

3D Numerical Study of Pressure Loss Characteristics and Filtration Efficiency through a Frontal Unplugged DPF

2010-01-0538

Published
04/12/2010

Xiaogang Zhang, Paul Tennison and William Ruona
Research & Innovation Center, Ford Motor Company

Copyright © 2010 SAE International

ABSTRACT

The main objective of this paper is to investigate the performance of partial filtration DPF substrates using 3-D Computational Fluid Dynamics (CFD) methods. Detailed 3-D CFD simulations were performed for real world sizes of DPF inlet and outlet channel geometries. Two concepts of partial filters were studied. The baseline geometry was a standard DPF with the front plugs removed. The second concept was to eliminate half of outlet plugs in addition to the inlet plugs to improve the pressure drop performance. The total filter efficiency was defined in current study to quantify the overall filter filtration efficiency which combines the effects from wall flow efficiency and flow through efficiency. For baseline case, 45% of total exhaust gas was found to go through the inlet channels, and the total trap efficiency was as high as 60%. However, only a 10% pressure loss reduction was found due to the removal of the outlet channel plugs from the DPF inlet side. With the further reduction of the number of inlet channel plugs by 50%, the pressure loss can be reduced from 3kPa to 1.6 kPa while still maintaining a 40% total PM trapping efficiency. The effects of wall permeability, DPF length and total exhaust mass flow were also investigated. Additionally, the percentage of exhaust flow going through inlet channels and total filtration efficiency increase as a function of wall permeability, DPF channel length and total exhaust mass flow rate were studied.

INTRODUCTION

Diesel Particulate Filters (DPFs) are widely used to meet EPA 2007 and 2010 Particulate Matter (PM) emission requirements. During the soot loading process, the soot is collected initially inside the porous walls and eventually forms a soot cake layer on the surface of the DPF inlet channel walls. A densely packaged soot layer and reduced

mean pore size due to Particulate Matter (PM) deposition will reduce overall DPF wall permeability which results in increasing pressure loss across DPF substrate. A regeneration process is required to burn out the soot collected inside DPF. One of the most important parameters in the evaluation of the performance of a given DPF substrate is the Maximum Soot Load (MSL) capacity. On one hand, with a soot load beyond MSL, a DPF substrate may be subjected to durability issues, such as a Ring-Of-Crack (ROC) failure. On the other hand, low a MSL value can have a negative effect on fuel economy due to more frequent DPF regeneration events which needs to burn diesel fuel to generate higher exhaust gas temperature through the exothermal reaction.

A regular DPF, as illustrated in [Fig. 1 \(a\)](#), consists of two different types of channels. A channel with a plug at the flow outlet is called an inlet channel. Inlet channels accept PM rich exhaust gas flow from the inlet cone or pipe in front of a DPF. A channel with a plug at the flow inlet is called an outlet channel. Outlet channels accept the exhaust flow from the neighboring inlet channels through the porous filter wall and expel the PM filtered exhaust gas to the outlet cone or pipe downstream of the DPF. Inside the DPF, the exhaust gas goes through the porous wall between two channels where the particulate matter is collected. The backpressure (pressure loss through the DPF substrate) and soot trapping efficiency are directly dependent on the filter geometrical parameters such as cell density (cells per square inch or CPSI), wall thickness, wall permeability, filter diameter and filter length. Previous works [1, 2, 3] have focused on pressure loss characteristics and velocity profiles inside the inlet and outlet channels and the filter wall with or without a ROC for square and triangle channel geometries. It was noted that even with a ROC, a DPF can still retain significantly high filtration efficiency [3]. As an extension or continuation of that result,

