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Soot Filtration Recent Simulation Analysis in Diesel Particulate Filter (DPF).

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Abstract

Diesel Particulate Filter (DPF) is one of the prominent after-treatment devices invented to reduce particulate matter (PM) emission from diesel engines. With the latest emission standard becoming more stringent in order to maintain the environment sustainability, the study on soot filtration phenomenon occurring inside the DPF is crucial. In addition, the advancement of computer technology contributes to better understanding by simulating the soot filtration process. The flow pattern and velocity of exhaust gas are analyzed in order to examine the flow path and thus the area for soot deposition inside the channel. After a certain soot deposition time, a pressure drop is created and different patterns are observed during initial stage, soot loading and regeneration steps. The soot cake formation also affects the efficiency and pressure drop of the DPF. Hence, these understanding can be adopted for advanced research in optimizing the DPF design and efficiency.

Keywords: Diesel Particulate Filter (DPF), soot filtration, pressure drop, soot cake, regeneration.

Nomenclature

d_p	soot diameter (m)
U_z	axial velocity (m/s)

1. Introduction

Nowadays, research and development (R&D) activities for diesel engines are becoming more extensive and participated by many parties such as automobile makers and scientists. The development of highly efficient, direct injection (DI) diesel engines is an example to enhance diesel engine technology [1]. Apart from their well-known for high power output, diesel engines are also economical on fuel usage. Moreover, carbon dioxide (CO_2) emission from diesel engines is relatively low compared to gasoline engines. Therefore, diesel engines also play an important role in reducing global warming problem [2].

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Table 1
EU emission standard for heavy-duty diesel engines, g/kWh (smoke in m^{-1})

Tier	Date	Test	CO	HC	NO_x	PM	Smoke
Euro I	1992 < 85 kW	ECE R-49	4.5	1.1	8.0	0.612	
	1992 > 85 kW		4.5	1.1	8.0	0.36	
Euro II	1996.10		4.0	1.1	7.0	0.25	
	1998.10		4.0	1.1	7.0	0.15	
Euro III	1999.10 EEVs Only	ESC & ELR	1.5	0.25	2.0	0.02	0.15
	2000.10	ESC & ELR	2.1	0.66	5.0	0.10 0.13a	0.8
Euro IV	2005.10		1.5	0.46	3.5	0.02	0.5
Euro V	2008.10		1.5	0.46	2.0	0.02	0.5
Euro IV	2013.01		1.5	0.13	0.4	0.01	
a – for engine with swept volume of less than 0.75 dm^3 per cylinder and a rated power speed of more than 3000 min^{-1}							

However, the main problem encountered by diesel engines is the significant amount of soot particles emitted to the environment [2]. The excessive amount of soot particles in the surrounding can contribute to respiratory and immune system problems. Moreover, several recent studies found that soot particles are potential carcinogen in human being [3]. This is because the nano-sized soot particles can penetrate into human lungs during breathing [4]. Thus, stringent emission law is enforced from time to time to sustain the environment (see Table 1).

For this reason, the after-treatment devices such as Diesel Oxidation Catalyst (DOC), Diesel Particulate Filter (DPF) and Selective Catalyst Reduction (SCR), are invented to control the emission from diesel engines. This paper will focus more on Diesel Particulate Filter (DPF) since the device is able to filter out more than 90% of soot particles [4, 5]. The invention of DPF started in the last 20 years with various types of filter media and geometric configuration [2]. The compact arrangement without neglecting the filtration efficiency and back pressure drop, demonstrated by the wall-flow monolith honeycomb design, makes this type of DPF the best [1]. The arrangement of the inlet and outlet channels can be viewed in Fig. 1. Usually, the cross section of the channel is square and the whole arrangement is like checkerboard with alternating blocked ends [2, 6]. Typical porous media used in DPF are either porous ceramic or sintered metal due to their high temperature resistance (~1200°C) [7] to withstand the temperature of exhaust gas [8].

