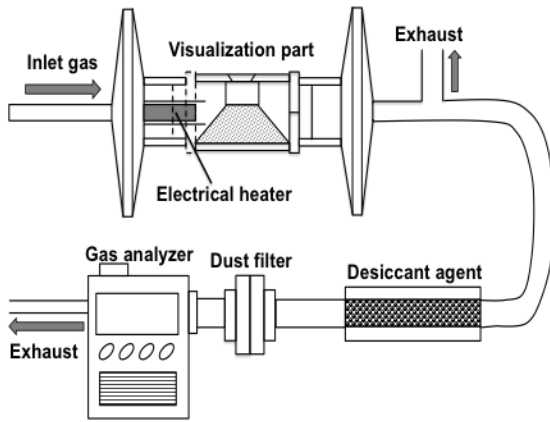


Fig. 6 The experimental setup for DPF regeneration testing.

3. Analytical model

Figure 7 shows a schematic illustration of analytical model for a hexagonal DPF. There are six inlet channels of the circumference of outlet channel. Here, a wall between the inlet and the outlet channels is defined as an inlet/outlet wall, while a wall between both inlet channels is defined as an inlet/inlet wall. The wall thickness and the length of each side of hexagonal cell are denoted by W and L , respectively. The pressures of the inlet and outlet channels are P_i and P_o , respectively.

In the hexagonal DPF, two types of flow can be considered. One is a flow passing through the inlet/outlet wall straightly, where the superficial velocity is defined by u_1 and the effective cross sectional area is $L/2$. The other is a flow which is introduced from a vertical inlet/inlet wall and turned toward the outlet channel direction parallel to the vertical wall, where the apparent superficial velocity is defined by u_2 for the flow parallel to the vertical inlet/inlet wall and the effective cross sectional area is $W/2$. The length of the bypass flow was assumed by $W' + L/2$ ($= W/\cos\theta + L/2$). Moreover, the superficial velocity for the soot layer deposited on the vertical inlet/inlet wall is defined as $u_2' = (W/L) u_2$.

On the basis of the abovementioned types of flow, it is assumed that soot introduced into the inlet channels will be deposited on both surfaces of the inlet/outlet and the inlet/inlet walls with respect to time.

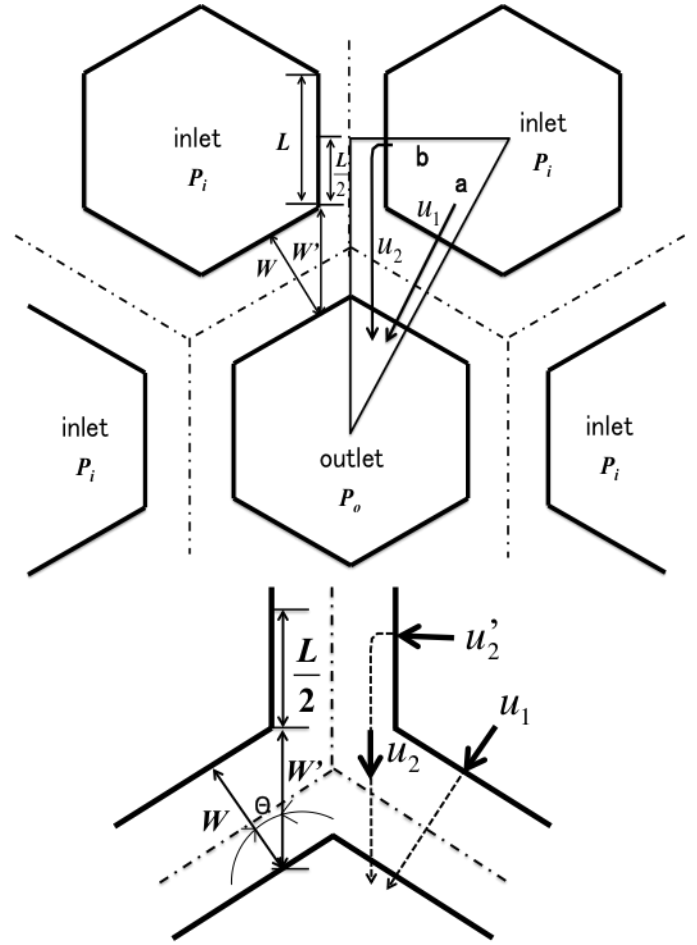


Fig. 7 Schematic Illustration of the analytical model for the hexagonal DPF.

