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Filtration modelling in wall-flow particulate filters of low soot penetration thickness

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ABSTRACT

A filtration model for wall-flow particulate filters based on the theory of packed beds of spherical particles is presented to diagnose the combined response of filtration efficiency and pressure drop from a reliable computation of the flow field and the porous media properties. The model takes as main assumption the experimentally well-known low soot penetration thickness inside the porous wall. The analysis of soot loading processes in different particulate filters shows the ability of the proposed approach to predict the filtration efficiency as a function of the particle size distribution. Nevertheless, pressure drop and overall filtration efficiency are determined by the mode diameter of the raw particulate matter emission. The results reveal the dependence of the filtration efficiency in clean conditions on the sticking coefficient. However, the dynamics of the pressure drop and filtration efficiency as the soot loading varies is governed by the soot penetration thickness. This parameter is closely related to the porous wall Peclet number, which accounts for the porous wall and flow properties influence on the deposition process. The effect of the transition from deep bed to cake filtration regime on the pressure drop is also discussed underlying the importance of the macroscale over microscale phenomena.

1. Introduction

Nowadays Diesel engines are widely used in passenger and heavy-duty vehicles, especially in European countries. Compared to spark ignition engines, Diesel engines provide high torque at low regime, excellent reliability, higher tolerance to fuel properties and better fuel economy reducing CO_2 emission [1].

The evolutionary process undergone by Diesel engines has been intimately related to their high emissions of NO_x and particulate matter. The progressively more constraining emission regulations throughout the world, like current Euro 6 for passenger car and light commercial engines in Europe [2], have imposed air quality standards that require the use of after treatment devices to be met. This is the case of particulate filters (PF), whose early developments date from the 80's [3,4] but that were not implanted as a standard equipment in Diesel engines up to the beginning of the century [5]. In fact, the growing awareness of the important role of particulate matter in Earth's climate [6] as well as the significant damage that soot can produce to human health [7] and environment [8] are leading to reduce particulate matter emission limits. In Euro 6, these limits are being imposed to both emitted particulate matter mass and number. Additionally, limits apply to Diesel and new generation of direct injection gasoline engines [9]. In this context, wall-flow particulate filter systems represent the only proven technology to meet limits on emitted particle numbers [10] providing at the same time the best balance between filtration efficiency and pressure drop [11].

In this paper a model able to predict the filtration efficiency of wall-flow particulate filters is presented and discussed. The filtration computation is coupled with a pressure drop model in order to provide a complete description of the filter performance evolution from clean [12] to soot loaded conditions [13]. The experimental validation of the model evidences the relationship between these phenomena and the need to address both of them as an only process. This approach, usually neglected in filtration efficiency analysis, is shown to be required to provide a robust description of the change in porous wall properties as a function of the soot loading. Thus, a reliable prediction capability is obtained from the detailed description of the flow field along monolith channels, the soot penetration into the porous wall, the properties of the porous substrate and the particulate layer distribution.

The pressure drop generated by the filter varies as a function of

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the trapped soot mass, whose amount is dictated by the filtration efficiency. This magnitude is in turn depending on the porous media microstructure and affected by the fluid-dynamic field. The proposed model assumes the porous wall behaves as a packed bed of spherical particles. The Kuwabara's flow field around the collector unit [14] is applied. The soot penetration into the porous wall is restricted to be partial in order to agree with experimental evidences, which point out a very fast formation of a soot layer on the surface of the porous wall [15]. This result was already obtained at the early developments of wall-flow DPFs by Murtagh et al. [16]. Recent works focused on the influence of filtration velocity and particulate matter characteristics on soot loading characteristics [17] and the development of experimental techniques applied to the analysis of loaded DPFs [18] have also addressed this result. Similarly, soot and ash characterization at the catalyst-substrate interface performed by Kamp et al. [19] also indicates that the soot penetration is very reduced. These experimental insights have been corroborated by different computational studies applying the Lattice Boltzmann method to the microscale analysis of the pressure drop [20] and soot accumulation [21] processes.

According to the proposed approach, the porous wall is divided into two layers. The layer facing the inlet channel is the one responsible of the soot filtration. Soot penetration comprises a very small fraction of the porous wall thickness, usually below 5% [13]. The remaining part of the porous wall is simplified to be kept completely clean. Concerning the particulate layer, a model based on porous wall saturation is proposed to control a smooth increase of the particulate layer filtration efficiency during the initial phase of its formation. This process is also governed by the change in effective filtration area. It controls the initial growth rate of the particulate layer thickness, as experimentally described by Choi and Lee [22]. Finally, the model is validated against experimental data obtained during soot loading tests in several wall-flow PFs. The coupled modelling of filtration efficiency and pressure drop is presented as the way to unequivocally diagnose the soot penetration into the porous wall as a function of the operating conditions and the substrate properties. This allows describing the profile and change of the porous wall properties along the channels as a function of the soot loading. The analysis of the transition phase from deep bed filtration regime to cake filtration also considered. The final section of the paper is devoted to assess the ability of the model to account for the particle size distribution effect on the filtration efficiency.