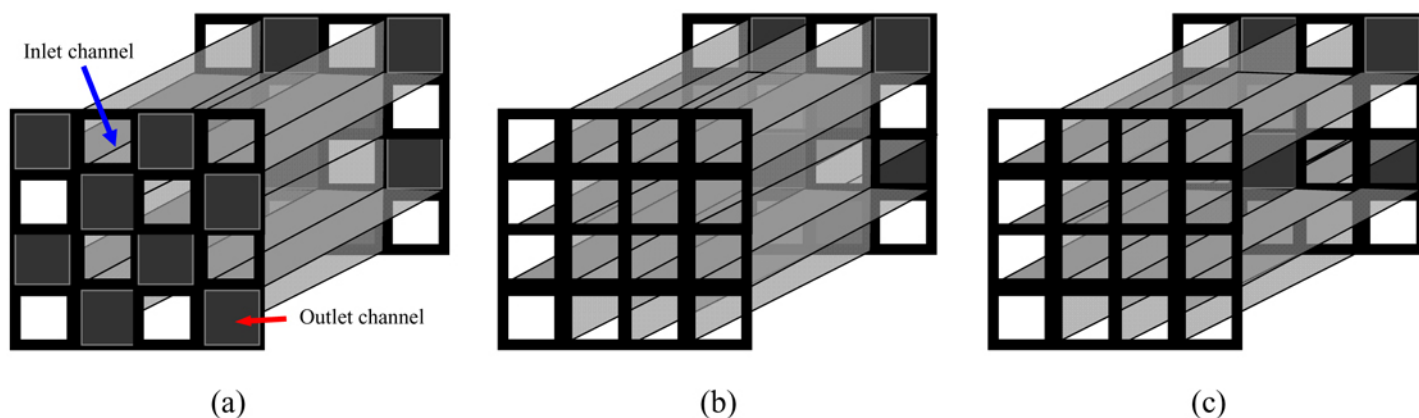


Figure 1. (a) cell structure of traditional DPF; (b) cell structure of front unplugged DPF (PDPF) investigated in current study; (c) PDPF with only half of the inlet channels are plugged.

this paper explores the possibility that a DPF can be designed to operate in a “partial filtration” application.

The total pressure loss through a DPF substrate contains contributions from both channel flow and wall flow (Darcy flow). The transition from channel flow to Darcy flow is dependent on filter wall permeability and DPF channel length for a given DPF structure. At lower filter wall permeabilities and/or shorter DPF channel length, the majority of the pressure loss is from Darcy flow through the filter wall. Both higher flow resistance across filter wall and reduced flow cross-sectional area as a result of a shorter DPF contribute to higher levels of pressure loss due to Darcy flow. At higher filter wall permeabilities and/or longer DPF channels, the gas flow can easily pass through the filter wall and most of the pressure loss is due to channel flow inside the inlet and outlet channels.

The baseline geometry of a Partial Diesel Particulate Filter (PDPF) design that achieves partial PM removal is shown in [Fig. 1 \(b\)](#). This PDPF is constructed based on a regular DPF with the identical CPSI, wall thickness and filter wall permeability. The only difference from a standard DPF is that the outlet channel plugs, typically located at the front of the DPF, have been removed. In this configuration the exhaust gas can flow inside all the channels. As such, the number of flow through channels and wall flow channels are the same. [Figure 1 \(c\)](#) illustrates another scenario where the number of flow through channels is 4 times the number wall flow channels. This is mainly to trade off between back pressure and total trap efficiency.

For simplicity in the following discussion, we will continue to utilize the terminology of inlet and outlet channels, where outlet channels are actually flow through channels and inlet channels remain the same as in traditional DPF design.

<figure 1 here>

The idea of a partial PM filter/trap or PDPF could be utilized in multiple different diesel applications or even potentially in a gasoline engine aftertreatment system. As emission regulations become tighter in various emerging markets in the world, more stringent PM reduction requirements (and the associated hardware) are inevitable. A partial DPF would be attractive to maintain lower back-pressure while meeting interim PM standards that may not require the 98%+ filtration efficiency seen with a standard DPF. A partial DPF could also be used in an EGR application to help prevent fouling and/or plugging issues that can be seen in various advanced EGR systems. As gasoline engine applications such as gasoline turbo direct injection (GTDI) start running more like a diesel (i.e. lean) they will likely experience an increase in engine out particulate matter. The high backpressure associated with a regular DPF (or GPF for gasoline) is a significant concern for gasoline engines, thus a partial filtration filter could be applied dependent upon the total filtration requirements for a given application. For HD and MD diesel engines in North America, a close coupled partial DPF (perhaps in conjunction with an underbody standard DPF) could also be an attractive concept to promote passive soot regeneration and thus reduce the regeneration frequency for the regular DPF and benefit the application's overall fuel economy. These are just some potential examples of where a partial filtration filter could be utilized.

