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A Simulation Study on DPF with Inhomogeneous Wall Structure Based on Microcosmic Channel Model

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ABSTRACT

A two-dimensional gas-particle two-phase model has been developed based on Eulerian-Eulerian and Eulerian-Lagrangian approach. In this paper, the performance of the Diesel Particulate Filter (DPF) with a thin dense layer on the substrate wall of inlet channel is investigated by coupling microcosmic channel model with filtration model. The velocity field and filtration efficiency of the DPF with thin dense layer was studied and compared with that of the DPF without thin dense layer considering different space velocities, layer permeabilities and particle sizes. Besides, the dynamic of particle deposition inside the porous media of the DPF with layer was simulated by coupling the transient deep-bed filtration model with the DPF microcosmic channel model. The deposition mass distributions inside porous wall of particles with three different sizes were discussed. Results show that the existence of the thin dense layer can bring a much more uniform through-wall velocity along the inlet channel. The presence of the thin dense layer can raise the filtration efficiency of the DPF obviously, especially for particles with medium size. Meanwhile, affected by the existence of the thin dense layer, most particles are collected by the layer and the amount of particles penetrating into the porous wall decreases significantly. The penetration depth into the porous wall of 100 nm particles is much deeper than that of 10 nm and 1000 nm particles.

Keywords: Diesel Particulate Filter, inhomogeneous wall structure, gas-solid two-phase flow, velocity field, particle deposition distribution

1. INTRODUCTION

Due to different methods of combustion, diesel engines have advantages such as high thermal efficiency, strong power, low fuel consumption and excellent durability comparing with gasoline engines [1]. At the same time, non-premixed combustion makes the diesel particulate emissions significantly higher than that of gasoline engines, which causes PM the main pollutant emitted from diesel engines. A large amount of carcinogens are adsorbed on the surface of the particulate matter, which will cause serious chronic damage to human health [2]. With emission regulations become more and more strict in many countries, Diesel Particulate Filter has been widely used for its excellent performance.

In order to achieve superior performance of filtration and regeneration, scholars have carried out extensive and long-term work through experimental and numerical simulation [3-6]. In the early stage, most of the researches on DPF were mainly macroscopic. With the emission regulations have been increasingly stricted, DPF needs to be continuously optimized, then the research have been focused on the exploration of microscopic process [7]. At present, the research of DPF dynamic filtration process has been a hot topic in particle capture. From 1-D to 3-D model [8], more and

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more filtration models have been proposed, so as to realize accurate simulation of microscopic dynamic deposition process in DPF.

DPF filtration efficiency and pressure drop are trade-off [9], pursuing high filtration efficiency blindly will lead to the increase of DPF pressure drop. Therefore, exploring how to make the DPF higher filtration efficiency and lower pressure drop has been a top issue for optimizing DPF performance. In the last ten years, unconventional wall structure has been gradually recognized to optimize the relationship of filtration efficiency and pressure drop [10-12]. This structure adds a thin dense layer which can adopts catalyst coating to improve regeneration performance of DPF at the same time [13], while the other part still display high porosity. Thomas Bollerhoff et al. [14] developed a new filtration model to optimize the design and operation of the DPF microstructure. The impact of the thin dense layer on filtration efficiency, pressure drop and passive regeneration was investigated. Flow distribution, pressure drop, heat/mass transfer and soot oxidation in the filter were took into account in the model. The complex interaction between catalysis and soot oxidation can be simulated in great detail. J. Adler et al. [15] validated that a thin fine porous filter membrane could increase filtration efficiency in the initial period and the pressure drop caused by membrane would be outbalanced after soot loading through experiment and simulation. Additionally, comparing the influence of pore size and porosity on filtration efficiency and back pressure behavior. Kazuki Nakamura et al. [16] also researched filtration layer performance both theoretically and experimentally. Soot deposition simulation was conducted to search the optimal situation that layer thickness distribution along the DPF length matches to filtration velocity distribution. The performances of the SiC-DPF with the filtration layer experimentally confirmed considering transient pressure drop， initial soot filtration efficiency, and the repeatability of pressure drop after several times of regenerations. Yukio Mizuno et al. [17] developed a dual layer wall structure of diesel particulate filter by forming a surface layer with small pores and high porosity, pressure drop, filtration efficiency and robustness of DPF were researched by experiment. Meanwhile the layer located on the gas inlet side and outlet side were compared to investigate the influence of layer location. However, there are few simulation works on layer DPF, since it has been valued for its important guiding role in optimization of DPF performance and uneven catalyst coating in recent years. In order to optimize the DPF performance such as filtration and regeneration, the current investigations of DPF with layer are still far from enough.

