

Analysis of Asymmetric and Variable Cell Geometry Wall-Flow Particulate Filters

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ABSTRACT

Asymmetric and Variable Cell (AVC) geometry Diesel Particulate Filters (DPF) occupy an increasing portion of the DPFs currently offered by various DPF manufacturers, aiming at providing higher filtration area in the same filter volume to meet demanding emission control applications for passenger cars but also for heavy duty vehicles. In the present work we present an approach for designing and optimizing such DPFs by providing a quantitative description of the flow and deposition of soot in these structures. Soot deposit growth dynamics in AVC DPFs is studied computationally, primary and secondary flows over the inlet channels cross-sectional perimeters are analyzed and their interactions are elucidated. The result is a rational description of the observed growth of soot deposits, as the flow readjusts to transport the soot particles along the path of least resistance (which is not necessarily the shortest geometric path between the inlet and outlet channel, i.e. the wall thickness). The theoretical description is in excellent agreement with experimental data obtained with two different families of AVC DPFs operated in the exhaust of a diesel engine and can be employed to design new DPF configurations with substantially lower pressure drop than existing designs.

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INTRODUCTION

Diesel Particulate Filters (DPFs) have entered their fourth decade of life and are here to stay as the undisputable most effective technology for the abatement of particle emissions from Diesel engines. As their application expands from passenger cars to heavy duty vehicles, off-road machinery and in the near future to marine and locomotive emission control the industry is in constant search for new designs and configurations to improve on all operational aspects of DPF technology.

DPFs are in their most prevalent form multichannel monolithic reactors direct descendants of the honeycomb structured catalytic converted substrate. For many years the geometric configuration of these reactors has relied on a multichannel assembly configuration with equal numbers of inlet and outlet channels of identical cross-sectional geometry obtained by the alternate plugging of the basic honeycomb structure. Various channel geometries have been described in the scientific and patent literature but the predominant cell shape is that of a square channel. Only in the last decade this trend has been broken as the introduction of asymmetric cell designs [1, 2, 3] has been pursued to provide additional filtration area and storage space for the ashes that inevitably accumulate in the DPF. In [4] the first computational study of such asymmetric cell designs has been undertaken and the mechanism of soot deposit growth dynamics in asymmetric channel designs was

elucidated: the flow readjusts to transport the soot particles along the path of least resistance (which is not necessarily the shortest geometric path between the inlet and outlet channel) and in this fashion the utilization of the entire internal surface area of the inlet channels becomes possible. This has explained the "paradox" of soot deposit growing on filter walls between adjacent inlet channels which presumably have no pressure difference between them. Follow-up studies [5, 6, 7] have addressed modeling aspects of asymmetric cell DPFs, with varying degrees of simplification and in all cases adopting a single valued "wall/filtration velocity" without explicit considerations of secondary flows phenomena over the different parts of the (generally nonsquare) cell geometry.

Very recently [8-9] the concept of asymmetric DPF designs has been extended to the so called asymmetric hexagonal (HEX) shape configuration. In this design there are more inlet channels than outlet channels and in this fashion a larger filtration area is obtained. So far all asymmetric cell DPF designs have relied on one type of inlet channel and one type of outlet channel while their assignment into each particular configuration, is effected by the plugging pattern. We can then use the general term Asymmetric and Variable Cell (AVC) geometry to describe the general class of such DPF designs. A particular asymmetric cell design [1], that of the octo-square (OS) has recently [10] been modified to provide an asymmetric and variable cell DPF layout (the so-called,

Valuable Plugging Layout, VPL). The VPL configuration introduces the concept of two different types of inlet channels and one type of outlet channel (Figure 1).

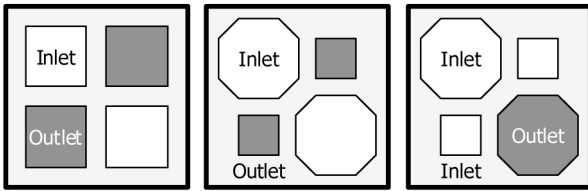


Figure 1. DPF cell configurations. Left: Square symmetric. Center: Octo-square asymmetric (one type of inlet-one type of outlet channel). Right: VPL asymmetric [10] design (two types of inlet channels one type of outlet)