When the front plugs for the outlet channels are removed, the exhaust gas can instantaneously flow into any channel (both inlet and outlet) inside the DPF. However, since the mass flow distribution between those channels is only dependent on the pressure resistance along each flow path, thus the primary flow path would be the exhaust gas flow through along outlet channels, as shown in [Fig. 2](#) from point “A” to point “B”. The only pressure resistance in the channel flow is from the friction loss on the surface of channel. It is expected that more exhaust gas would flow through this path, however, the mass flow rate inside outlet channel may increase along the flow path. This is because that in addition to the primary

path, there is an alternative path (secondary flow path) through which the exhaust gas can enter the inlet channels first and then pass through the filter wall and enter the outlet channels. Under this scenario, the resulting total flow resistance is a combination of the channel flow inside both the inlet and outlet channels as well as the Darcy flow through the porous filter wall. In general, a higher flow resistance is expected through the secondary flow path. The distribution of mass flow between these two flow paths is solely determined by the flow resistance through each flow path. The flow resistance is related to the DPF geometrical parameters such as filter wall permeability, cell structure (CPSI), wall thickness, substrate length and the total exhaust gas mass flow rate.

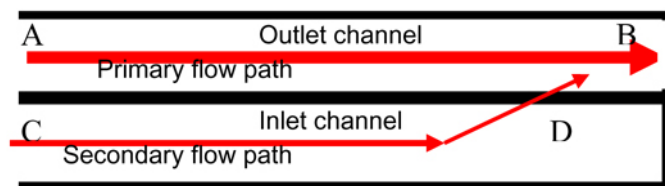


Figure 2. Illustration of the exhaust flow paths inside the concept DPF (front unplugged DPF geometry).

As the exhaust gas flows through the primary path, a certain pressure loss is generated from point “A” to point “B” as illustrated in Fig. 2. The pressure loss across an outlet channel increases with an increase of exhaust mass flow rate. At the front of the DPF, the static pressures at point “A” and “C” are equal. If there was no exhaust gas flow inside the inlet channel, the static pressure at point “C” and point “D” would be the same. Thus, the pressure difference between point “D” and point “B” is the same as between point “A” and point “B”. This pressure difference will drive exhaust gas flow across the filter wall from point “D” to point “B”, and as a result exhaust gas starts to flow inside the inlet channel. As exhaust gas starts to flow inside the inlet channel, the static pressure at point “D” is reduced, and thus the difference between point “D” and point “B” is also reduced. As long as a static pressure difference exists between point “D” and point “B”, a certain amount of exhaust gas will be drawn through the filter wall from the inlet channel to the outlet channel. This process continues on until a constant static pressure difference between point “D” and point “B” is reached. This mechanism drives the phenomenon that exhaust gas flow will always be present inside the inlet channel.

As the channel length decreases, the flow resistance along the channel is reduced. Thus, for the same exhaust gas mass flow rate flowing across an outlet channel the pressure loss will decrease. As a result, a higher mass flow rate will be found inside the outlet channel and a lower exhaust mass flow rate inside the inlet channel. This can have a negative effect on

the total filtration efficiency, however, it will be a benefit to pressure loss reduction. The filter wall permeability also has a dominant effect on the mass flow distribution such that a higher permeability results in a higher mass flow rate through the inlet channel.

The total DPF filtration efficiency will be affected by the mass flow distribution between the inlet and the outlet channels. The filtration efficiency involves the same two flow mechanisms, channel flow and Darcy flow, that contribute to the pressure loss. Usually the filtration efficiency is very high, more than 99%, for regular DPF with wall flow. While a much lower efficiency, typically around 20% to 40%, is found for flow through substrates with channel flow only¹. Todd et al. [4] reported the development of partial filter technology utilizing a metallic substrate with a corrugated surface. They found out that the DOC alone produced 30% PM reduction on the test engine. In the proposed PDPF system, the overall trap efficiency that will certainly be lower than that of a regular DPF due to the very low trap efficiency for the portion of exhaust gas flowing through the open or outlet channels.

