Multi-Scale Modelling and Experimental Measurements of Soot Filtration in DPFs
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1. Introduction

There is an established awareness concerning the health effects caused by soot emissions of diesel exhausts in automotive applications. It is widely accepted that soot particles emitted by diesel engines act as carriers for a number of substances associated with health effects, and long-term exposure to fine particulate matter is a proven risk factor for cardiovascular disease mortality, as suggested by many authors [1].

Nowadays, soot emissions can be reduced by physically trapping the particles within on-board Diesel Particulate Filters (DPFs). The filter gets progressively loaded by filtering the soot laden flue gases, thus causing an increasing pressure drop, until regeneration takes place. The DPFs described in this work are wall-flow monoliths, characterized by a chessboard-wise structure. Hence, channels are alternatively plugged at the inlet, thus allowing the gas to enter the filter, while at the end of the filter the plugs are reversed, in order to force the gas flowing through the porous walls of adjacent channels.

This work presents some experimental observations concerning spatial distributions of soot inside the channels of a DPF, at the end of a loading cycle. Tests were done with two different geometries of the filter housing, which demonstrated to considerably affect the outcome of the results. In particular, the two geometries were responsible for different velocity profiles at the inlet of the filter, resulting in one case in a strong maldistribution at the filter inflow, while in the other case in a rather less pronounced unevenness.

Some considerations are drawn about the most suitable CFD model to reproduce the behaviour of a DPF under various operating conditions, aiming at predicting the spatial and temporal distributions of deposited soot concentration.

2. Experimental data

Experimental tests have been carried out on lab-scale DPFs in order to assess the soot deposition profile inside the filter channels. The tested filter here reported has 300 cpsi, is 17.7 cm long and 2.54 cm in diameter. As mentioned, two different filter housings were investigated: Fig. 1 reports the first test rig, characterized by pipe of 4 cm in diameter (where the filter was canistered), connected through a conic surface to the gas inlet pipe (6 mm in diameter).

**Fig. 1  Sketch of the first filter housing.**
The filter was loaded through a synthetic soot generator (Aerosol Generator GFG-1000-PALAS) at a flow rate of 46 l/min. The soot mass flow rate was 6 mg/h, and loading lasted approximately 24h. Synthetic soot was employed in order to achieve reproducible data, since real diesel soot would be indeed too much dependent on the ever-changing driving conditions. Due to the geometrical shape of the conical junction, the inlet velocity of the gas at the front surface of the filter was extremely uneven. Therefore, each channel of the filter experienced a different inlet velocity. In particular, the flow into the central channels was higher due to the persistence of a gas jet, generated in correspondence to the 6 mm pipe outflow, and not dissipated in the cone. These phenomena occur also in real full scale DPFs, since the adduction pipe is far smaller than the monolith’s diameter and an uneven distribution of the gas into the channels occur.

In order to verify such behavior, the cake thickness inside the channels was evaluated from SEM images, thus obtaining a mean value from local measurements (Fig. 2). The measurements include channels from the centre to the periphery of the filter, each one evaluated at different axial positions: this was done by cutting the filter in segments, still preserving the structure of the layer as can be seen in Fig. 2. When comparing channels at the same axial position (channels are named 1 up to 4 from centre to periphery in Fig. 3-right) it appears that lateral channels are poorly loaded, while the central ones are considerably involved in soot filtration, being the cake almost two-fold thick. Instead, if one focuses on the thickness in a single channel, at different axial positions (Fig. 3-left) it appears that in channel 1 (central one) the cake has a minimum thickness at around half of the total filter length, while the edges are more heavily loaded since there velocity is higher. In the other channels (2-3-4 and 5-6-7), whose profiles are similar, soot cake is thinner and with a lower variation along the axial coordinate, indicating a lower through-wall velocity, due to a poor inlet flow.

Fig. 2 Thickness of the soot layer along the filter, measured (SEM figure) at the midline of the inlet channel 7 (face at z=2cm): 150X and 1200X.