In this paper, in order to investigate the characteristic of inhomogeneous wall structure DPF, Eulerian-Eulerian and Eulerian-Lagrangian method are used to deal with particle deposition distribution in porous media and particle motion in fluid flows respectively. Brownian motion, Saffman lift, Drag force and Gravity are all considered. The flow field, pressure drop characteristics and particle deposition distributions of the DPF with layer covering are investigated using numerical simulation approach. Various layer permeabilities, space velocities and particle sizes are considered in this study. Based on the transient deep-bed filtration model coupled DPF microcosmic channel model built in the paper, the impact of the thin dense layer on DPF performance is studied and compared with the performance of DPF with no layer covering.

2. MODEL DESCRIPTION

In order to investigate the impact of the thin dense layer on the velocity field of the DPF, a two-dimensional wall-flow DPF microcosmic channel model was built. The structural parameters of the DPF are shown in Table 1. Three kinds of layers with different layer permeabilities were selected in this study. The layer properties are given in Table 2.

Table 1. DPF parameters.

Content	Specifications
Cell Type	Square Cell
Dimensions	Φ 110 mm × L 160 mm
Wall Thickness	0.39 mm
Channel Width	1.397 mm
Porosity	0.4
Permeability	1×10^{-12} m^2

Table 2. Layer properties.

Content	Specifications
Layer Thickness	0.039 mm
Mean Pore Size	4 μm
Permeability of Type A	5×10^{-13} m^2
Permeability of Type B	1×10^{-13} m^2
Permeability of Type C	5×10^{-14} m^2

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Figure 1 shows the computational domain of the DPF model.

Figure 2 is mesh models of the DPF. The CFD meshes of the DPF model were constructed with totaling 752000 quads. The gird size is uniform and as fine as 0.02mm.

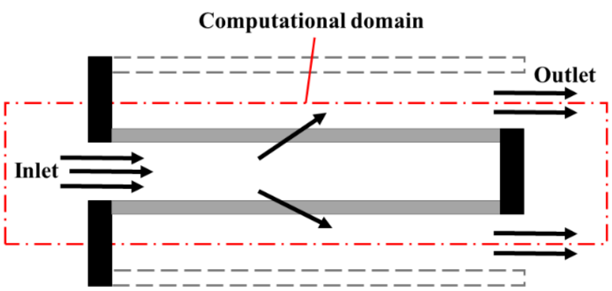

Figure 1. Computational domain.

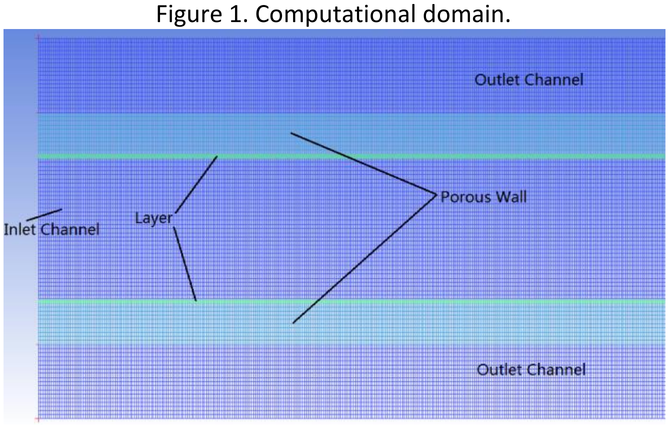

Figure 2. Grid diagram of DPF close to inlet.