The working principle of DPF can be explained in three steps [8]. First is the filtration process by depositing soot particles from exhaust gas when the gas passes through the porous wall. The collected soot particles can increase the back pressure since the soot plugged at the porous wall will block the flow of the exhaust gas. This phenomenon will result in increased fuel consumption and reduced engine power output [4, 5]. The second step is the regeneration process to oxidize the collected soot. The regeneration process will take place if the temperature inside the DPF exceeds 550°C [1, 8]. However, the exhaust gas temperature is just 100-200°C under normal driving condition [1, 8]. Therefore, the regeneration process can be achieved either actively using electric heating or passively using fuel-borne catalyst. The last process is the rearrangement of the ashes collected as to maintain the next filtration process and efficiency.

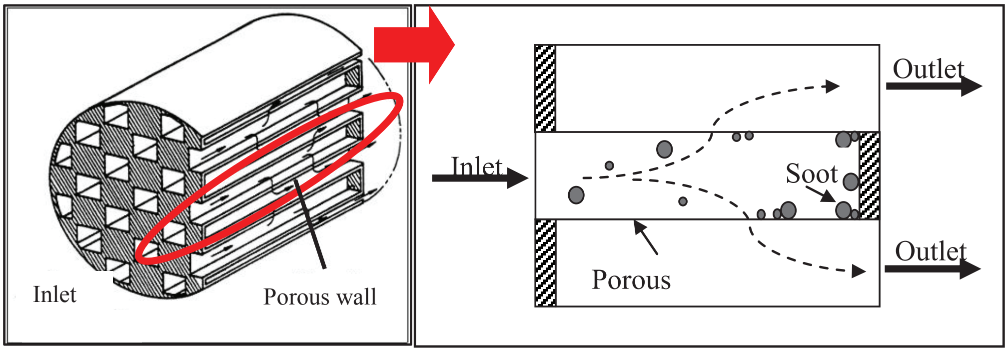

Fig. 1. The example of wall-flow monolith honeycomb design (left). The detail view inside the wall-flow monolith honeycomb design shows the flow of the exhaust gas from the inlet towards the outlet and soot collection inside the channel (right).

Better understanding on DPF is very essential to optimize its efficiency and design. Similarly, the reliability and durability of the DPF can be predicted by having detailed research from various approaches. However, the simulation approach is more recommended than experimental approach since the typical inlet size is about 2 mm and the thickness of the wall is just 0.2 mm [4]. Besides, the simulation approach can achieve higher level of analysis details such as exhaust gas flow pattern inside the DPF. Moreover, the cost and time consumption by having repeated experiment can be significantly reduced by adopting the simulation approach.

2. Filtration process of soot particle

Filtration stage in DPF is a very simple and basic step. Combustion of fuel inside the combustion chamber will produce exhaust gas consisting of several elements such as unburned HC and soot particles. The upward movement of piston during exhaust stroke will channel out this exhaust gas from combustion chamber towards exhaust piping system. Before the hazardous gas is released to the environment, the gas needs to flow through the porous wall inside the DPF. Hence, the filtration takes place to separate the soot particles from the flue gas.

2.1. The exhaust gas flow and velocity

In order to understand the phenomena occurring inside the DPF, the flow pattern of exhaust gas through the DPF is one of the main focus items. The observation starts when the exhaust gas enters the inlet channels of DPF, passes through the porous wall and then leaves the outlet channels. Bensaid et al. [3] proposed the 2-D idea to observe the development of velocity profile at different axial location of inlet and outlet channels inside the DPF.

Fig. 2 shows the axial velocity of the exhaust gas containing soot particles at different axial distance inside the DPF. The x-axis represents two parameters, which are the axial velocity, U_z (m/s) and also the horizontal distance (mm) with inlet entrance as reference. Whereas, the y-axis represents the vertical distance (m) or the height of the channel by using the centre of the channel as starting point. The size of soot particles, d_p is equal to 2 µm on the left and 100 nm on the right.