4. Governing equations

The pressure drops for the flow through the inlet/outlet wall and the bypass flow are defined as ΔP_1 and ΔP_2 , respectively, which should be equal to pressure drop between inlet and outlet channels, $P_i - P_o$, as follows.

$$P_i - P_o = \Delta P_1 = \Delta P_2 \quad (1)$$

The pressure drop is usually expressed by Darcy's law and the Forchheimer term⁽⁸⁾⁻⁽¹²⁾ as follows.

$$\Delta P = \frac{\mu}{k} u w + \beta \rho u^2 w \quad (2)$$

Here, ΔP shows the pressure drop across the filter, μ the dynamic viscosity, k the filter wall permeability, u the superficial velocity, w the filter thickness, ρ the flowing gas density and β the Forchheimer coefficient. In this study, since the flowing gas velocity u is small, the second term becomes negligibly small compared with the first term.

The pressure drops, ΔP_1 and ΔP_2 , for the inlet/outlet wall flow and the bypass flow are expressed as follows.

$$\Delta P_1 = \frac{\mu}{k} u_1 W + \frac{\mu}{k_{soot}} u_1 x(t) \quad (3)$$

$$\Delta P_2 = \frac{\mu}{k} u_2 \left(\frac{W}{\cos \theta} + \frac{L}{2} \right) + \frac{\mu}{k_{soot}} \left(\frac{L}{W} \right) u_2 y(t) \quad (4)$$

Here, the first term in Eqs. (3) and (4) is Darcy's term for the flow through the wall, while the second term is also Darcy's term for the flow through the layer of soot, as described as $x(t)$ and $y(t)$, deposited on the wall. Since the wall structure is homogeneous in any direction as shown in Fig.3, the permeabilities, k , for both Eqs. (3) and (4) are the same.

It is assumed that the soot layer thickness of inlet/outlet and inlet/inlet walls increases in proportion to the superficial velocity with respect to time as follows.

$$x(t) = \alpha u_1 t \quad (5)$$

$$y(t) = \alpha \left(\frac{W}{L} \right) u_2 t \quad (6)$$

Here, α is a fitting parameter estimated from the experimental results for a whole DPF made of aluminium and titanium.

The total volumetric flow, which is given, is distributed into the inlet/outlet wall flow and the bypass flow as follow.

$$L u_1 + W u_2 = Q \quad (7)$$

Using the abovementioned equations, the superficial velocities, u_1 and u_2 could be solved discretely for each time step, where the time increment is set up at $\Delta t = 10$ sec.

5. Results and Discussion

5.1. Analytical results

Figure 8 shows variation of superficial velocities, u_1 and u_2 , of the inlet/outlet wall flow and the bypass flow with respect to time. At the beginning of soot deposition, the velocity of inlet/outlet wall flow, u_1 , is greater than that of bypass flow, u_2 since the flow path of the bypass flow is longer than that of the inlet/outlet wall flow. With increasing soot layer thickness, u_2 became greater than u_1 since the second term in Eq. (3) increases faster than that in Eq. (4) as shown later.

Figure 9 shows variation of flow rate for the inlet/outlet wall flow and the bypass flow with respect to time. The flow rate is evaluated from the product of the velocity and the cross sectional area. At the beginning of soot deposition, the flow rate through the inlet/outlet wall is much higher than that of the bypass flow since the velocity u_1 and the cross sectional area $L/2$ are higher than those of the bypass flow, u_2 and $W/2$. However, with increasing soot layer thickness, both second terms in Eqs. (3) and (4) become dominant. In addition, u_2 is approximately two times higher than u_1 . As a result, both flow rates become much the same 5000 seconds later.