In order to have a better understanding of the deep-bed filtration process and obtain the particle deposition distributions inside the porous wall. A transient deep-bed filtration model has been established based on the classical “unit collector” filtration theory and coupled with the two-dimensional DPF microcosmic channel model. Konstandopoulos et al. first proposed the well-known “unit collector” model and this model can achieve a good estimate of the collection efficiency evolution with soot loading of DPF[18]. In this model, the filter wall was divided into several slabs, whose filtration efficiency was calculated by tracking the amount of the particulate mass accumulated in each slab. This method also used in our model and the update of the porous media properties (“unit collector” size, porosity, permeability etc.) is performed by tracking the mass of particles collected in each slab.

3. MODEL VALIDATION

In order to validate the model, the simulation predicted soot mass deposition rate was compared with that of the literature [19]. The DPF structural parameters and boundary conditions used in the simulation are imported from the literature with an inlet velocity of 3 m/s and filter permeability of $5 \times 10^{-13}\ m^2$. Figure 3 shows the comparison of the soot mass deposition rate profiles at the wall surface along the axial coordinate of 200 nm particles between the simulation and the literature. The differences between the results are mainly due to the effects of the inlet and outlet. In the literature, there is an upstream region before the inlet of the filter which allows a flat velocity profile, and similarly, after the filter, there is a downstream region which allows the flow to fully develop, while in this study, the effects of the inlet and outlet on velocity fields are not considered.

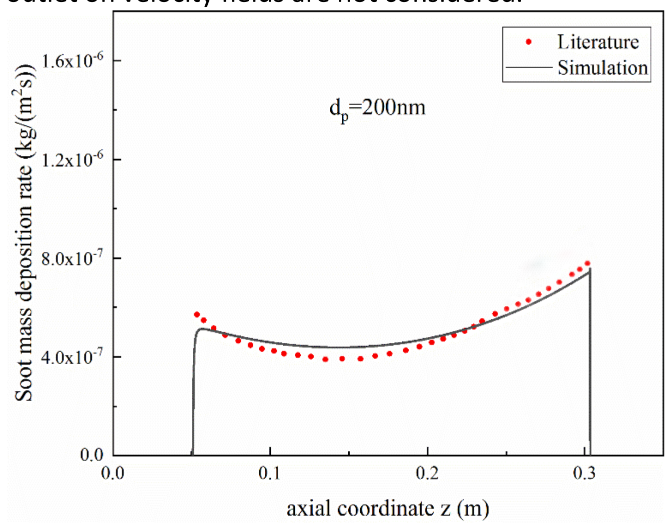

Figure 3. Soot mass deposition rate at the wall surface along the axial coordinate.

4. RESULTS AND DISCUSSION

4.1 Layer Impact on Velocity Field

The velocity field inside DPF channels has direct impact on the motion of particles, especially the through-wall velocity which has a close relationship with the filter filtration efficiency and particle deposition distributions on the wall surface along the inlet channel. Therefore, in order to investigate the effect of layers on velocity field inside DPF channels, simulations have been performed under different space velocities (SV, the ratio between inlet velocity and DPF trap length). The inlet gas flow temperature is $523.16\ K$, the density of gas is $0.615\ kg/m^3$, the dynamic viscosity of gas is $2.97 \times 10^{-5}\ kg/(m \cdot s)$ and the density of soot particle is $2000\ kg/m^3$.

Figure 4 shows the through-wall velocity field inside DPF channels with the space velocity of $30\ s^{-1}$, $100\ s^{-1}$ and $200\ s^{-1}$. For the through-wall velocity, a “U” shape distribution can be observed

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along the inlet channel with relatively high velocity at the inlet and the rear-part of the inlet channel. Besides, compared with the DPF without layer covered, obvious differences on the velocity field can be observed for the DPF layer covered. On the effect of the layer, the linear relation between the velocity and distance along the DPF channel improves and the through-wall velocity distribution along the inlet channel becomes more uniform. The lower the permeability of the layer, the more uniform the through-wall velocity can be observed. It is obvious that as the space velocity increases, the linear relations between the axial velocity in inlet and outlet channel get worse and the uniformity of the through-wall velocity weakens. The through-wall velocity at the fore-part of the inlet channel decreases while the through-wall velocity at the rear-part of the inlet channel rises. Meanwhile, the impact of the layer on DPF velocity field becomes more and more obvious with the increase of the space velocity. The presence of the layer can suppress the changes of the velocity field inside DPF channels when the space velocity rises. Besides, the lower the permeability of the layer, the stronger the suppression effect on the change of the DPF velocity field.

