

3D Numerical Study of Pressure Loss Characteristics and Soot Leakage Through a Damaged DPF

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ABSTRACT

Diesel Particulate Filters (DPF) are widely used to meet 2007 and beyond EPA Particulate Matter (PM) emissions requirements. During the soot loading process, soot is collected inside a porous wall and eventually forms a soot cake layer on the surface of the DPF inlet channel walls. A densely packaged soot layer and reduced pore size due to Particulate Matter (PM) deposition will reduce overall DPF wall permeability which results in increasing pressure drop across the DPF substrate. A regeneration process needs to be enacted to burn out all the soot collected inside the DPF. Soot mass is not always evenly distributed as the distribution is affected by the flow and temperature distribution at the DPF inlet. As a result, the heat release which is determined by the burn rate is locally dependent. High temperature gradients are often found inside DPF substrate as a result of these locally dependent burn rates. DPF substrate failures such as a Ring-Off Crack (ROC) can be observed due to high thermal stresses during regeneration events.

The main objectives of the current paper were to understand the effects of a ROC failure on flow distribution and pressure loss, as well as soot leakage characteristics utilizing a 3-D Computational Fluid Dynamics (CFD) tool. Detailed 3-D CFD simulations were performed for a realistic sized DPF inlet and outlet channel geometry with a small crack in the transverse direction. Initially, the general flow and pressure distribution characteristics inside the inlet and outlet channels, as well as inside filter wall, are studied in

baseline case where a ring-off crack failure is assumed at the center of DPF. Then the effects of filter wall permeability, crack location and exhaust mass flow rate on flow and pressure distributions are investigated. The total filter efficiency was defined in the current study to quantify overall filter filtration efficiency. The total filtration efficiency combines the effects of wall flow efficiency for both the upstream and downstream half substrates and the flow through efficiency for only the downstream half substrate because of exhaust gas leakage through a crack. Additionally, the effects of filter wall permeability, exhaust mass flow rate, ROC location on pressure drop changes, percentage of gas leakage and total filtration efficiency are investigated. These numerical results can potentially be utilized to assist in improving On Board Diagnostic (OBD) accuracy.

INTRODUCTION

Unlike a flow through substrate, where exhaust gas flows through many individual channels from inlet to outlet, gas flow inside a DPF substrate behaves differently. Two different types of channels exist inside a DPF: an inlet channel with a plug at flow outlet side and an outlet channel with a plug at flow inlet side, as elucidated in Fig. 1. Gas flow has to go through the porous wall between two channels where soot particulates are collected inside in wall or on the surface of the inlet channel. The backpressure (pressure loss through DPF substrate) and PM filtration efficiency are directly dependent of filter geometrical parameters such as Cell number Per Square Inches (CPSI), wall

thickness, wall permeability, filter diameter and length. In previous studies [1, 2], pressure loss characteristics and velocity profiles inside inlet and outlet channels and filter wall were investigated for DPFs with square and triangle channels. A flow transition was found as filter wall permeability and exhaust mass flow rate increase.

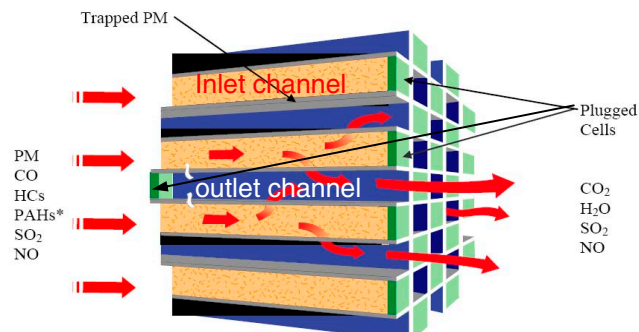


Figure 1, Exhaust gas flows through DPF channels and walls.

The total pressure loss through a DPF substrate has contributions from channel flow and wall flow (Darcy flow). At lower filter wall permeabilities, compared with channel flow, a very high pressure difference is required for the flow to go through filter wall. Under such conditions, the pressure loss through the inlet channel is reduced by a higher gas density resulting from a higher static pressure inside the inlet channel. At higher filter wall permeabilities, the gas flow can easily pass through the filter wall, and most of the pressure loss is contributed by channel flow inside the inlet and outlet channels. When a ring-off crack occurs, a small gap in the transverse direction is created and the DPF substrate channels are divided into two parts¹: an upstream section with channels opened at the flow exit and a downstream part with channels opened at the flow inlet. The gas flow becomes complicated in this transition region. A portion of the exhaust gas can bypass from an inlet channel to an outlet channel directly through the gap instead of following a downstream inlet channel and then passing through the filter wall to an outlet channel. The amount of exhaust gas bypassed through a crack is determined by the filter wall permeability, exhaust mass flow rate and the crack location.