Figure 10 shows variation thickness of the soot layer deposited on the inlet/outlet wall (dot-dashed line) and the inlet/inlet wall (dotted line) with respect to time. This is for the case of wall thickness of $300 \mu\text{m}$. Soot starts to be deposited on the inlet/outlet and inlet/inlet walls simultaneously with respect to

time. The thickness increases in proportion to the time. As time passed enough, the flow rate will be much the same as shown in Fig. 9: as a result, both increase rate of soot layer are also much the same. Consequently, only at the beginning of soot deposition, the increase rate of the soot layer on the inlet/outlet wall is greater than that of the inlet/inlet wall.

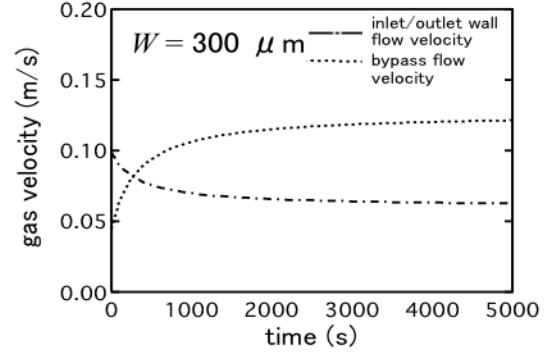


Fig. 8 Variation of inlet/outlet wall flow u_1 and bypass flow u_2 with respect to time

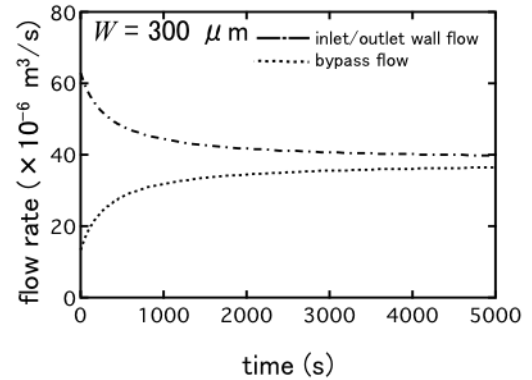


Fig. 9 Variation of flow rates for the inlet/outlet wall flow and the bypass flow with respect to time

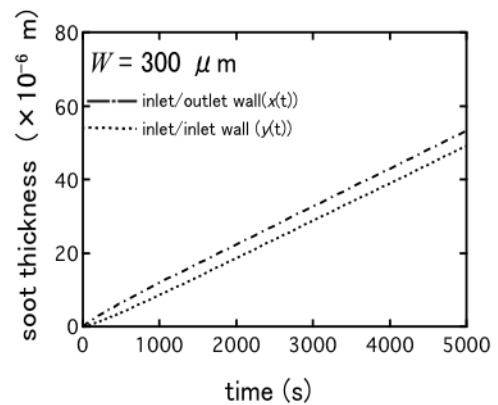


Fig. 10 Variation of thickness of soot deposited on the inlet/outlet and inlet/inlet walls with respect to time.

Figure 11 shows variation of pressure drop between the inlet and outlet channels with respect to time for the cases of wall thickness of 50, 100, 300 and $600 \mu\text{m}$. Before deposition of soot at $t = 0$, the pressure drop becomes highest in the case of the wall

thickness of 600 μm among those since the first term in Eqs. (3) and (4) is dominant. As time passed from the beginning, the second term in Eq. (3) will be dominant since the soot layer increases. In this case, with decreasing wall thickness from 600 to 50 μm , the apparent cross sectional area for the bypass flow becomes narrower, which results in smaller flow rate. As a result, thickness of soot layer on the inlet/outlet wall surface increases faster with decreasing wall thickness. For example, in the case of wall thickness of 600 μm , the soot layer thickness on the inlet/outlet wall is 1.1 times higher than that of the inlet/inlet wall at the elapsed time of 2000 seconds. On the other hand, in the case of wall thickness of 50 μm , it is 1.5 times higher than that at the same elapsed time. Consequently, the pressure drop increases quickly in the case of wall thickness of 50 μm . On the other hand, after time passed enough, the increase rate of pressure drop are much the same in any cases since the soot layer will be dominant for the pressure drop.