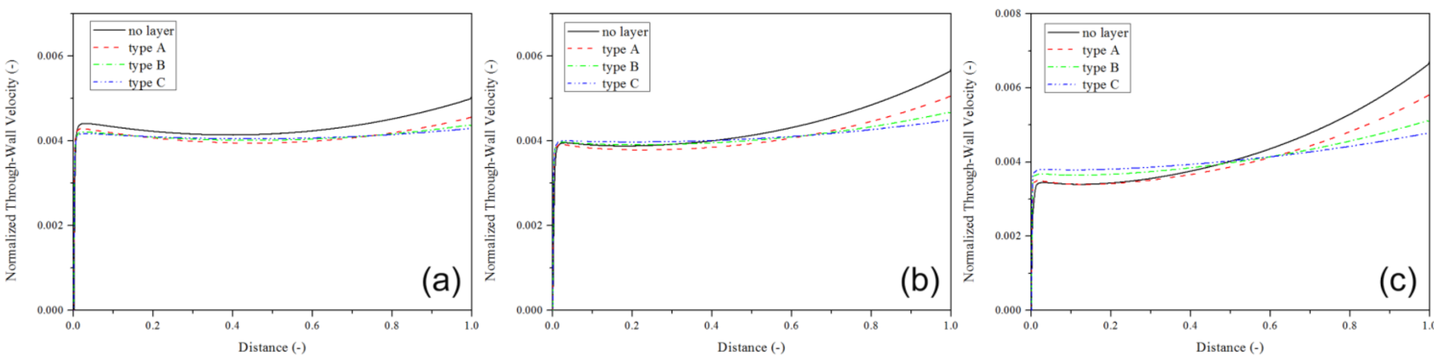

Figure 4. Through-wall velocity profiles under different space velocity, (a) SV =30 s-1, (b) SV=100 s-1, (c) SV=200 s-1.

Figure 5 shows the pressure drop of the DPF under various space velocities. It can be observed that with the increase of space velocity, the pressure drop of DPF climbs. There is a good linear relation between the pressure drop and the space velocity. The pressure drop of the DPF with layer covering is higher than that of the DPF with homogenous wall structure. As the permeability of the layer decreases, the pressure drop of DPF and its slope with the space velocity increase.

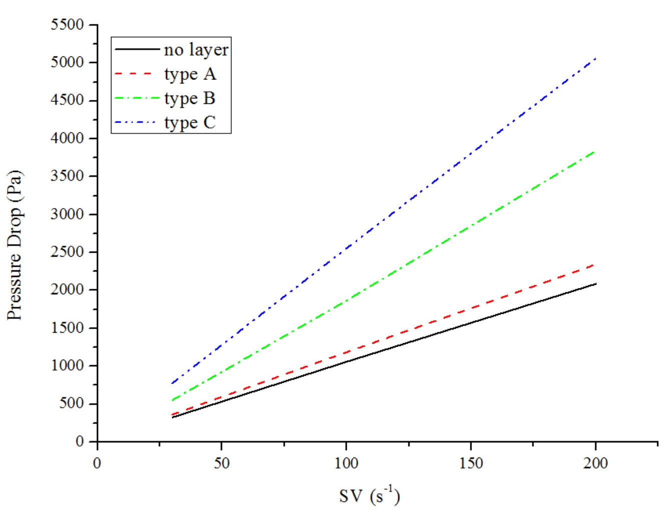

Figure 5. Pressure drops of homogeneous and heterogeneous wall structure DPFs.