The advent of such AVC DPFs in the market necessitates the extension of the DPF simulation framework that we have elaborated since 1989, recently reviewed in [11, 12]. The goal of the present paper is then to introduce a rational and tractable mathematical description of asymmetric and variable cell geometry DPF designs. The present work is concerned with the loading phase of such DPFs and aims to describe the flow dynamics and pressure drop under soot loading. For reasons of methodological clarity the filtration characteristics and regeneration behavior of such DPFs will be presented in different forthcoming contributions. The structure of the present paper is as follows. First we introduce a general description accounting for two types of inlet channels (motivated by the VPL [10] design) which subsequently is reduced to the one type of inlet channel variety such as the OS and HEX designs. The model is parameterized for arbitrarily shaped inlet and outlet channels. We employ experimental data from tests with OS and VPL DPFs to validate the approach and then we conclude by providing insights on the secondary flows and soot deposit growth dynamics in such designs to arrive at optimized configurations.

THEORETICAL

Case 1: Two Types of Inlet Channels

The starting point is an AVC filter constructed with *two types of inlet channels* and *one type of outlet channel*. The mathematical formulation is based on a unit cell which is the basic symmetry unit of the structure (Figure 2).

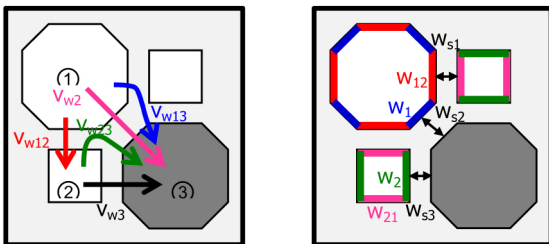


Figure 2. Left: Primary and secondary wall-flows and filtration velocities. Right: The different soot deposits growing in each wall of a VPL type DPF under the action of each filtration/wall velocity. Inlet channels are designated as 1 and 2 while outlet channel as 3.

The wall velocities are defined with respect to the initial inlet channel perimeter(s) and the same convention is also used for the channel velocities which are defined with respect to the clean channel cross section. Such a definition allows for a structurally simpler and therefore advantageous mathematical model formulation, while at the same time all balance equations are rigorously enforced at the appropriate boundaries and control volume surfaces. Values of velocities over any other control surfaces can be calculated after the flow solution and soot deposit growth/shape has been obtained. The filter is assumed to operate under gas-solid thermal equilibrium conditions (which in practice includes variable gas temperature with slow variation with respect to the characteristic time of filter heating). Let us assign the index '1' to the primary inlet channel (the larger one) the index '2' to the second inlet channel and the index '3' to the outlet channel (having similar geometry to that of channel '1'. The wall between channels '1' and '2' is denoted as wall '1', between channels '1' and '3' as wall '2' and between channels '2' and '3' as wall '3'. The cross section of channel with index i per unit cell is denoted as A_i and the perimeter of the wall with index i is denoted as Π_i (this perimeter is always taken from the side of the channel with smaller index). The two inlet channels have always larger local pressure than the outlet channel. The local pressure difference between the inlet channels can have any sign so it must be taken into account by the corresponding mass balances. With reference to Figure 2 the gas moves from channel to channel in the following ways: (i) from channel '1' to channel '2' across wall '1' with velocity v_{w12} , (ii) from channel '1' to channel '3' across wall '2' with velocity v_{w2} (iii) from channel '1' to channel '3' along wall '1' with velocity v_{w13} (iv) from channel '2' to channel '3' across wall '3' with velocity v_{w3} (v) from channel '2' to channel '3' along wall '1' with velocity v_{w23} .

All the above flow paths are found to be potentially significant and they must be included in the model. The sign convection for the velocities is that they are positive if their direction is the already described previously and negative if their direction is the opposite one.

The gas mass balances for the three types of channels are:

$$A_1 \frac{\partial u_1}{\partial z} = -\Pi_1 v_{w12} - \Pi_1 v_{w13} - \Pi_2 v_{w2} \quad (1)$$

$$A_2 \frac{\partial u_2}{\partial z} = \Pi_1 v_{w12} - \Pi_1 v_{w23} - \Pi_3 v_{w3} \quad (2)$$

$$A_3 \frac{\partial u_3}{\partial z} = \Pi_1 v_{w13} + \Pi_2 v_{w2} + \Pi_1 v_{w23} + \Pi_3 v_{w3} \quad (3)$$

where u_1, u_2, u_3 are the cross section averaged velocities in channel '1', '2', '3' respectively.

