CHEMICAL ENGINEERING TRANSACTIONS
VOL. 81, 2020
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it
Guest Editors: Petar S. Varbanov, Qiuwang Wang, Min Zeng, Panos Seferlis, Ting Ma, Jiří J. Klemeš

ISBN 978-88-95608-79-2; **ISSN** 2283-9216
DOI: 10.3303/CET2081105

Study on the Effect of Structural and Working Parameters on the Back Pressure of Diesel Particulate Filter

Qirong Yang[a], Xiaori Liu[a,*], Tiechen Zhang[a], Nannan Sun[b], Zhen Zhang[a]

[a]School of Energy and Environmental Engineering, Hebei University of Technology, Tianjin 300401, China
[b]Institute of Engine Technology, WEICHAI Power Co. Ltd, Weifang261061, China
liuxiaori@hebut.edu.cn

Diesel particulate filter is one of the most effective and direct methods to filter diesel particulate matter. Many factors affecting the efficiency and pressure of diesel particulate trap are studied in this paper. Based on AVL-BOOST software, the simulation model of DPF is established. Based on the calculation of multi plans which control the different parameters such as geometry, temperature, porosity and other factors of the diesel particulate filter, the effect of these parameters on efficiency and pressure of diesel particulate filter is studied, to understand the influence relations between different parameters. The models of pressure drop are introduced. The effects of monolith length, monolith volume, mass flux, boundary and initial temperature on pressure drop are analysed. Results show that the structure of DPF has little impact on pressure drop; DPF regeneration does not change the effects of monolith length, monolith volume, loaded soot mass on pressure drop; When the temperature is 773 K, the mass flux has an important influence on pressure drop; The soot consumption rate is no longer changing when the temperature reaches 873 K; The coupling of temperature and parameters affects the pressure drop. The importance of filter structural parameter to calculate the pressure drop and filtering efficiency is further analysed. The results further improve the theoretical analysis of DPF efficiency characteristics, DPF regeneration time and subsequent experiments.

1. Introduction

Engine pollution mainly comes from four components - particulate matter (PM), hydrocarbons (HCx), nitrogen oxides (NOx) and carbon monoxide (CO). The particulate matter is mostly made up of tiny particles of carbon or carbides. Diesel Particulate Filter (DPF) can reduce the amount of soot produced by engines by more than 90 %. DPF can effectively reduce the emission of particulate matter (Montajir et al.,2007). First, it captures the particulate matter in the exhaust gas and then oxidises the captured particles to realise DPF regeneration. The regeneration of DPF is that in the long-term work, the gradual increase of particles in the DPF will cause the back pressure of the engine to rise, and that makes the engine performance degradation. So it is necessary to periodically remove the deposited particles to restore the filter performance of DPF. The particulate matter that emitted from diesel engines has been a concern. PM can be suspended in the air for a long time, it is polluting the environment and affecting human physical and mental health. With the increasingly strict diesel emission standards, DPF has become one of the necessary technologies for diesel vehicles to conform to the standards. DPF must be designed with the consideration of filtration efficiency, pressure drop, high temperature resistance, etc. The carbon filtration efficiency of DPF can reach over 90 %. During filtration, particulate deposition in the filter will lead to the increase of exhaust back pressure of the diesel engine. The catalyst-coated filters showed pressure drop values very similar to that of the uncatalysed filters (Meloni and Palma, 2018).
Exhaust back pressure has an important influence on the engine economy, power performance and sound quality. It also affects the quality and capture efficiency of DPF. So back pressure is one of the important indexes in the process of design DPF. Chen et al. (2013) studied the capture of PM by DPF under various conditions, they proved that DPF is very efficient in capturing PM. But, in the two working conditions of cold start and sharp deceleration, the capture efficiency will be reduced due to the back pressure. The excessive exhaust back pressure leads to the increase of inflation loss, the decrease of engine combustion efficiency, the decrease of power output and the deterioration of fuel economy. The low exhaust back pressure will increase the cost of