Computational Fluid Dynamics (CFD) methods have been widely used in the development of complicated vehicle exhaust systems in various areas such as flow, temperature and pressure distributions [5], thermal management of skin temperature and heat insulation, two-phase flow and flow mixing [6, 7, 8, 9], chemical reactions and species transportation. Additionally, CFD tools are becoming a standard method to evaluate flow uniformity inside substrates. 3-D simulation of a complete exhaust system can predict the pressure drop performance with high accuracy. For the current paper, a systematic study was conducted to evaluate the total filter trap efficiency for partial PM trap or PDPF design concepts. First, the general fluid flow and pressure distribution characteristics inside the inlet and outlet channels, as well as inside the filter wall, were studied for the baseline case. Next, a comparison of fluid flow and pressure distribution was conducted for a regular DPF, flow through substrate and a PDPF. Then, a modification of the baseline PDPF, where only half the inlet channels were plugged, was investigated to minimize pressure loss and retain decent total filtration efficiency. In the end, the effects of filter wall permeability, DPF length and exhaust mass flow rate on DPF pressure drop, total filtration efficiency were investigated. These numerical results can be used to guide future direction towards partial trap system development.

¹This filtration efficiency is usually obtained through experimental testing. It is dependent upon filter material, channel structure, size and length. 30% was used for this study.

NUMERICAL METHOD, BOUNDARY CONDITION AND 3-D MESH GENERATION

Individual 3-D DPF channels with and without front plugs were modeled to be able to obtain detailed information such as velocity and static pressure distributions inside the two different channels (inlet and outlet channels), as well as across the porous filter wall. To reduce the computational time and the complexity of the problem, the computational domain only consisted of two quarters of an inlet channel and two quarters of an outlet channel. A cordierite DPF with 200 CPSi and 20 mil wall thickness was chosen as the baseline geometry. The DPF diameter and length are 8 and 10 inches respectively. Symmetrical boundary conditions were used on the four sides of the CFD domain. Laminar flow was enforced for the flow inside DPF channels and the filter wall. The filter wall was treated as a porous fluid domain and the flow resistance was calculated from wall permeability which is based on the mean pore diameter inside wall. Any pressure loss contributions from exit effects due to the flow expansion downstream of the DPF outlet were not considered in the current study. The focus was on the effect of the pressure loss change and the mass flow distribution between the two channels due to the removal of front plugs.

Typically, the requirement for a flow uniformity index in front of DPF substrate is at least 0.95. A uniform flow is assumed at the flow inlet for the current study. In the baseline case, the exhaust gas mass flow rate for the specified computational domain is calculated based on a 1500 kg/hr total mass flow rate through the exhaust system and the DPF geometrical parameters.

The CFD meshes were carefully constructed in the vicinity of filter wall, as shown in Fig. 3 (a). To minimize the computational time, a coarse mesh was used in most of the computational domain where no significant change of flow velocity or static pressure was expected. At the flow transition region (from uniform flow at the flow inlet to fully developed flow), the mesh size is as fine as 0.05 mm. Beyond the flow transition region, all the way to the center of channel, a coarser mesh was built, as shown in Fig. 3 (b). In the region close to the flow exit, a finer mesh was used again, as shown in Fig. 3 (c). The same method was used for the mesh generation inside filter wall and its vicinity area, see Fig. 3 (d).

<figure 3 here>

As opposed to 3-D CFD simulation of just the flow and pressure distribution inside a regular DPF in previous study [3], the mass flow redistribution at the front of the PDPF needs to be considered in the current study. As was described earlier, the mass flow distribution between the inlet and outlet

channels only depends on the pressure resistance characteristics of the individual flow paths inside PDPF. In order to capture the mass flow redistribution in front of PDPF for the current study, a new computational domain was added in front of PDPF for 3-D calculation of flow redistribution in addition to the regular DPF channel flow domains. The length of this domain is constructed to be 5 times as long as the channel width to ensure simulation accuracy with regards to flow impingement on the edge of filter wall and mass flow redistribution in front of DPF.