It can be shown that in any case of the practical filter operation the contribution of convective momentum transport term to the pressure drop along the channels is insignificant. The momentum balance for channel "1" can be written as:

$$\frac{\partial P_1}{\partial z} = -\alpha_1(t)\mu u_1 \frac{A_1}{A_{1t}(t)} \quad (4)$$

where P_i is the pressure in channel with index i , μ is the gas viscosity, α_1 is a coefficient that depends only on the shape and size of the channel cross section and $A_{1t}(t)$ is the remaining cross section of the channel after the abstraction of the soot cake cross section. The corresponding balances for the other channels are (given that there is no soot cake in channel "3"):

$$\frac{\partial P_2}{\partial z} = -\alpha_2(t)\mu u_2 \frac{A_2}{A_{2t}(t)} \quad (5)$$

$$\frac{\partial P_3}{\partial z} = -\alpha_3\mu u_3 \quad (6)$$

Let us denote as w_{s1} , w_{s2} , w_{s3} the thicknesses of the three walls respectively. The corresponding cake thicknesses are denoted as w_{12} , w_1 , w_2 respectively. It is noted that there is a possibility for cake development at the channel "2" side of the wall "1". The corresponding cake thickness is denoted as w_{21} . The gas permeance along wall "1" is described through an effective wall thickness w_{eff} which can be found by solving an appropriate flow in porous media problem, over the actual porous wall cross section. The wall flow rates are related to the pressure differences between the channels through the following equations:

$$v_{w12} = \left(\frac{\mu w_{s1} k_w}{k_s} + \frac{\mu(w_{12} + w_{21})}{k_s} \right)^{-1} (P_1 - P_2) \quad (7)$$

$$v_{w13} = \left(\frac{\mu w_{eff}}{k_w} + \frac{\mu w_{12}}{k_s} \right)^{-1} (P_1 - P_3) \quad (8)$$

$$v_{w2} = \left(\frac{\mu w_{s2}}{k_w} + \frac{\mu w_1}{k_s} \right)^{-1} (P_1 - P_3) \quad (9)$$

$$v_{w3} = \left(\frac{\mu w_{s3}}{k_w} + \frac{\mu w_2}{k_s} \right)^{-1} (P_2 - P_3) \quad (10)$$

$$v_{w23} = \left(\frac{\mu w_{eff}}{k_w} + \frac{\mu w_{21}}{k_s} \right)^{-1} (P_2 - P_3) \quad (11)$$

Where k_w and k_s are the specific permeabilities of the wall and of the soot cake respectively.

The evolution equations for the four soot cakes are:

$$\frac{\partial w_{12}}{\partial t} = \frac{v_{w1} \rho_g \phi_1}{\rho_s} \quad (12)$$

$$\frac{\partial w_{12}}{\partial t} = \frac{\Omega(-v_{w12} + v_{w23}) \rho_g \phi_2}{\rho_s} \quad (13)$$

$$\frac{\partial w_1}{\partial t} = \frac{v_{w2} \rho_g \phi_1}{\rho_s} \quad (14)$$

$$\frac{\partial w_2}{\partial t} = \frac{v_{w3} \rho_g \phi_2}{\rho_s} \quad (15)$$

Where ρ_g is the gas density, ρ_s is the soot cake density and ϕ_1 , ϕ_2 the local soot mass fraction in gas phase for channels "1" and "2" respectively. The function $\Omega(x)$ is defined as $\Omega(x)=x$ for $x>0$ and $\Omega(x)=0$ for $x\leq 0$.

The gas phase soot mass balances in channels are:

$$A_1 u_1 \frac{\partial \phi_1}{\partial z} = -\phi_1 \Pi_1 \Omega(-(v_{w12} + v_{w13})) \quad (16)$$

$$A_2 u_2 \frac{\partial \phi_2}{\partial z} = -\phi_2 \Pi_2 U(v_{w12} - v_{w23}) \quad (17)$$

The boundary conditions for the above equations are

$$P_3 = P_{atm} \text{ at } z=L, \quad A_1 u_1 + A_2 u_2 = (A_1 + A_2) u_o, \quad \phi_1 = \phi_2 = \phi_{in} \text{ at } z=0$$

where

u_o is the average inlet velocity of the channel and it can be found from the mass flow rate per unit open cell frontal area.

ϕ_{in} is the inlet mass flow rate.