Paper Received: 29/03/2020; Revised: 27/05/2020; Accepted: 04/06/2020
Please cite this article as: Yang Q., Liu X., Zhang T., Sun N., Zhang Z., 2020, Study on the Effect of Structural and Working Parameters on the Back Pressure of Diesel Particulate Filter, Chemical Engineering Transactions, 81, 625-630 DOI:10.3303/CET2081105

exhaust system development, and reduce the quality of sound. So controlling the back pressure at a reasonable value is important for performance engine and DPF. Peng et al. (2019) analysed the influence of structural parameters on DPF pressure drop. Previous articles only analysed the influence of a single factor on the pressure drop, such as the structure or temperature, but they have not analysed the effects of coupling of two factors on pressure drop. This article mainly studies from the temperature aspect, the influence of DPF structure on pressure drop at different exhaust temperatures and the influence of the coupling of exhaust temperature and DPF initial temperature are analysed.

2. The analysis of DPF pressure drop

The DPF pressure drop is composed of four parts: the pressure loss through the particle layer, the pressure loss through the filter wall, the friction loss in the inlet channel and the friction loss in the outlet channel. Among them, the pressure loss when the gas flows through the particle layer is related to the thickness of the loaded particle layer. The others are determined by the DPF structure and the state of the gas flowing. The model to calculate the pressure drop across DPF is the one derived for a clean filter by Konstandopoulos and Johnson (1989), which was extended to the loaded filter case by Konstandopoulos et al. (2000). This model calculates the pressure drop across DPF during loading and regeneration, based on the filter geometry, the mass loading and the properties of the exhaust gas (Kladopoulou et al.,2003). The formula can be obtained:

$$\nabla P = \frac{\mu Q}{2V_{trap}}(\alpha + w)^2 \left\{ \frac{w}{k_0 \alpha} + \frac{1}{2K_{soot}} \ln\left(\frac{\alpha}{\alpha - 2w_s}\right) + \frac{4FL^2}{3}\left[\frac{1}{(\alpha - 2w_s)^4} + \frac{1}{\alpha^4}\right]\right\} \tag{1}$$

Where, μ is the gas viscosity, kg/m· s^{-1}; Q is the exhaust volume flow rate, m^3/s; α is the channel width, mm; ω is the thickness of the filter layer, mm; V_{trap} is the volume of the filter, m^3; k_0 is the permeability of the filtration layer, m^2; K_{soot} is the layer permeability of stowage particles, m^2; ω_s is the thickness of stowage particle layer, mm; F is the coefficient of wall friction; L is the length of the filter channel, mm.
According to Eq(1), the mathematical model intuitively reveals the mathematical relationship between various parameters, which provides a research direction for the following simulation.

3. The establishment of simulation model

Using the AVL Boost software to build the simulation model. The software offers a variety of components that can simulate the cycles and aftertreatment of an internal-combustion engine. Figure 1 is the model of DPF established in AVL Boost, and then study the influence factors of DPF pressure drop.

Figure 1: The aftertreatment model of DPF

The basic parameters to simulate the running environment of DPF are shown in the Table 1 and Table 2. According to the mathematical model, the influence of DPF pressure drop can be considered in many aspects. The basic geometric parameters of DPF and the boundary conditions are considered and then the soot mass and initial DPF temperature are also studied. This paper will simulate DPF pressure drop from these aspects.

Table 1: Geometric and Initial Parameters

Monolith Volume	Length of Monolith	Initial of Monolith	Cell Density	Wall Thickness	Soot Mass
0.6795 L	0.2 m	499.85 K	200 (1/m^2)	3.988×10^{-4} m	10 kg/m^3

Table 2: Boundary Conditions

Time(s)	0	50	100	600
Temperature (K)	499.85	849.85	849.85	849.85
Mass Flux (kg/s)	0.006	0.003	0.003	0.003

4. Results

In order to better analyse the impact of each parameter on the pressure drop, the experiment changes one parameter and keep the others unchanged. The resulting is shown in the following Figures.