In the scenario with a ring-off crack, the total pressure drop across DPF substrate is reduced. The magnitude of reduction also depends on the filter wall permeability, crack size and location. A main contributor to the reduction in pressure loss is the exhaust flow bypassing

¹ Upon ring-off crack initiation the substrate may or may not completely separate into two parts. For the current study, complete separation is assumed.

the filter wall: i.e. less wall flow velocity. Contributions from the channel flow should remain roughly the same.

The percentage of exhaust gas mass flow bypassing the crack gap directly depends on the pressure behavior interactions between channel and Darcy flows inside the rear part of the substrate. With a dominated Darcy flow, more exhaust gas is expected to bypass through the crack gap. For most of the commercially available DPF substrates (SiC and Cordierite), PM trapping efficiency is over 99%. The total particulate filter efficiency will dramatically drop during conditions of flow bypass because a portion of the exhaust gas does not go through the filter wall. However, there may still be a 30-60% trapping efficiency for a flow through substrate depending on geometrical parameters of the substrate.

The exhaust bypass through a substrate crack is also greatly dependent on the size of the crack. If the crack is very small, for example less than 0.05 micro-meters, a minimal impact on pressure loss and filtration efficiency can be expected. For a majority of commercially available DPFs, the mean pore size diameter is approximately 0.02 micro-meters. By comparison the exhaust gas bypass is very little. As the crack size increases, the percentage of exhaust gas bypassed will increase and the total trap efficiency will decrease.

A ring-off crack is typically found around the geometrical center of a DPF substrate: perpendicular to flow direction. However, the ring-off crack may occur at any place where high temperature gradients and thermal stresses exist. In the current study, three ring-off crack locations are investigated: one close to flow inlet; one close to flow outlet and one at the center.

Computational Fluid Dynamics (CFD) methods have been widely used in the development of complicated vehicle exhaust systems for such varied areas as flow and pressure distributions [3], thermal management of skin temperature and heat insulation [4], two-phase flow and flow mixing [5, 6], chemical reaction and species transportation. CFD tools are becoming a standard method to evaluate flow uniformity inside substrates. Additionally, 3-D simulations of the complete exhaust system can accurately predict the pressure loss of the overall system.

Various experimental investigations have been conducted to identify the best method for soot leakage detection [7]. Seiler et al drilled holes in the DPF filter and studied the effect of hole size on total filtration efficiency [8]. A 25% drop of efficiency was found for a partially damaged DPF and 30-50% drop for heavily damaged DPF. Hauser studied the correlation between soot leakage and measured soot concentration from a soot sensor [9]. Data measured from a soot sensor followed PM emission very well for a partially cracked

DPF. It is quite challenging to experimentally evaluate the effect of crack size on back pressure reduction and overall particulate filter efficiency due to the lack of controllability of the ring-off crack size during part assembly/preparation. Ring-off crack gaps can vary from 0.05 mm to a few millimeters. Previous studies [7] have suggested that it is very unlikely to detect a failed DPF substrate based solely on the back pressure change of the system. A PM measurement device such as a soot sensor may be needed downstream of the DPF substrate to directly measure the PM mass concentration.

In the current paper, a systematic study was conducted to investigate the relationship between total filter trap efficiency and pressure loss and to determine the sensitivity of overall trap efficiency to pressure loss reduction under different wall permeabilities, ring-off crack gaps and varied exhaust mass flow rates.