Figure 12 shows variation of pressure drop with respect to the wall thickness at each time step. At the time before soot deposition, the pressure drop depends strongly on the wall thickness. However, at the elapsed time around 500 seconds, the pressure drop for all case becomes much the same since the soot deposition rate on the inlet/outlet wall surface for the thin wall is higher than that for the thick wall. As a result, on further elapsed time after 1000 seconds, the pressure drop becomes lowest for the case of wall thickness of about 300 μm .

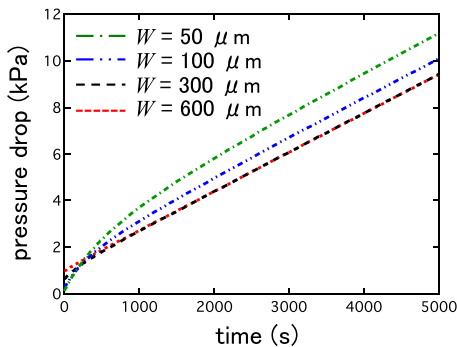


Fig. 11 Variation of pressure drop between inlet and outlet channels with respect to time during soot deposition for the cases of wall thickness of 50, 100, 300 and 600 μm

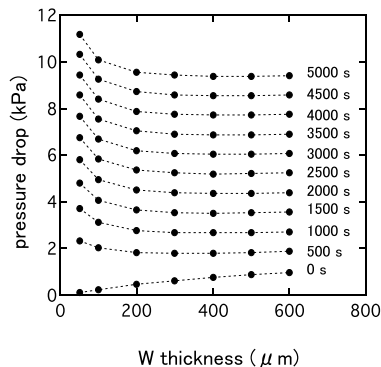


Fig. 12 Variation of pressure drop with respect to the wall thickness at each time step

Figure 13 shows variation of pressure drop through the wall and the soot layer in Eqs. (3) and (4). The total pressure drop ($P_i -$

$P_o = \Delta P_1 = \Delta P_2$) is also shown. In the case of wall thickness of 50 μm , since the second term in Eq. (3) is dominant, the pressure drop through the soot layer is very close to the total pressure drop at any elapsed time. On the other hand, since an increase rate of soot layer thickness on the inlet/inlet wall is small at the beginning, the pressure drop through bypass flow is dominant. However, as time passed, the soot layer thickness of both inlet/outlet and inlet/inlet walls become larger. As a result, the pressure drop through the soot layer becomes dominant. With increasing wall thickness, the difference of the pressure drop between the inlet/outlet wall flow and the bypass flow becomes smaller. In the case of the wall thickness of 600 μm , the soot layer on both walls will be a dominant for the total pressure drop.

5.2. Experimental results

5.2.1 Visualization of soot deposition process

Figure 14 shows photographs of surface viewed snapshots of soot deposition at each elapsed time of 25, 50, 75, 140 and 210 seconds from the beginning. The top and bottom parts show the inlet/inlet wall and the inlet/outlet wall, respectively. It is observed that the soot starts to be deposited on both surfaces of the inlet/outlet and the inlet/inlet walls simultaneously as estimated in the abovementioned analysis. As time passed, the inlet/outlet wall surface is covered faster compared with the inlet/inlet wall surface. The inlet/outlet wall surface is almost covered by soot at the elapsed time of 75 seconds, while the inlet/inlet wall surface is at the elapsed time of 210 seconds. The deposition process observed here is understood from the abovementioned analysis. As shown in Fig. 9, the flow rate through the inlet/outlet wall is, first, greater than the bypass flow rate, and then, the bypass flow rate increases as the soot layer thickness on the inlet/outlet wall increases. Depending on the thickness of soot on the inlet/outlet and inlet/inlet walls, the total flow rate is distributed into the inlet/outlet wall flow and the bypass flow. The flow distribution results in the difference of soot deposition rate as shown in Fig. 14.

