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A simple semi-numerical model for designing pleated air filters under dust loading

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ABSTRACT

In this work, we present a semi-numerical 2-D model for predicting the instantaneous pressure drop and collection efficiency of filters made up of rectangular and triangular pleats in both depth and surface filtration regimes. Inspired from previous CFD simulations, our semi-numerical model adopts appropriate average velocity profiles in the axial and lateral directions to approximate the flow field inside rectangular and triangular pleat channels. The model therefore circumvents the need to obtain a CPU-intensive solution for the partial differential equations governing the flow through a filter, i.e., Navier–Stokes equations. The above-mentioned analytical flow field can then be used to predict the trajectory of the particles flowing through the pleat channels by numerically solving the equation of motion for each particle—a simple set of second order ordinary differential equations. With the particles trajectories obtained, the deposition location and so the dust-cake profile can be approximated. This allows one to predict the instantaneous pressure drop and collection efficiency of a filter (filter's service life) with a CPU-time of practically zero min. The model developed in this work is aimed at providing the aerosol filtration industry with a fast, but yet fairly accurate method of designing pleated filters. A brief parametric study is presented for model demonstration. In addition, a comparison between the predictions of our model and some experimental data from literature is presented for completeness of the study.

1. Introduction

Most air filters are made of pleated fibrous media. This is to accommodate as much filtration media as possible in a limited space available to an air filtration unit (engine of a car, for instance). A variety of parameters contribute to the performance of a pleated filter. These parameters include, but are not limited to, geometry of the pleat (e.g., pleat height, width, and count), microscale properties of the fibrous media (e.g., fiber diameters, fiber orientation, and solid volume fraction), aerodynamic and thermal conditions of the flow (e.g., flow velocity, temperature, and operating pressure), and particle properties (e.g., diameter, density, and shape). In addition, an important parameter that strongly affects the performance of a filter through its service life is the dust deposition pattern—a non-linear function of the above-mentioned parameters [1–5]. Two filters with identical clean pressure drop and collection efficiency values, for instance, may exhibit very different performances as they collect particles over time. Despite its obvious importance, effects of dust loading on the performance of pleated filters have not been sufficiently studied in the literature, especially from a computational viewpoint. In this context, our group has contributed to the state of the art in modeling dust-loaded pleated filters by developing macroscale Computational Fluid Dynamics (CFD) simulation methods for surface and depth filtration of mono- and poly-disperse aerosols [3–5]. These macroscale CFD simulation methods were developed using the information that was previously obtained from microscale simulations of both clean and dust-loaded flat sheet media [6–12] (the terms microscale and macroscale simulations are used here to refer to simulations on scales comparable to fiber and filters dimensions, respectively). These studies themselves were inspired from the many pioneering simulations for clean or dust-loaded single fibers such as those given in Refs. [13–20]. All the above studies, as well as many others similar to them in nature, are developed on the basis of solving some simplified forms of the Navier–Stokes equations via a numerical method, i.e., solving a partial differential equation. Such CFD simulations are often computationally very expensive making the approach unattractive for a real-life industrial product development. The semi-numerical method presented in the current paper, is therefore aimed at developing a simulation method that is practically CPU-independent (i.e., the CPU time is extremely short). This model allows

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