NUMERICAL METHOD, BOUNDARY CONDITION AND 3-D MESH GENERATION

To evaluate the amount of exhaust gas bypass and the pressure loss characteristics inside a DPF with a ring-off crack, the individual 3-D DPF channels with a ring-off crack are simulated. To reduce computational time, the computational domain, depicted in Figure 2, consisted of two quarter inlet channels, shown in blue, and two quarter outlet channels, shown in yellow, and the corresponding filter wall, shown in pink, which separates the inlet channels and outlet channels. The air gap inside the ring-off crack is shown in brown. The baseline geometry is a cordierite DPF with 200 CPSI and 20 mil wall thickness. The diameter and length are 8 and 10 inches respectively. Besides the inlet and outlet sides of the computational domain, the other four sides are the combination of the center planes for the inlet and outlet channels, as well as the filter wall. Symmetrical boundary conditions are used on all four sides of the CFD domain. Laminar flow is enforced for flow inside DPF channels and the turbulent flow model is activated inside the flow transition region. The filter walls are treated as porous fluid media and the flow resistance is calculated from the permeability based on the mean pore diameter inside the wall.

The pressure loss contributed from entrance and exit effects due to flow contraction and expansion are not considered in the current study. The focus is on the effect of pressure loss variation due to the change of the internal structure from a ring-off crack.

A mass flow rate boundary condition is used at the flow inlet and a pressure outlet boundary condition is used at flow outlet. A 20 kPa gauge pressure is specified at the flow exit of the outlet channels. Although heat transfer is

not the focus in current investigation, energy conservation is considered to accurately calculate the flow density change along the flow direction based upon the local static pressure and exhaust flow temperature. Thermal conductivity of the exhaust is a function of the temperature and the thermal conductivity of the filter wall is based upon Cordierite DPF material properties at a defined porosity.

The filter wall is assumed to be a homogeneous porous media material with the porosity dependent on material permeability. The plugs at the outlet of inlet channel and inlet of outlet channel are assumed to have no exhaust flow. Those plugs are considered to have infinite thickness.

Typically, the flow uniformity index requirement at the front of a DPF substrate is a minimum of 0.95. The current study assumes uniform flow at the flow inlet. 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 entire catalyst system (including DPF) for the baseline case.

The CFD mesh was carefully constructed in the vicinity of filter wall and crack areas, as shown in Fig. 2. To reduce computational time, a coarse mesh was used for most of the computational domain where no significant change of flow velocity or static pressure would be expected. For the flow transition region, a mesh size as fine as 0.05 mm was used. As fluid flows towards the crack region, a finer mesh was built and eventually achieved the same size as the mesh in the transition region. As fluid leaves the gap area, the mesh becomes gradually coarser. The same method was used for the mesh generation in the side filter wall and vicinity.

Before conducting extensive 3-D CFD calculations, the grid dependency was studied based on the baseline case. The average mesh size inside inlet channel was changed from 0.1 mm to 0.05 mm while the mesh size inside filter wall was reduced from 0.05 mm to 0.03 mm. A less than 0.5% change of exhaust mass flow rate bypassing the crack gap was the targeted criteria. 3-D CFD results show that when the average grid size inside the inlet and outlet channels, and the grid size inside the filter walls are less than 0.06 and 0.04 respectively, the magnitude of the change of the bypassed exhaust flow rate is less than 0.5%. In the current study, all mesh sizes in the transverse direction are 0.05 mm on average inside the channels and 0.03 mm inside the filter wall.

