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Experimental and computational approach to the transient behaviour of wall-flow diesel particulate filters

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ABSTRACT

The implementation of tight vehicle emission standards has forced manufactures to use aftertreatment systems extensively. In addition to pollutant emissions abatement, these devices have a noticeable impact on the wave pattern. This fact affects the muffler design criteria. All monolithic aftertreatment devices produces a damping effect because of the honeycomb structure and the narrow channels. However, this response is more marked in wall-flow diesel particulate filters (DPF) because of the alternatively plugged ends and the dissipative properties of the porous substrate.

The main goal of this paper is to assess the transient fluid-dynamic behaviour of wall-flow DPFs using experimental and modelling techniques. The experimental data were gathered in clean and loaded conditions. The DPF was subjected to a variety of pressure excitations to characterise its transient behaviour in the time and frequency domains. Afterwards, the DPF response was evaluated under engine-like operating conditions in an unsteady flow gas stand. Once the main characteristics of the response were known, a non-linear gas-dynamics model was proposed for analysis and prediction. The model accounts for space and time gradients, combining the thermo-and fluid-dynamic solution with a model based on a packed bed of spherical particles that defines the meso-structure of the loaded substrate.

1. Introduction

As a result of the restrictions imposed by regulations on particulate matter emissions from compression ignition engines, diesel particulate filters (DPFs) have become an indispensable device in exhaust lines [1]. Similarly, current and incoming standards on spark ignition engines combined with developments associated with turbocharged and direct injection gasoline engines [2] are also demanding the use of gasoline particulate filters (GPF) as the only system proven to fulfill limits on emitted particle numbers [3].

The development of particulate filters is constrained by the need of high filtration efficiency, so that standards in mass and number of emitted particles are fulfilled, together with a reasonable pressure drop. A good trade-off between these two aspects must be complemented with suitable characteristics of the substrate making possible safe and reliable regeneration as well as providing good thermal and mechanical responses [4]. These characteristics define the filter capability to abate particulate matter emissions, its influence on engine performance and the life cycle and maintenance requirements of the system.

The complexity of the concurrent phenomena has given rise to the study of alternatives, comprising the consideration of different substrate materials [5] and even flow path-lines [6]. Among all of them, cordierite and SiC wall-flow monoliths have shown the best balance between all requirements [7]. Therefore, manufacturers have massively installed wall-flow DPFs in both heavy-and light-duty compression ignition engines since their use became commonplace at the beginning of the present century [8].

Wall-flow DPFs are monolithic structures with alternatively plugged axial parallel channels at each end. The exhaust gas goes into the inlet channels and finds the closed end so that it is forced to flow across the porous wall of the ceramic substrate. During this process, particles are firstly collected inside the porous wall in a regime known as deep bed filtration. When the porous wall gets saturated, the soot is then deposited on its surface forming the particulate layer and reaching filtration efficiency above 95% even for ultra-fine particles [9]. However, the geometrical characteristics of this solution lead to a non-negligible pressure drop that increases the exhaust back-pressure, specially as the DPF gets loaded. This effect directly implies a fuel penalty [10] to which is added the

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subsequent regeneration. In fact, the most effective way to promote soot oxidation appears to be the use of active strategies such as late fuel injection [11], NO_2 assisted passive regeneration [12] or the use of fuel-borne catalysts [13].

Strategies aiming to reduce the wall-flow DPF effects on engine fuel economy are mostly based on pressure drop control. Promising solutions, such as the optimization of DPF sizing [14] or the use of inhomogeneous substrates [15], pre-turbo DPF location [16] and pre-DPF water injection [17] have been proposed. Most of these strategies have also very positive effects on passive regeneration capability [18] and provide higher flexibility than active regeneration control strategies based exclusively on pressure drop [17]. The benefits brought by these techniques cover also the effects of ash [19] and their ability to be combined with particular solutions aiming at increasing ash storage capacity, such as asymmetrical cell design [20].

Although the main purpose of the wall-flow DPF is the reduction of particulate matter emissions, its presence affects the unsteady wave dynamics in the exhaust system [21]. The flow path, the canning and the absorbent ceramic material composing the wall-flow monolith introduce a dissipative effect upstream of the muffler [22]. This modifies the boundary conditions for muffler design, usually leading to a substantial volume reduction [23] or even to its removal in cases of severe packaging restrictions [24], with the subsequent repercussion on exhaust backpressure. The use of computational models able to predict the DPF behaviour under different soot loading and unsteady flow conditions are an advantage to reduce the time and cost of the development process.