4.2 Layer Impact on Filtration Efficiency

Based on the “unit collector” theory, the filtration efficiencies of DPF for 10nm, 100nm and 1000nm particles are calculated. Figure 6 shows the DPF filtration efficiency with the space velocity of $200\ s^{-1}$. As it is shown in the figure, the filtration efficiencies of DPF for 10nm and 1000nm particles are much higher than that for 100nm particles. This phenomenon can be explained using the collection efficiency of collectors. For 10nm particles, the Brownian diffusion mechanism plays a crucial role, the collection efficiency of the Brownian diffusion for 10nm particles is very high, while for 1000nm particles, the deposition of particles on collectors is dominated by the interception mechanism which has extremely high efficiency for 1000nm particles. However, for 100nm particles, with the decrease of the particle size, the interception collection efficiency of collectors drops while the Brownian diffusion collection efficiency for 100nm particles rises but is still much lower than that of 10nm particles, which results in a relatively lower filtration efficiency of DPF for 100nm particles. Besides, an obvious drop of the filtration efficiency can

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be observed for 10nm and 100nm particles at the rear-part of the DPF channel, which is mainly due to the high through-wall velocity at this area shown in Figure 8. The increase of the through-wall velocity can lead to a decrease of the Brownian diffusion collection efficiency of the collector.

Meanwhile, it can be observed in Figure 8 that the presence of the layer can raise the DPF filtration efficiency for 10nm, 100nm and 1000nm particles compared with the filtration efficiency of DPF without layer, especially for 100nm particles. Besides, with the decrease of the layer permeability, the filtration efficiency at the fore-part of the inlet channel decreases slightly while the filtration efficiency at the rear-part of the channel rises, which result in a more uniform distribution of DPF filtration efficiency along the DPF channel.

By comparing the through-wall velocity distributions in Figure 4 with the DPF filtration efficiency distributions in Figure 6, it can be concluded that the area where the through-wall velocity rises obviously is the area where the DPF filtration efficiency drops significantly. This phenomenon especially for the particles of which the deposition efficiency on collectors is affected greatly by the Brownian diffusion.

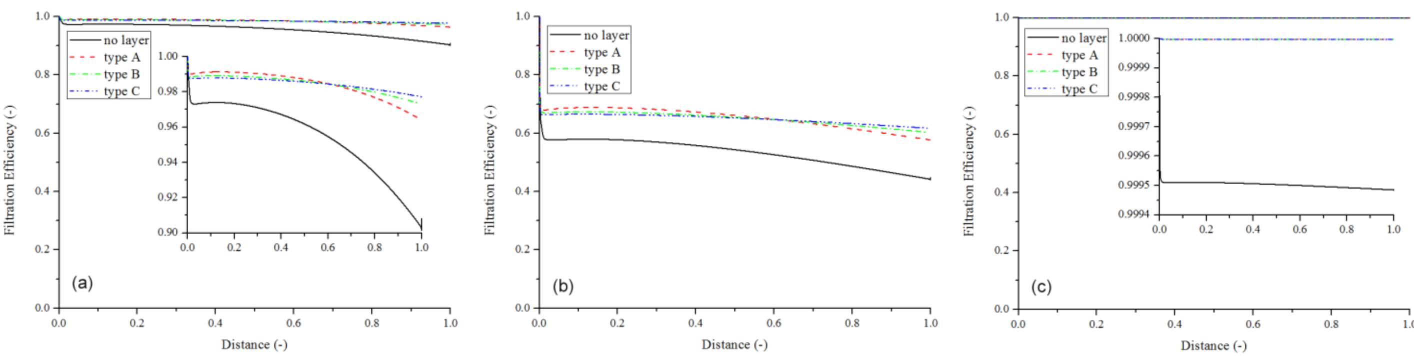

Figure 6. Filtration efficiency for different particle sizes when the space velocity is 200 s-1, (a) dp=10nm, (b) dp=100nm, (c) dp=1000nm.