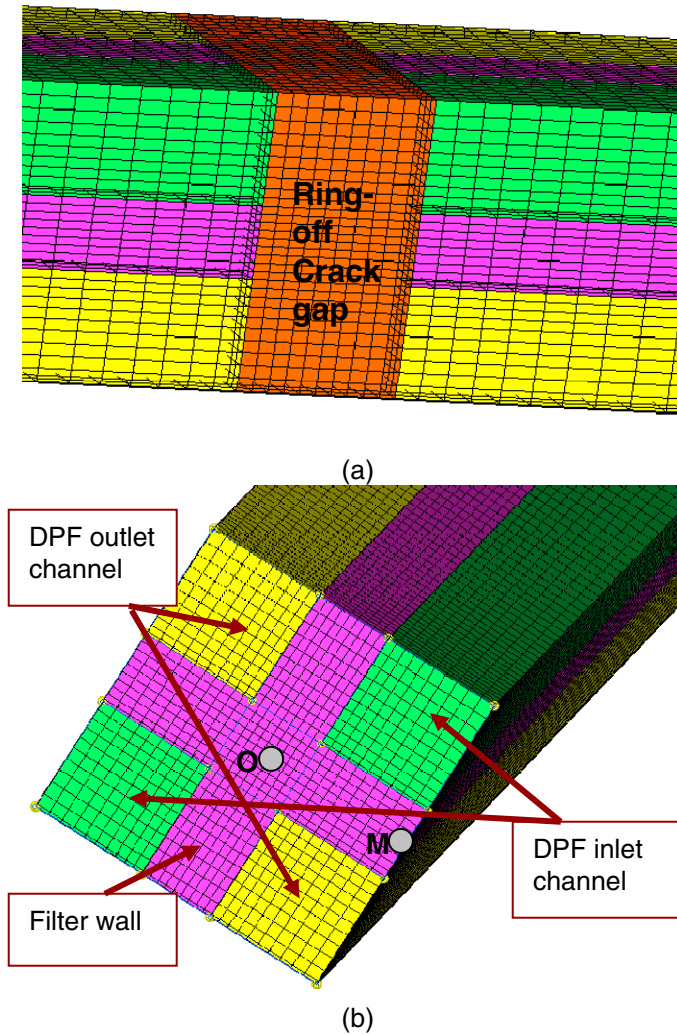


Figure 2, CFD mesh in the vicinity of DPF crack (a); and flow inlet and filter wall (b).

The PM trapping efficiency deteriorates when a ring-off crack occurs. A portion of the raw exhaust gas can bypass through the crack gap and can flow directly into outlet channel. Two basic mechanisms are involved in the PM filtration process: wall flow and channel flow. Filtration efficiency is quite high for the wall flow mechanism and is considerably lower for the channel flow mechanism. Only a small portion of the total soot contained in the exhaust gas will be collected by the channel flow mechanism. For the current study, the total filtration efficiency is defined as below.

$$\eta_{total} = \frac{\dot{m}_{wa} \times \eta_{wa} + \dot{m}_{gap} \times \eta_{ch} \times \frac{L_2}{L_{dpf}}}{\dot{m}_{total}} \quad (1)$$

Where $\dot{m}_{wa}$ and $\dot{m}_{gap}$ are exhaust mass flow through filter wall and crack gap respectively. η_{wa} and η_{ch} are the trapping efficiencies of the filter wall and channel flow mechanisms. L_2, L_{dpf} are the lengths of the downstream portion of the cracked DPF and the whole DPF respectively. For an undamaged DPF, $\dot{m}_{gap} = 0$, and $\eta_{total} = \eta_{wa}$.

CFD RESULTS AND DISCUSIONS

The Characteristics of Velocity and Pressure Distributions inside Channels and Filter Wall

A baseline study was conducted to investigate the flow and pressure distributions inside the channels of a DPF with a ring-off crack (ROC). The DPF cell structure, size and length are 200/20, 8 inches and 10 inches, respectively. The filter wall permeability and crack size are $1.8423e-13$ and 0.1 mm, respectively. For the initial baseline case, the ring-off crack is located at the axial center of substrate. The inlet boundary condition was specified as a mass flow rate. $2.07e-5$ kg/s per half channel was used for the baseline calculations². CFD results for baseline case are discussed below.

1. Velocity distribution characteristics inside the channels and filter walls for the baseline case

The velocity distributions inside a DPF channel are an important aid to understanding the soot loading characteristics within the DPF channel. Accurate soot loading information is a critical part of avoiding an uncontrolled DPF regeneration which can lead to an escalated temperature gradient and can potentially cause a DPF ring-off crack failure.

For an undamaged DPF, the velocity magnitude inside inlet channel decreases and reaches zero at the end of inlet channel where the channel is plugged and no gas flow is allowed to pass. The outlet channel is essentially the opposite, the flow velocity starts from zero and reaches its maximum value at the end of the outlet channel.

The velocity distribution inside the DPF channels changes due to the presence of a ring-off crack inside the substrate. Figure 3 depicts the velocity magnitude

² With a cell structure of 200/20, and 8 inches diameter, total exhaust gas flow rate is 1500 kg/hr based on $2.07e-5$ kg/s mass flow rate per half DPF channel.

distribution for a diagonal cross-sectional plane of an inlet channel along the flow direction. The gas flow inlet is on the right side. A very low velocity region (colored by blue) at the center represents the penetration flow through the porous filter wall. A ring-off crack is located at the axial center of the DPF substrate. The distorted (off-center crack location) view is a result of the view angle. Due to the view angle; it looks like it is very close to the end of inlet channel. Even with a very small crack (0.1mm), the flow redistribution is visible with the sudden change of color from red to green as a portion of the exhaust gas bypasses the filter wall directly into the outlet channels.

