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Modeling particle-loaded single fiber efficiency and fiber drag using ANSYS–Fluent CFD code

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ABSTRACT

In this paper, we present a methodology for simulating pressure drop and collection efficiency of a filter medium during instantaneous particle loading using the ANSYS–Fluent CFD code, enhanced with in-house subroutines. The simulations are comprised of a numerical solution of the Stokes equations for obtaining the air flow field, and Lagrangian particle tracking, for determining the particle collection efficiency and particle deposition sites on the fibers. The modeling strategy presented in this work allows one to track particles of different sizes and simulate the formation of 3-D dendrite particle deposits in the presence of aerodynamic slip on the fiber surface. In particular, the deposition of particles on a fiber, and on previously deposited particles, is made possible by developing in-house subroutines, which mark the cells located at the deposition sites and modify their properties so that they resemble solid particles. Fiber drag and single fiber collection efficiencies are obtained from simulations for fibers and particles of different diameters for demonstration purposes. Effects of particle capture mechanisms on a filter's pressure drop and collection efficiency are presented and discussed with respect to the studies reported in the literature. More specifically, two fiber diameters of 1 and 20 μm are used to demonstrate that the normalized single fiber collection efficiency increases with increasing mass of the loaded particles on the fibers (i.e., time) if the particle capture mechanism is interception or diffusion, but stays almost invariant if the capture mechanism is inertial impaction. Fiber drag (resembling the filter's pressure drop) seems to increase because of particle deposition, but at different rates for different particle capture mechanisms.

1. Introduction

Classical theories of particle filtration via fibrous filters have been developed for clean media. These theories were based on an exact or a numerical solution of the flow field around a perfectly clean fiber placed normal to the flow direction in a two-dimensional configuration [1,2]. Classical filtration theories have resulted in a variety of easy-to-use semi-empirical expressions for predicting the performance (i.e., collection efficiency and pressure drop) of fibrous filters (see [1,2] for comprehensive reviews). However, filters do not remain clean during the course of their operation. Particles deposit on the fibers and form complicated dendrite structures. The deposited particles affect the flow field around the fibers as the air streamlines change in response to the changes in the filter's morphology, and render the aforementioned expressions inaccurate. Therefore, existing pressure drop and collection efficiency expressions are only valid for the early stages of a filter's life.

Despite its obvious importance, filtration theories have not been sufficiently developed to provide accurate predictions for the performance of particle-loaded filter media. The most computationally affordable approach to account for the changes in a filter's internal structure is to assume that the deposited particles form a homogenous porous coating with a given porosity around the fibers, and to allow this coating to grow according to some simple mathematical rules (often in 2-D domains). However, such an approach comes at the expense of neglecting the microstructure of the particle deposits, which can lead to considerable errors in predicting the flow streamlines, and therefore collection efficiency and pressure drop, especially for the particles captured via interception or inertial impaction mechanisms (e.g., [3–5]). As will be discussed later in this paper, a more realistic model of the particle loading process is one that captures the dendrite shape of the deposits and updates the flow field based on such morphological changes.

The geometry of a loaded fiber changes depending on the particle deposition mechanism. If the mechanism is mainly interception, the deposition pattern will be on the fibers' lateral sides. By increasing the Stokes number $Stk = \rho_p d_p^2 C_c V / 18\mu d_f$, the particle deposition mechanism changes to the inertial impaction. In this regime, the particles do not follow the streamlines perfectly, and

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