2. Filtration modelling background in particulate filters

A correct modelling of the filtration process depends on the computation of the characteristics of the dispersed particles, the carrying fluid and the porous medium. Fuchs [23] and Friedlander [24] proposed filtration theories based on aerosol collection by an isolated collector making use of the Stokes [25] and Tomotika and Aoi [26] solutions for the flow field respectively. However, these flow fields are inadequate for filtration theories in packed beds as they do not take into account the mutual interference effects of neighbouring collectors [27]. Kuwabara [14] and Happel [28] proposed similar solutions for the flow field both considering null velocity on the collector surface and null vorticity or vanishing shearing stress at the outer boundary respectively. Difference is on the grain velocity [29], which affect the boundary condition. In spite of the similarity, the Kuwabara's solution resulted to be a better approximation of the flow field in packed beds. This has been stated concerning fibrous filters, as discussed by Kirsh and Fuchs [30], and spherical collectors. Lee and Gieseke [31] analysed the pressure drop in systems of multiple spheres based on the Kuwabara's flow field and proposed a theoretical expression to model the collection efficiency in a packed bed based on this approach [27].

Models based on the single collector sphere approach to calculate the filtration efficiency of wall-flow PFs and its evolution with soot loading have grown in popularity and acceptance. Konstandopoulos et al. [32] proposed the porous wall discretization in the perpendicular direction to the axial flow in the channels. The porous substrate is divided into slabs, whose filtration efficiency is calculated based on Brownian and interception collection mechanisms applied to a single collector unit. Therefore, the amount of soot that is not deposited in each slab is tracked to the following one thus obtaining the soot distribution across the porous wall and the overall filtration efficiency. This approach imposes the penetration of a non-negligible amount of soot across the porous wall [33]. As discussed in Section 1, such a result contradicts experimental and Lattice-Boltzmann computation evidences, which point out very low soot penetration thickness. On the other hand, the transition from deep bed to cake filtration regime is controlled by the so-called partition coefficient. This parameter defines the fraction of mass collected in the first slab that contributes to form the particulate layer based on the definition of the blocked cross-section area of the single sphere.

The use of the partition coefficient means that the filtration process in the particulate layer is completely controlled by the porous wall properties instead of the growth dynamic of the soot deposits collected on it. To avoid this concern, Johnson et al. [34] propose to compute the filtration efficiency of the particulate layer as a function of the particulate layer thickness and the efficiency of the single collector unit, which is represented by the mean diameter of the aggregate particles. However, the maximum value of the filtration efficiency must be set from empirical data.

Also based on the slabs model, Tandon et al. [35] included the influence of the inertial contribution on the filtration efficiency applying the expression proposed by Langmuir [36]. In this model the change of the filtration efficiency during the deep bed filtration is modelled by two regimes distinguished by a transition permeability. Firstly a rapid increase of the filtration efficiency is obtained due to the reduction in porous wall porosity and increase in collector unit diameter. This regime lasts until the porous wall permeability decreases up to the transition limit. Once this value is reached, the additional soot deposition results in the reduction of the number of collectors due to the blocking of some of the pores. As a consequence, the increase of the filtration efficiency is more gradual. Once the number of collectors has dropped below a critical amount, the particulate layer starts its growth. Although this approach was shown to calculate accurate filtration efficiency, it was not coupled to a pressure drop model. Therefore, the effects of the increasing filtration velocity because of the effective filtration area reduction during the transition phase were not evaluated on pressure drop.

Bollerhoff et al. [37] proposed a model discretizing the porous wall into slabs but using the single sphere approach only to assess the clean filtration efficiency. The change in filtration efficiency of a single sphere as soot is collected is approached by a wall saturation index. On the other hand, the transition phase to cake filtration regime is governed by two overlapped mechanisms. The first mechanism sets a value for filtration efficiency in the particulate layer during its initial formation. This mechanism depends on the porous wall porosity so that the cake filtration regime begins once the porous wall porosity is below a critical value. The second mechanism is responsible of the modelling of the last phase of the cake formation once it comprises a dense particle structure. Therefore, the filtration efficiency depends on the soot mass amount collected in the particulate layer.