Fig. 3 Experimental thickness of the soot layer along the filter. Left: different axial positions (▼-ch.1, ▲-ch.2, ●-ch.3, ■-ch.4); right: channel locations (face at z=2cm).
In order to reach a more even deposition of soot inside the channels of the filter, a new housing was designed: as depicted in Fig. 4, the filter was canistered in a pipe of 3.8 cm in diameter, having a much longer inflow region (150 mm), a less pronounced conic junction (90 mm instead of 30 mm in Fig. 1), and a greater inlet pipe diameter (10 mm instead of 6 mm) affecting the gas velocity. The pressure was measured at the front and at the back of the filter (sampling points are denoted by $P$ in Fig. 4), which account for the real pressure drop across the filter. Instead, in the first filter housing, the sampling point was before the conic junction, thus including the expansion losses in the total measured pressure drop.

![Fig. 4 Sketch of the second filter housing.](image)

This configuration reduced considerably the effects of maldistribution at the filter inlet, as can be seen by the measurements of cake thickness in Fig. 5 (obtained with the same procedure as described for Fig. 2 and 3). The cake thickness shown in Fig. 5 with the ♦ symbols represents the mean value of the soot layers measured in channels from 1 to 7 (the channel labeling follows the same rules discussed so far). The deviation from the mean value is expressed by the vertical bar, which takes into account the maximum and minimum mean thicknesses of each channel. A certain variation of the cake thickness in the channels is observed at 5 cm and 9 cm from the inlet, but no clear accumulation in one or some of the channels emerges like in Fig. 3 in correspondence of channel 1. Beside differences in cake accumulation, the same trend is confirmed in both housing systems, leading to a greater concentration at the beginning and the end of the filter. It has to be pointed out that this feature is not due to inertial effects, that might cause a deviation of the particles trajectories from the streamlines of the fluid, and their entrainment at the end of the filter. Indeed, the soot particles produced by the generator are commonly below 600 nm, for which inertia is negligible. As a matter of fact, such accumulation is induced by the peculiar profile of the through-wall of both gas and particles, as described in our past papers [2-3].

![Fig. 5 Experimental thickness of the soot layer along the filter, housed as in Fig. 4. ♦-mean value, and maximum deviations.](image)
During soot loading, the pressure drop across the filter was recorded. In the first housing, this was done by measuring the relative pressure before the filter inlet, while in the second case it was obtained as the difference between the pressure before and after the filter itself. The two pressure drop profiles are compared in Fig. 6. In both plots the phases of soot filtration are clearly visible: firstly, soot accumulates in the pores of the filter wall, causing a progressive modification of the filter porosity, permeability and collection efficiency, and the pressure evolution in this step (called depth filtration) is mainly determined by the physical parameters of the filter material. Subsequently, a soot layer starts building on the top of the occluded filter pores (cake filtration step). This step is characterized by a steady increase of the pressure drop, indicating the progressive thickening of the cake with time. Fig. 6 shows in both plot a loss of linearity in the last part of the curve, because of a reduced open area available for the gas, which increases the gas velocity (and the friction) inside the channels.

From Fig. 6 it appears that the bare filter pressure drop measured in the first housing (Fig. 6-left) is considerably higher than that in the second one (Fig. 6-right), and this is mainly due to the fact that the sampling point was before the conic junction in the former case, thus accounting for both the filter pressure drop and the loss caused by gas expansion effects. However, the maldistribution at the filter inlet and the unevenness of soot deposition in the filter channels was found not to greatly influence the evolution of the pressure drop as long as soot is collected. The reason lays in the limited number of channels involved by such maldistribution, while most of them experience soot loadings similar to the ones of the second housing (compare channels 2 to 7 in Fig. 3 with Fig. 5).

Even if the pressure drop does not change considerably from one case to the other, soot deposition profiles have also another important implication: during regeneration, depending on the ignition temperature and on the oxygen concentration, the soot cake burns with different rates according to its deposition profile inside the filter. During regeneration, the time scale of the soot ignition phenomenon is very small, and as soon as soot ignites, local gradients of temperature become immediately quite high. If in some regions an excessive amount of soot deposited occurs due to the maldistribution of the inlet flow, the high heat released during to combustion could cause cracks or melting of the porous support.