Several observations can be made from the Fig 2. The axial velocity profile starts to develop at an early stage, then attains maximum velocity around midway and finally drops when reaching the end of the inlet channel. In contrast, the axial velocity gradually increases and reaches the maximum at the end of the outlet channel. This shows that the exhaust gas passes through the porous wall mainly around the middle of the channel (88 mm) towards the end. Thus, the expected outcome is that most of the soot particles are filtered and trapped from this area onwards.

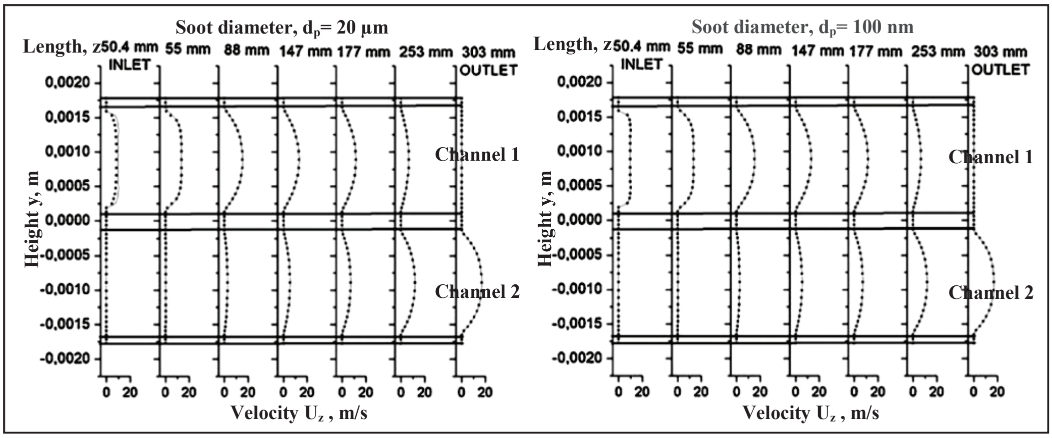

Fig. 2. Axial velocity profiles at different axial coordinate for gas (solid line) and soot particles (dots) inside the inlet and outlet channel for d_p = 20µm and d_p = 100nm [3].

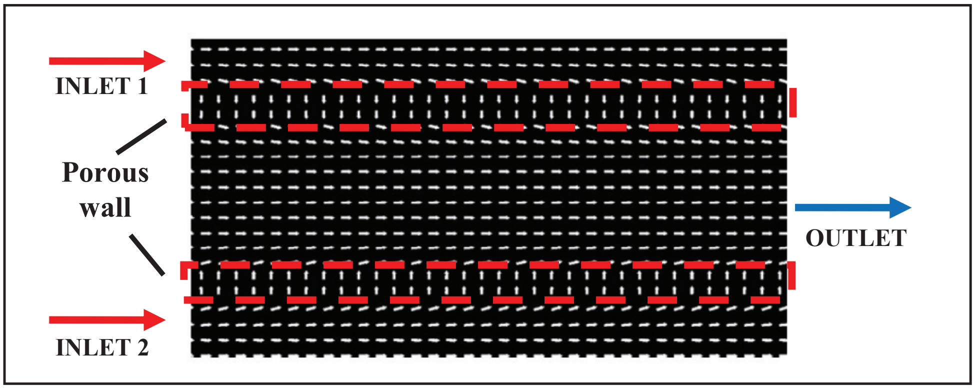

Fig. 3. Enlarged view of the exhaust gas flow at the porous wall [2].

Next, the critical area to be observed in exhaust gas flow analysis is the porous wall. Hayashi et al. [2] observed the overall flow of exhaust gas inside DPF in device scale and exposed the detailed view inside the channel represented by arrows to indicate the direction of the exhaust gas flow, regardless of the magnitude of the velocity (see Fig. 3). The horizontal arrows represent the flow inside the channels while vertical arrows indicate the porous wall. This finding proves that the exhaust gas passes through the porous wall perpendicularly to the channels [2].