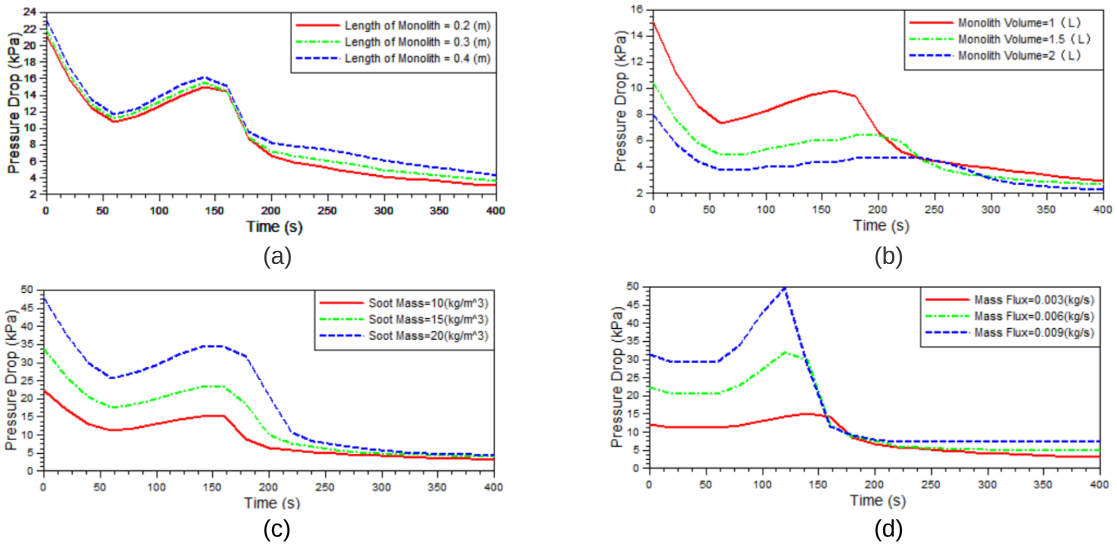


Figure 2: Pressure drop with (a) different length, (b) different volume, (c) different loaded soot mass, and (d) different mass flow

Figure 2a and Figure 2b show the effect of monolith length and volume on pressure drop. Figure 2a shows that when the length increases, the pressure drop also increases. The difference between curves is little, so simply changing the DPF length has little effect on the pressure drop. In Figure 2b, the pressure drop is different and decreases with the increase in volume. Figure 2c and Figure 2d show the influence of loaded soot mass and mass flow on pressure drop. Observing Figures, the pressure drop increases with the increase of loaded soot mass and mass flow. But the mass flow has a greater effect on the pressure drop.

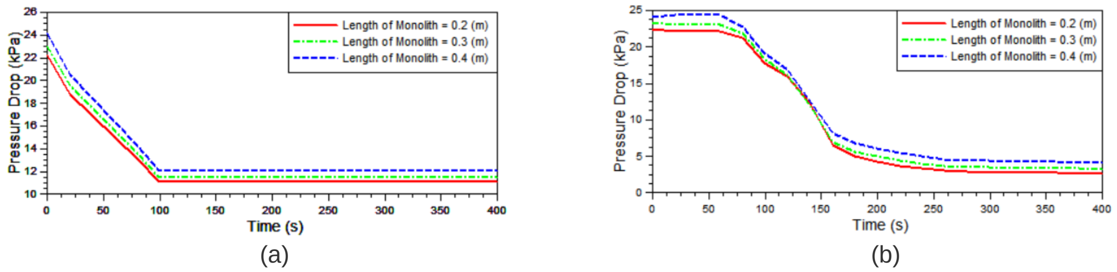


Figure 3: Pressure drop with different length when the inlet temperature is (a) 473 K, (b) 773 K