The total PM trapping efficiency will deteriorate when a portion of exhaust gas bypasses the filter wall and goes through the DPF from an inlet of an outlet channel to an outlet of an outlet channel. As discussed earlier, two mechanisms are involved in PM filtration process: wall flow and flow through. Trapping efficiency is very high for the wall flow mechanism and considerably lower for the flow through mechanism. Only a portion of soot contained inside this part of the exhaust gas will be collected by the flow through mechanism. For the current study, the total filtration efficiency is defined to account for this phenomenon as noted below.

$$\eta_{total} = \frac{\dot{m}_{inlet_to_outlet} \times \eta_{wa} + \dot{m}_{outlet_to_outlet} \times \eta_{ch}}{\dot{m}_{total}} \quad (1)$$

Where $\dot{m}_{inlet_to_outlet}$ and $\dot{m}_{outlet_to_outlet}$ are exhaust mass flow rates go from inlet channel to outlet channel and from outlet channel to outlet channel respectively. η_{wa} and η_{ch} are trapping efficiency of the wall flow and flow through mechanisms respectively. For a traditional DPF:

$$\dot{m}_{outlet_to_outlet} = 0,$$

$$\dot{m}_{inlet_to_outlet} = \dot{m}_{total}, \text{ and } \eta_{total} = \eta_{wa}.$$

CFD RESULTS AND DISCUSSIONS

VELOCITY AND STATIC PRESSURE DISTRIBUTION CHARACTERISTICS INSIDE CHANNELS AND FILTER WALL

A baseline study is conducted to investigate flow and static pressure distribution inside PDPF channels with the removal of all inlet plugs. DPF cell structure (Cells Per Square Inch