Analysis of exhaust gas flow has been further investigated by Yamamoto et al. [4]. He studied exhaust gas flow inside a porous wall, where the exhaust gas passed through from the inlet to outlet channels. In order to obtain the inner structure of the porous wall, 3D X-Ray CT technique was applied since this method is non-destructive and able to visualize the real inner structure. Later, the images caught by this technique were converted into digitalized data for simulation purpose. In Fig. 4, the left side shows the exhaust gas flow from the inlet channel through the porous wall and finally flows out to the outlet channel. This findings become another evidence to show that the exhaust gas flow is perpendicular through the porous wall [2, 4].

In addition to the analysis on flow pattern, the study also focuses on the normalized velocity of exhaust gas passing through the porous wall. The normalized velocity is defined as local velocity divided by the average velocity for the porous wall cross section. Bensaid et al. [3] identified the normalized velocity of exhaust gas at the end of the channel by using particulate size of 100 nm. This is because that area has the highest soot deposition rate and the size of 100 nm is appropriate to represent the particulate size from common-rail direct injection diesel engines [3].

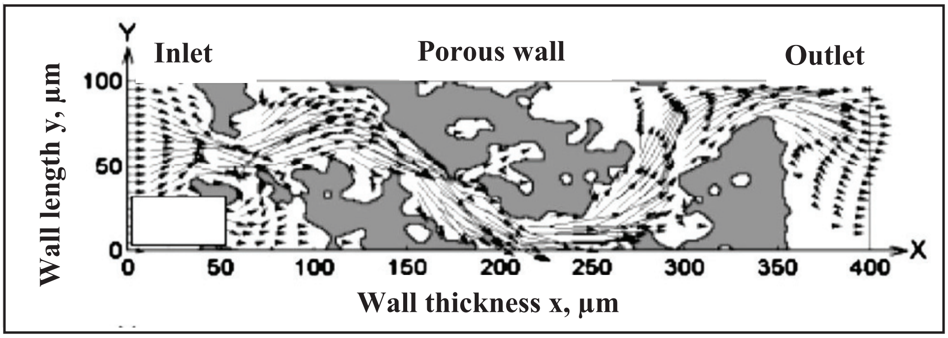

Fig. 4. The profiles of exhaust gas flow across the porous wall under steady state [4].

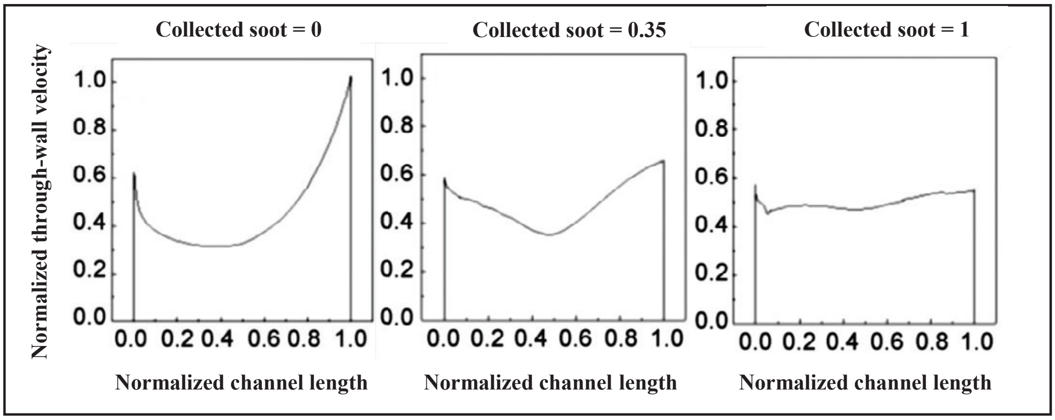

Fig. 5. The normalized velocity of the exhaust gas through the wall relative to the collected soot [3].