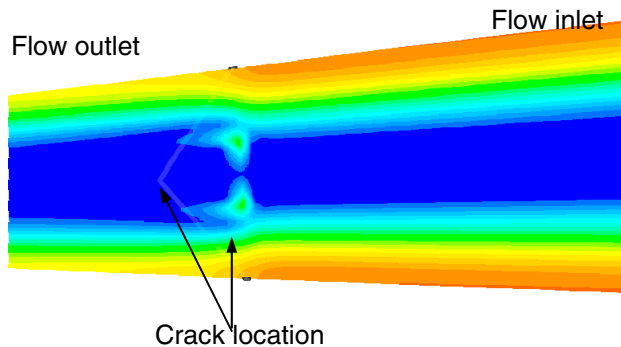


Figure 3, Velocity magnitude in a diagonal cross-section plane of an inlet channel for the baseline case.

A magnified view of the velocity vectors in the area of the ring-off crack is shown in Fig. 4. Velocity vectors are colored by magnitude and are shown in two planes. The XZ plane is a diagonal plane across an inlet channel and the XY plane is a diagonal plane across an outlet channel. A sudden decrease in velocity along the opposed Z direction is seen in "zone 1" on the XZ plane, while a rapidly increasing velocity zone is seen in "zone-2" on the XY plane. The velocity change represents the flow bypassing from the inlet channel to the outlet channel.

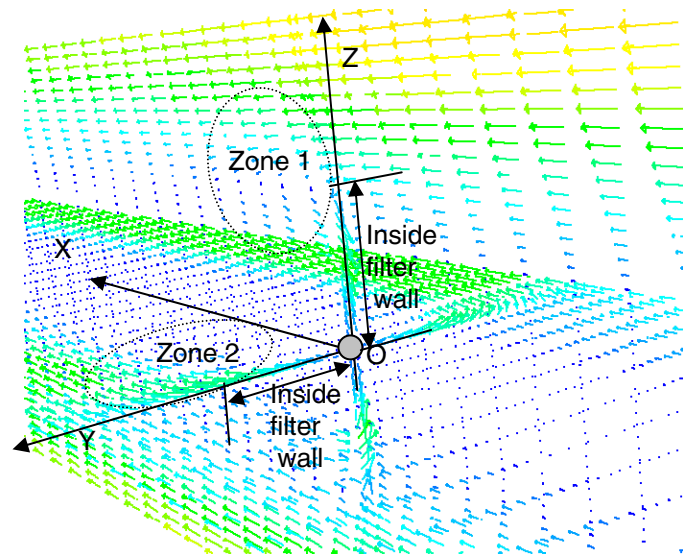


Figure 4, Velocity vectors on diagonal cross-section planes of an inlet and outlet channel for the baseline case.

The velocity magnitudes along the centerlines of the inlet (in black) and outlet (in red) channels are plotted in Fig. 5. At the ROC location a rapid decrease in velocity magnitude is seen in the flow of the inlet channel and a sudden increase is seen in the outlet channel due to the exhaust gas bypassing through the crack. At the front of an inlet channel, a nonlinear increase of velocity is observed due to the uniform velocity assumption at the flow inlet boundary. As exhaust gas flows through an inlet channel, a typical uniform velocity profile develops until the flow is fully developed with the maximum velocity at the center of the channel. As the gas mass flow decreases along the channel due to the wall flow phenomenon, the velocity magnitude decreases as the fluid flows towards the crack location. The inlet channel centerline velocity magnitude (in black) decreases in a linear fashion downstream of the ROC. In contrast to the inlet channel behavior, the velocity magnitude in the outlet channel (in red) increases in a linear fashion both before and after the ROC (with the exception of the jump at the crack location).

The higher velocity magnitude at the flow outlet results from the exhaust gas density change due to local static pressure variations. Lower pressure results in lower gas density. Even though temperature has opposite effect on density, the density change due to temperature is very small across converter due to the fiber mat insulation. Thus, for a fixed mass flow rate and cross-sectional flow area, a lower density results in a higher velocity magnitude.