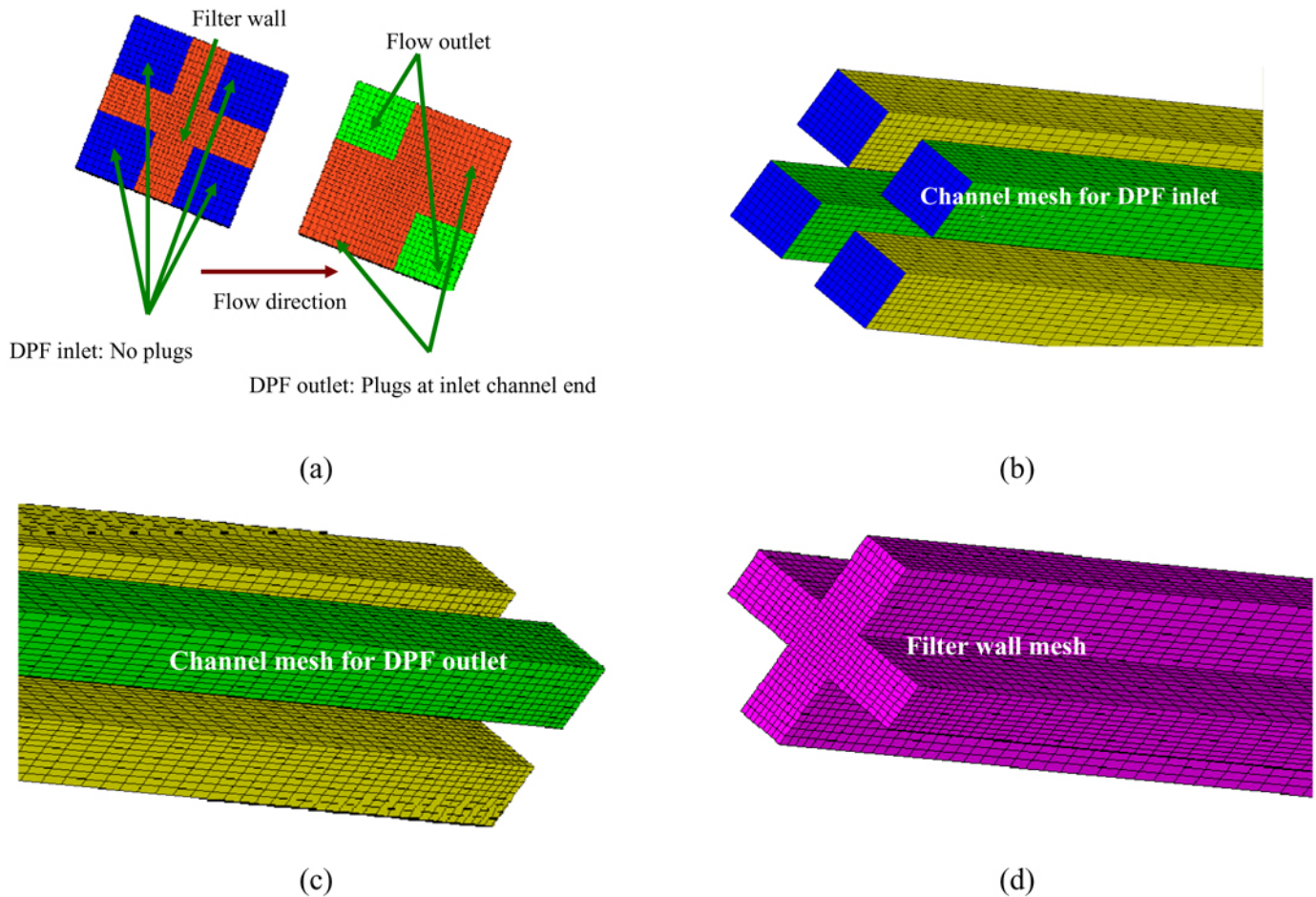


Figure 3. CFD meshes: (a) in the vicinity of the DPF inlet and outlet; (b) DPF channels close to the inlet; (c) DPF channels close to the outlet and (d) the DPF filter wall.

(CPSI)/wall thickness), diameter and length are 200/20, 8 inches and 10 inches respectively. An intermediate filter wall permeability of $1.8423\text{e-}13 \text{ m}^2$ is used in baseline study. A homogenous flow resistance inside filter wall is assumed. A uniform flow is specified at the inlet of computational domain. Mass flow rate inlet boundary condition is used, and $3.45\text{e-}5 \text{ kg/s}$ per half channel is chosen for the baseline calculation². Outlet boundary condition is specified as static pressure. CFD results for baseline case are discussed below.

1. Velocity and Static Pressure Distribution Characteristics inside Channels and Filter Walls for Baseline Case

Velocity distribution is plotted in the diagonal planes of the inlet and outlet channels in Fig. 4. A lower velocity zone exists in front of PDPF due to a larger hydraulic diameter with the filter wall presented. In this flow entrance region, the total mass flow is redistributed into each inlet and outlet channels. As shown in Fig. 4 (a), in the front of PDPF, the flow velocity is slightly higher inside outlet channel which

means more exhaust gas flows into outlet channel. As exhaust gas moves towards to the outlet side of PDPF, as shown in Fig. 4 (b), much higher flow velocity is evidenced inside outlet channels due to the combination of exhaust mass flow from both inlet and outlet channels. On the other hand, due to the plugs at the outlet of inlet channel, gas velocity reaches zero at the end of inlet channel. Wall flow velocity, is considerably lower than that of channel flow.

<figure 4 here>

Figures 5(a), (b) and (c) show the static pressure distribution on the center planes of inlet and outlet channels. As expected the static pressure was uniform and higher at the flow inlet. The static pressure decreases along the flow direction inside both channels. However, the rate of change is much slower inside inlet channel. In the front of the PDPF, the static pressure is slightly lower inside an outlet channel due to higher gas velocities. The static pressure difference between inside inlet and outlet channels is magnified as exhaust gas

²With a cell structure of 200/20, and 8 inches diameter, total exhaust gas flow rate will be 1500kg/hr based on $3.45\text{e-}5 \text{ kg/s}$ mass flow rate per half DPF channel