5.2.2 Visualization of regeneration process

Figure 15 shows photographs of surface viewed snapshots of DPF regeneration at each elapsed time of 30, 60, 90, 120 and 150 seconds from the beginning when the soot deposition was finished. The top and bottom parts show the inlet/inlet wall and the inlet/outlet wall, respectively. The soot layer thickness on the inlet/outlet wall surface is thicker than that on the inlet/inlet wall. However, the flow rates for the inlet/outlet wall flow and the bypass flow are much the same, for example, at the elapsed time of 5000 seconds as shown in Fig. 9. As a result, the soot deposited on the inlet/inlet wall is disappeared faster than that on the inlet/outlet wall as seen at the elapsed time of 90 seconds in Fig. 15. Even after the soot on the inlet/inlet wall was disappeared, the working gas with oxygen is continuously distributed into the bypass flow. As a result, since only a part of the working gas is introduced into the remained soot layer on the inlet/outlet wall, the regeneration time becomes longer and the maximum temperature becomes lower compared with the conventional DPF, as reported in the engine bench test using the hexagonal (HEX) cells⁽⁵⁾.

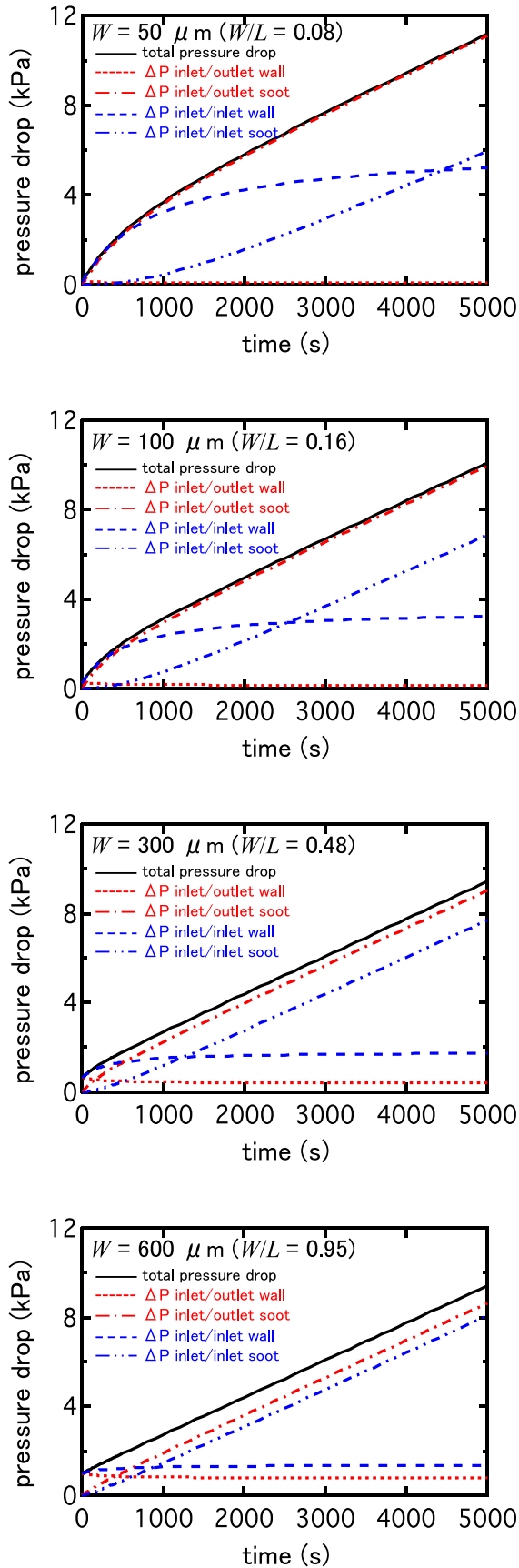


Fig. 13 Variation of pressure drop through wall and soot layer for the inlet/outlet wall flow in Eq. (3) and for the bypass flow in Eq. (4) with respect to time