A detailed prediction of the soot deposition profiles inside the channels of the filter through a mathematical model could be useful to tailor the trap design, both to accumulate soot through patterns allowing low pressure drops, and to drive a “safe” regeneration with no major thermal cracks produced by hot spots (this is useful also in the perspective of catalytically coated filters, currently under investigation).
3. Numerical simulation

Two grids should be adopted to properly simulate this system with CFD codes: the channel scale grid (Fig. 7) and the filter scale grid, from which one fourth of the DPF is depicted (Fig. 8). The three-dimensional geometry adopted to simulate the channel scale consists of four modeled channels: two of them allow the gas to enter the filter, while the other two are plugged (see Fig. 7); at the end of the filter, plugs are reversed. Before the inlet of the filter, there is an upstream region where a flat velocity profile is set. Similarly, after the filter, the flow fully develops in a downstream region. As far as the boundary conditions of the domain are concerned, the lateral faces are set as periodic. This allows modeling the behaviour of real DPFs, characterized by a periodic structure of hundreds of cells per square inch, only in the hypothesis that an even flow rate enters in each DPF channel. Details on these calculations and on their implementation in the CFD code Fluent through User-Defined-Subroutines can be found in our previous work [2,3].

![Fig. 7](image1)

**Fig. 7** Sketch of the grid used to simulate the flow field in the four channels constituting the computational domain.

![Fig. 8](image2)

**Fig. 8** Sketch of the grid used to simulate the full scale DPF.

The full scale grid aims at solving the flow field inside the filter housing, and therefore to compute the proper gas flow rate entering each channel of the filter. For the sake of clarity in Fig. 8, the complete grid of the filter housing, of which the DPF grid is only a part, is not shown. It can be seen that channels are included in the model, but instead of being solved individually by computing the internal flow field, they are considered as having an equivalent viscous resistance, such as the resulting pressure drop corresponds to the one predicted by the channel model. In turn, this grid gives the inlet flow rate into each channel, depending on its radial position. Not all the channels are solved explicitly, since interpolation can be used to lighten the computational cost. The ongoing investigation is focussed on optimizing computational costs arising from the coupling of the two scales models, during the soot loading phase. As a preliminary result, Fig. 9 shows the computed inlet velocities into the DPF channels along a filter radius, at the beginning of the filtration process (bare filter). It is
clearly visible that a strong maldistribution of the flows is predicted in the case of first test-rig (Fig. 9-left), since the gas inlet from the 6 mm pipe is very close to the DPF frontal surface. Moreover, the gas strongly decelerated when approaching to the DPF inlet, thus being forced to recirculate back, with the consequence that the inflow in the channels is not perpendicular to the inlet DPF surface.

![Fig. 9 Computed axial component of the inlet velocity into the bare filter, housed as in Fig. 1 (left) and Fig. 4 (right).](image)

4. Conclusions

Features of cake deposition profiles inside the channels of a DPF are here investigated: experimental SEM observations reveal that the soot layer thickness is not constant along the axial coordinate, being minimum at around half of the channel length. In addition, according to the distribution of the gaseous flow at inlet of the filter, the behaviour of soot deposition is strongly affected by the channel position with respect to the radial coordinate. It emerges that, according to the filter housing and the inlet flow pipes, a strong gas maldistribution could occur at inlet of the filter itself, thus making some channels far more loaded of soot rather than others.

This has some important implications in the regeneration step, since soot combustion has to be carried out uniformly inside the filter, and in particular without unpredicted heat release in some points, due to excessive soot accumulation. A multi-scale model for the description of soot filtration through DPFs is therefore needed: beside the channel scale model, which was already presented in past papers, a full scale model is under development, in order to reproduce the features encountered in the experimental SEM observations.

5. References