Fist attempts to model unsteady flow in catalytic honeycomb structures were restricted to the linear regime and date back to the work of Glav et al. [25]. The first work exclusively devoted to wall-flow DPFs was presented by Allam and Åbom [26], who proposed a linear 1D model. The main limitation of this first effort was the lack of wall boundary layers, that were included in later works [21]. Finally, they developed a new version of the model including a correct description of the visco-thermal boundary layers for square cross-section channels [27]. The model proposed by Allam and Åbom is the basis for the definition of the transfer matrix in other linear models such as the 3D-FEM models proposed by Hua et al. [22] to improve the prediction of the DPF response at very high frequencies. FEM modelling has been also explored by Gao et al. [28] with further discussion on the correction of the viscosity. Recently Hua et al. have explored the validity of the plane wave assumption in large monoliths by means of BEM and FEM techniques. An important influence of the inlet and outlet characteristics on the design of the muffler system has been found [29].

The purpose of this paper is to assess the behaviour of wall-flow DPFs in unsteady flow by combining experimental and modelling approaches. The experimental campaign was the basis for the subsequent computational study and covered clean and soot-loaded DPF conditions. For every soot loading condition, the DPF was firstly subjected to tests in an impulse test rig, i.e. to unsteady pressure excitations at room temperature. The unsteady behaviour under engine-like operating conditions was evaluated in a gas stand equipped with a rotary valve providing a periodic excitation superimposed to a mean flow. The use of this facility allowed controlling the flow characteristics, such as the gas temperature, while keeping constant the soot loading. Finally, for the proper interpretation of the experimental results a non-linear gas dynamic model of the DPF was developed. The proposed model solves the 1D compressible unsteady non-homentropic governing equations [30] in the monolith channels as well as the inertial pressure drop in the inlet and outlet canning volumes. Temperature gradients in the axial and radial directions are described by means of a heat transfer sub-model based on nodal discretization of the monolith porous medium [31]. The change of the meso-structural properties of the porous medium, for both the porous substrate and the particulate layer, are computed as a function of the soot loading [32] assuming an equivalent packed bed of spherical particles [32]. These features of the model provide an accurate description in the time and frequency domains of the observed effects in terms of pressure drop and pressure wave transmission and reflection.

2. Experimental facilities and test campaign

The unsteady behaviour of the DPF was explored considering two basic test facilities: experiments without mean flow in an impulse test rig and experiments with mean flow in a flow test rig able to provide pulsating flow with temperature control. The main characteristics of the tested DPF are summarised in Table 1. All tests were performed with fresh air. Although the use of air instead of simulated exhaust gas has effects on the fluid thermal properties and hence on the speed of sound, the use of air is preferable. The most important reason is the need to avoid the variation of the soot loading during the tests. Use of air allows keeping constant soot loading in every kind of test and provides flexibility and repeatability to extend the test campaign. Additionally, it use defines a clear baseline for thermal properties assessment since the specific heat is only dependent on temperature but not on the fuel-air equivalence ratio, which should be considered as additional parameter in the case of exhaust gas use.

2.1. Impulse test rig

Experiments without mean flow were performed in an impulse test rig able to control the amplitude and the duration of an isolated pressure excitation travelling along the piping installation and the DPF. This kind of test allows evaluating the reflection and transmission characteristics of the system avoiding any influence of reflections from the pipe ends of the test rig. Payri et al. [33] presented the experimental method applied in the impulse test rig for the measurement of the frequency response to weakly nonlinear transient excitations. The validation of the method was performed against one-dimensional unsteady nonlinear flow calculations of well-known simple filter geometries. In some cases, only quantitative deviations from the expected linear behaviour were observed, due to the extra amount of dissipation associated with nonlinear flow. In other cases, however, qualitative differences may appear, with changes in the detail of the results which, in principle, can be explained by attending to the possibility of nonlinear energy exchange between harmonics.

Fig. 1 shows schematically the setup of the test rig [33]. The incident pulse is generated at room temperature by means of a high-speed electrovalve that controls the discharge from a pressurised air tank. The electrovalve is connected to a long duct

Table 1
Geometrical characteristics of the DPF.

Length	[m]	0.2
Diameter	[m]	0.132
Plug length	[mm]	3.2
Wall permeability	[m^2]	2.49×10^{-13}
Porosity	[%]	41.5
Mean pore diameter	[μm]	12
Cell density	[cpsi]	200
Filter cell size	[mm]	1.486
Number of channels	[–]	4246
Filtration area	[m^2]	2.5
Inlet cone volume	[cm^3]	500
Outlet cone volume	[cm^3]	450