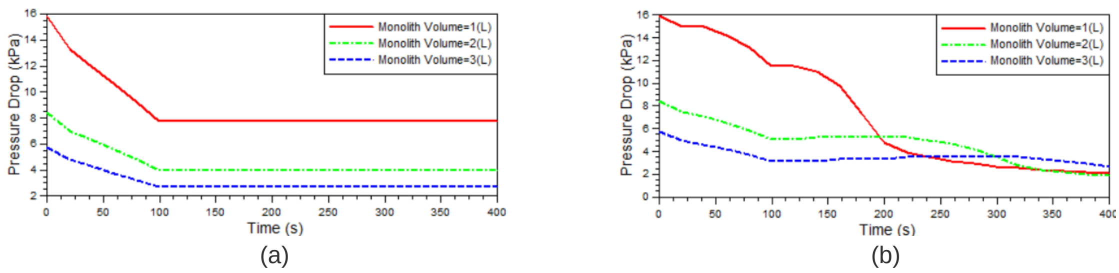
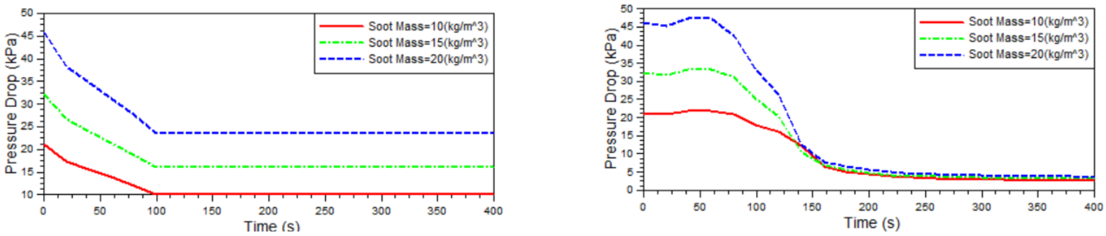


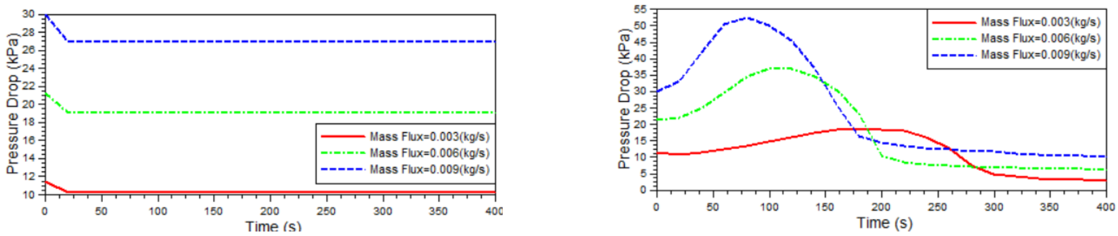
Figure 4: Pressure drop with different volume when the inlet temperature is (a) 473 K, (b) 773 K



(a) (b)

Figure 5: Pressure drop with different loaded soot mass when the inlet temperature is (a) 473 K, (b) 773 K

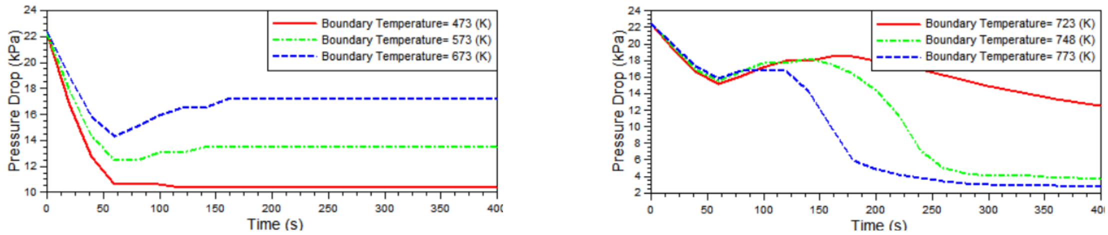
Because there is a temperature change in the simulation. The influence of each parameter on pressure drop under normal operation and the regeneration of DPF is considered. The inlet temperature of DPF regeneration condition is about 773 K, and the DPF inlet temperature ranges from 453 K to 683 K under various working conditions in normal mode. When the inlet temperature is about set to 773 K, the regeneration can be safe and efficient. To consider the DPF regeneration, the text temperature is 773 K. Figures 3 to 5 show the influence of DPF structure (length and volume) and soot mass on pressure drop when the exhaust temperature is 473 K and 773 K. When the exhaust temperature reaches the regeneration temperature, the pressure drop drops to a minimum and remains stable. Compared Figure 3b and Figure 5b with Figure 3a and Figure 5a, the pressure drop decreases for a longer time as the particles in DPF are consumed because of regeneration. Figure 3b and Figure 5b show that the pressure drop starts to decrease at about 60 s and remains stable at 150 s. However, it can be seen from Figure 4 that even considering the consumption of particles in DPF, the influence of volume on pressure drop is almost unchanged. When the temperature reaches the regeneration temperature, the pressure drop decreases due to the consumption of particulate matter. But simply changing the structure has little effect on the pressure drop.