By referring to Fig.5, the initial normalized velocity, which represents the exhaust gas velocity before entering the porous wall, is almost constant along the process. However, the normalized velocity at the centre and towards the end of the porous wall changes and finally become stable. This occurs because, after the porous wall becomes dense with the deposited soot, the subsequent particulates will be filtered out by cake filtration. The formation of soot cake layer with constant thickness ensures a stable normalized velocity through the porous wall.

2.2. Soot cake

Continuous soot loading and deposition processes will result in a layer formed on the wall surface, called a soot cake. This soot cake increases the filtration efficiency, and the pressure drop increases linearly with time along with the thickness of soot cake [3]. Thus, the analysis on the soot cake build up with respect to time and location is discussed here.

Benjamin et al. [6] investigated the soot cake thickness with respect to the time of filtration process. The thickness of soot cake increases and then declines drastically before continuing to build up again afterwards (see Fig. 6a). This shows that the accumulation of soot after a certain period builds a soot cake on the wall and the regeneration process removes it to restore the filtration capability and avoid clogging of DPF. In fact, Bensaid et al. [11] discovered the soot cake thickness by referring to the normalized channel length. At the beginning of soot loading, the soot cake is formed at the end of the channel (see Fig. 6b). This phenomenon is in agreement with a previous research finding [3] that the soot is deposited at the end of the channel (see Fig. 2). Later, the growth of soot cake thickness with time becomes constant and stable along the normalized channel.

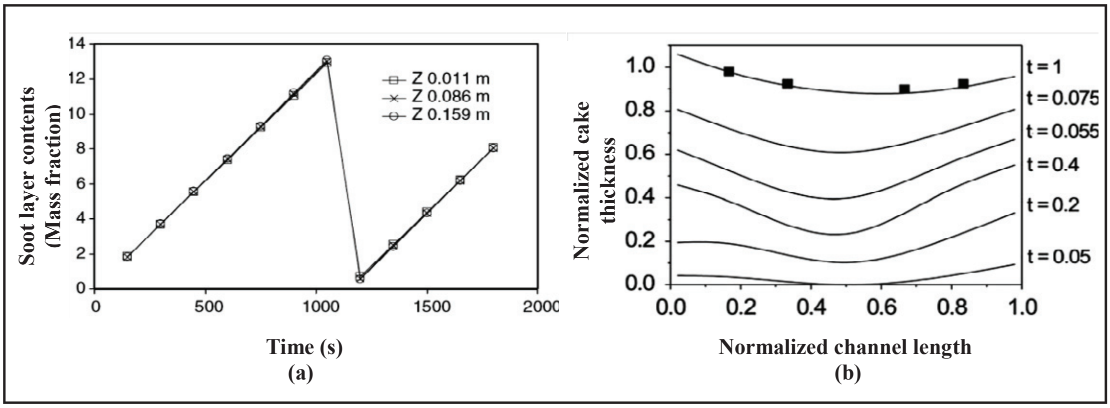

Fig. 6. The observation on soot cake thickness growth inside the DPF with respect to (a) time [6] and (b) location [11].

3. Conclusion

In this paper, the analysis on a DPF using simulation approach specifically on soot filtration has been reviewed. The paper discusses about the flow pattern and velocity, size of soot particles, pressure drop and also soot cake growth. The summary of the review are presented as follows;

1) The area starting from the middle towards the end of the channel is the area where most soot particles are deposited based on the axial velocity of the exhaust gas. Inside the porous wall, the flow is normalized and reaches constant velocity after soot cake formation.

2) The soot cake increases the filtration efficiency and also the pressure drop. Regeneration process removes the soot cake thus avoiding DPF from clogging. The growth of soot cake thickness starts at the end of the channel and increases constantly along the channel.

Further author’s research can be enhanced by the knowledge and facts from these conclusions. The flow of exhaust gas inside the porous wall is normal to the wall, thus can be assumed as one dimension and simplified for simulation purpose. Moreover, the deposited soot starts from the middle of the channels and the soot layer growth begin at the end of the channels. Thus, for further analysis especially during regeneration process, the most focusing area is at the end of the channel because more soot is collected.

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