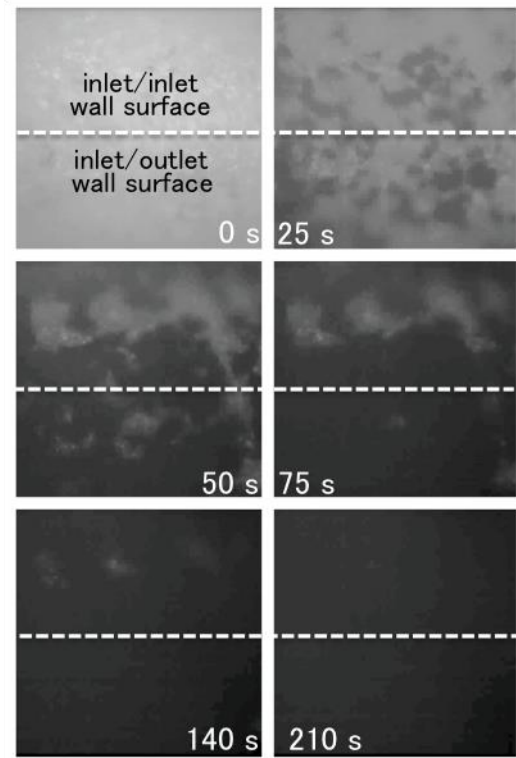


Fig. 14 Photographs of surface viewed snapshots of soot deposition on the inlet/inlet wall surface (top) and the inlet/outlet wall surface (bottom) at each elapsed time

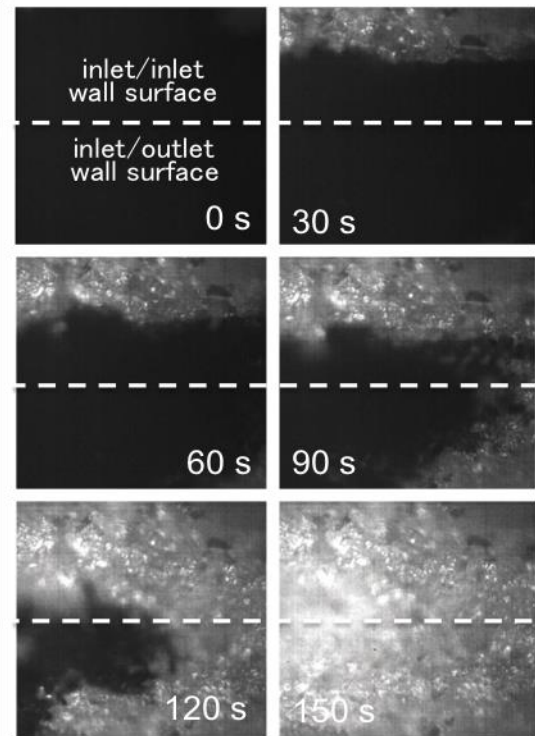


Fig. 15 Photographs of surface viewed snapshots of DPF regeneration on the inlet/inlet wall surface (top) and the inlet/outlet wall surface (bottom) at each elapsed time

6. Conclusions

The phenomena of soot deposition and oxidation in an aluminum titanium oxide DPF with hexagonal cells were investigated through visualization experiment and a simple analysis based on Darcy's law through wall and soot layer. The results obtained here as follows.

In the trapping process, the working gas is distributed into the inlet/outlet wall flow and the bypass flow (inlet/inlet flow), depending on the pressure drop through the soot layer on the inlet/outlet wall. With increasing soot layer thickness on the inlet/outlet wall, the flow rate of the bypass flow increases. As a result, even on the inlet/inlet wall surface, soot is trapped.

In the regeneration process, even after the soot on the inlet/inlet wall was completely oxidized, the working gas is supplied continuously. As a result, the regeneration time for the hexagonal cell DPF becomes longer and the maximum temperature becomes lower than those for the conventional DPF.

Acknowledgment

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