(a) (b)

Figure 6: Pressure drop with different mass flow when the inlet temperature is (a) 473 K, (b) 773 K

Observing Figure 6a and Figure 6b, the influences of mass flow on pressure drop are studied when the exhaust temperature is 473 K and 773 K. Firstly, when the temperature is at 473 K, the pressure drop increases with the increase of mass flow, but the pressure drop curve remains stable. Secondly, when the temperature is 773 K, the pressure drop curve shows an upward trend, then the curve goes down to a stable value. The time of the above phenomenon will advance with the increase of mass flow, and the waveform of the curve will become steeper and steeper. Because of the regeneration of DPF, the increase of mass flow will accelerate the consumption of particulate matter in DPF, then the pressure drop curve changes significantly.



(a) (b)

Figure 7: Pressure drop when the inlet temperature is (a) 473 K, 573 K, 673 K, (b) 723 K, 748 K , 773 K

Figure 7 shows the influence of boundary temperature on pressure drop. The pressure drop increases with the increase of temperature. When DPF is in normal operation, the pressure drop is maintained at a high value due to the increase in temperature. Figure 9a is the pressure drop curve of the exhaust temperature over 773 K. Because of DPF regeneration, the pressure drop curve can plummet. The rate of decline increases as the temperature increases. When the temperature reaches above 873 K, the pressure drop will not change with the increase of the temperature. From Figure 7a and Figure 7b, the pressure drop already decreases when the temperature reaches over 673 K, and the decreasing rate of pressure drop increases with the increase of temperature. Figure 8 shows that the mass decline rate increases with the increase of temperature, this phenomenon is reflected in the pressure drop curve. When the temperature reaches 723 K, the soot mass consumption is obvious, DPF regeneration has begun, and become drastic with the temperature increasing. But the soot consumption rate is no longer changing when the temperature reaches 873 K.

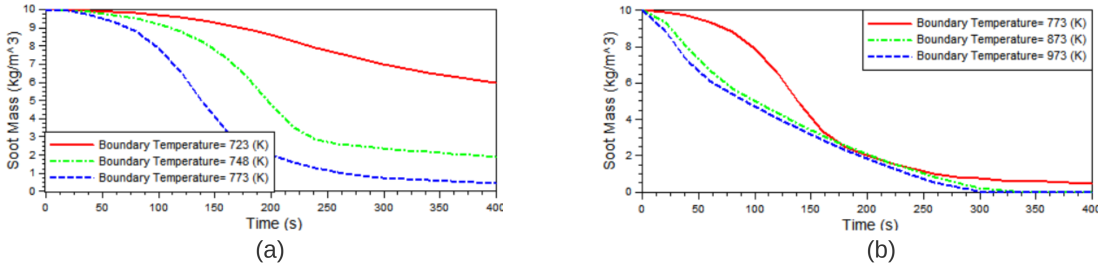


Figure 8: Soot mass when inlet DPF temperature is (a) under 773 K, (b) over 773 K