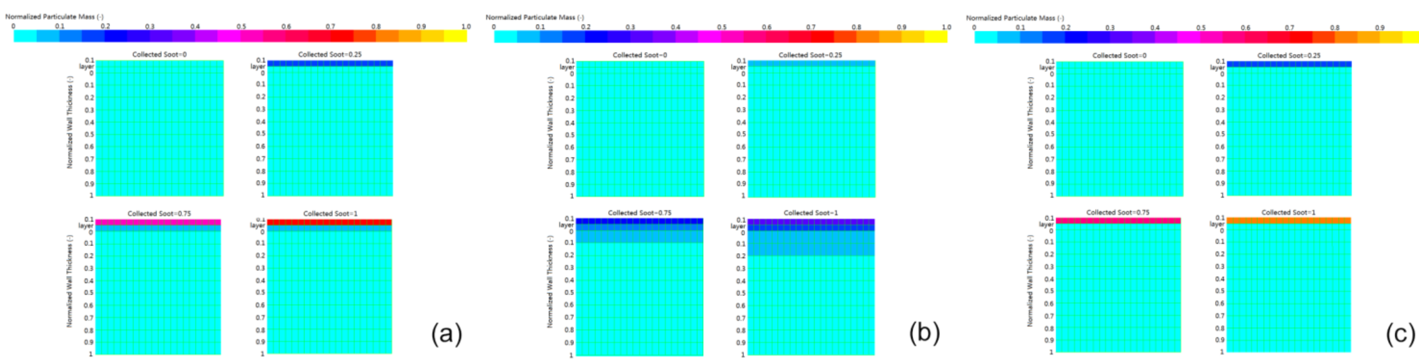

Figure 7. Mass deposition distributions of particles with different particle sizes inside porous media when the space velocity is 30 s-1, (a) dp=10nm, (b) dp=100nm, (c) dp=1000nm.

4.3 Layer Impact on Particle Deposition Distribution Characteristics in DPF

Using the transient deep-bed filtration model, the particle mass deposition distributions inside porous wall of DPF are depicted. The simulations were performed under the space velocity of $30\,s^{-1}$. The Type B (the initial layer porosity of 0.35 and the initial layer permeability of $1 \times 10^{-13}\,m^2$) was selected as the representative of the layer.

Figure 7 shows the mass deposition distributions of 10 nm, 100 nm and 1000 nm particles inside porous media of DPF with layer of Type B. The mass of the collected soot in the porous wall in process is normalized by the mass of the collected soot at the end of the simulation. In each subfigure, four moments in the soot particle deposition process are selected, that is when the collected soot is 0 (the initial moment of the simulation), 0.25, 0.75 and 1 (the last moment of the simulation) respectively. It can be seen from the Figure 7 that for 10 nm and 1000 nm particles, almost

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all the particles depositing in the porous media are collected in the layer. The mass of 10 and 1000 nm particles penetrating into the porous wall can be ignored. However, for 100 nm particles, the depth of particle mass penetrating into the porous media is much deeper than that of 10 and 1000 nm particles, and the particle mass depositing in the porous wall increases while the particle mass collected in the layer decreases. The results above are mainly due to the differences on collection efficiency of collectors for particles with various sizes. The lower collection efficiency for 100 nm particles results in the decrease of particle mass collected in the layer and the extension of the depth of particle deposition in porous media.

CONCLUSION

In this study, the impact of the thin dense layer on DPF velocity field, filtration efficiency and particle deposition distribution characteristics are investigated using numerical simulation method.

The through-wall velocity of DPF with a thin dense layer covering is more uniform than that of the DPF without layer. When the space velocity is raised, the presence of the layer can suppress the non-uniform distribution of the through-wall velocity.

The presence of the thin dense layer can raise the filtration efficiency of the DPF obviously, especially for particles with medium size. With the increase of the permeability of the layer, the uniformity of the filtration efficiency along the inlet channel is improved while the pressure of the DPF climbs as well.

As for the deep-bed filtration phase of the DPF, most particles are collected in the layer, especially for 10 nm and 1000 nm particles. The penetration depth into the porous wall of 100 nm particles is much deeper than of 10 nm and 1000 nm particles.

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