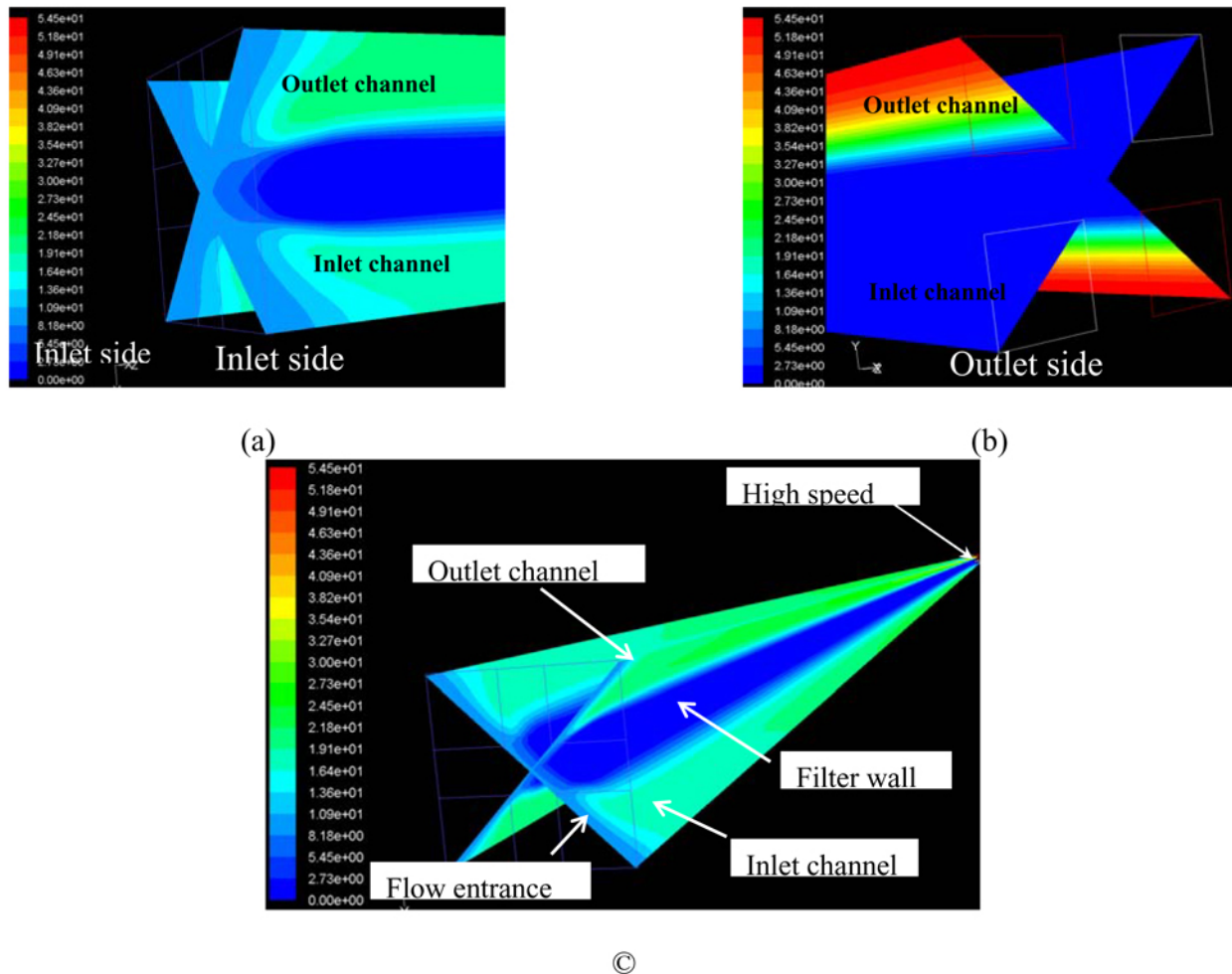


Figure 4. Velocity magnitude distribution at (a) flow inlet; (b) flow outlet and (c) on the diagonal planes of the inlet and outlet channels for the PDPF baseline case.

flows downstream towards the PDPF outlet. The high pressure difference is the driving force for exhaust gas flow movement inside an inlet channel and across the PDPF wall from an inlet channel to an outlet channel.

<figure 5 here>

Figure 6 plots the profiles of velocity magnitude along the centerlines of inlet and outlet channels. The red line is for an outlet channel and white for an inlet channel. As is shown, both velocities at the flow entrance are almost the same. These two velocities diverged from one another as the exhaust mass flow gets redistributed between the inlet and outlet channels. Initially the velocity inside the inlet channel increased due to flow development from uniform to fully developed flow and from minimal mass flow exchange between the inlet and outlet channels. The velocity then decreased and reached zero at the end of PDPF due to the flow exchange between the inlet and outlet channels resulting from the plugs at the end of inlet channel. The opposite was

seen in an outlet channel where the velocity increased and reached a maximum at the flow outlet of the PDPF channel. The rapid increase of velocity close to flow inlet is the result of flow development, and rapid increase of velocity close to the end of channel results from increased gas exchange activity between inlet and outlet channels.

Figure 7 plots the velocity magnitudes at the center (red line) and the corner of the filter wall (white line). Note, a much higher velocity was seen across the center of wall than at the wall corner. Also, the velocity magnitude increased exponentially along the flow direction at the center of filter wall. In such situations, the majority of soot, assuming a uniform concentration in the exhaust gas, will be collected at the rear side of PDPF.