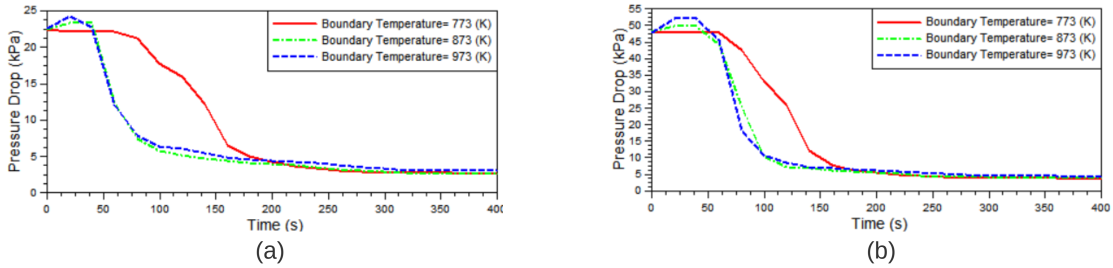


Figure 9: Pressure drop with different inlet temperature when loaded soot mass is (a) 10 kg/m^3, (b) 20 kg/m^3

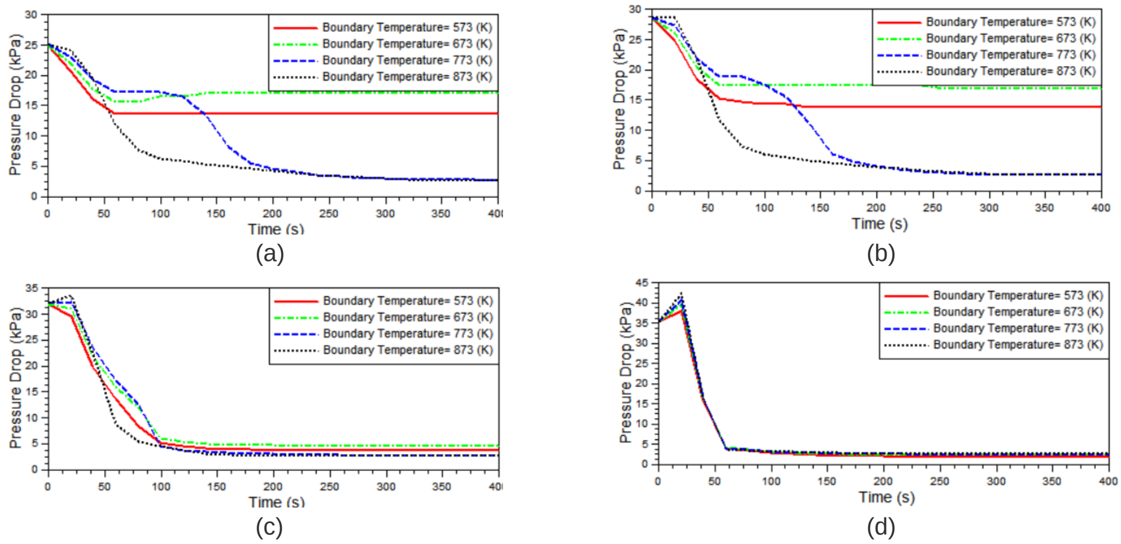


Figure 10: Pressure drop with different inlet temperature when initial DPF temperature is (a) 573 K, (b) 673 K, (c) 773 K, (d) 873 K

As shown in Figure 8b, the rate of particle decline is unchanged when the temperature is over 873 K. Figure 9 show that the initial value of the pressure drop increases and the reaction time is prolonged. But the shape of the pressure drop is the same. Through the analysis of Figure 5 and Figure 9, the loaded soot mass has little impact in pressure drop.

The four pictures of Figure 10 show the influence curve of pressure drop with inlet temperature at DPF initial temperature of 573 K, 673 K, 773 K and 873 K. The curves in Figure 10a and 10b are similar when the initial DPF temperature is 573 K and 673 K; Figure 10c and 10d show that the curves are similar when the initial temperature is 773 K and 873 K. Considering the influence of DPF regeneration when the temperature reaches 773 K and 873 K, the pressure drop drops significantly, and the particles in DPF reach the ignition temperature. As the DPF temperature increases, the initial pressure drop increases. Comparing four Figures, the inlet temperature is constant, and the pressure drop will drop sharply when the initial DPF temperature reaches above 773 K. When the DPF temperature reaches above 773 K, the influence of boundary temperature on the pressure drop can be ignored. The curves almost coincide. When both the exhaust temperature and the initial DPF temperature are less than 673 K, the curve of pressure drop is similar to the pressure drop curve waveform when the exhaust temperature is considered, but the overall pressure drop increases with the increase of the initial DPF temperature. When the inlet temperature or the initial DPF temperature reaches 873 K, the consumption rate of particles in DPF will no longer change, and the pressure drop curve will remain unchanged. Keeping a temperature of 873 K is enough for DPF regeneration. Comparing with the inlet temperature, the increase of the initial DPF temperature will increase the initial pressure drop.

5. Conclusions

Considering the effect of DPF regeneration, the DPF structure and the loaded particle mass have little effect on the pressure drop. But the pressure drop fluctuates, and the pressure drop curve fluctuates more and more violently with the increase of mass flow. When the exhaust temperature reaches more than 673 K, the pressure drop rate accelerates with the increase of temperature, and the pressure drop rate is almost constant when the exhaust temperature exceeds 773 K. The pressure drop is no longer changing when the initial DPF temperature or the boundary temperature reaches 873 K. When the initial DPF temperature reaches above 773 K, the influence of boundary temperature on the pressure drop can be ignored. During DPF regeneration, it is not necessary to raise the inlet temperature above 873 K. To reduce the resistance of DPF, the initial DPF temperature should be reduced as much as possible.

Acknowledgements

This work was supported by Hebei Science and Technology Project(17274006D), National Engineering Laboratory for Mobile Source Emission Control Technology (NELMS2017B06) and the Student's Platform for Innovation and Entrepreneurship Training Program of China (201910080024).

References

Chen X., Li M. L., Hou X. J., Xu Y. Y., 2013, A study on the filtration characteristics of DPF for diesel vehicle, Automotive Engineering, 35(12), 1074-1077, 1104. (in Chinese)

Kladopoulou E. A., Yang L. S., Johnson J. H., Parker G. G., Konstandopoulos A. G., 2003, A study describing the performance of diesel particulate filters during loading and regeneration - a lumped parameter model for control applications, SAE Technical Paper Series, Detroit, Michigan, US, 112, 647-668. DOI: 10.4271/2003-01-0842.

Konstandopoulos A. G., Kostoglou M., Skaperdas E., Papaioannou E., Zarvalis D., Kladopoulou E., 2000, Fundamental studies of diesel particulate filters: transient loading, regeneration and aging, SAE Technical Paper Series, Detroit, Michigan, US, 109, 683-705, DOI: 10.4271/2000-01-1016.

Konstandopoulos A. G., Jonhnson J. H., 1989, Wall-flow diesel particulate filter-their pressure drop and collection efficiency, SAE Technical Paper Series, Detroit, Michigan, US, No.890405, DOI: 10.4271/890405.

Meloni E., Palma V., 2018, Temperature microwave regeneration of catalytic diesel particulate filter, Chemical Engineering Transactions, 70, 721-726.

Montajir R. M., Kusaka T., Kaori I., Kihara N., Asano I., Adachi M., Wei Q., 2007, Soot emission behavior from diverse vehicles and catalytic technologies measured by a solid particle counting system, SAE Technical Paper Series, Detroit, Michigan, US, 2007-01-0317, DOI: 10.4271/2007-01-0317.

Peng M.C., Lin J.Y., Xie H.N., Li J.L., 2019, Optimal and design of DPF channel structure parameters, Vehicle Engine, 240, 41-46. (in Chinese)