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Microfiber Filter Performance Prediction Using a Lattice Boltzmann Method

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Abstract. Fibrous filter media are made of small fibers (micro and nanoscale). In these cases, the Knudsen number can be appreciable and the slip phenomenon on the fluid boundary surfaces should be considered. For this purpose, the mesoscopic approach lattice Boltzmann method (LBM) can be applied to predict the flow, with appropriate boundary conditions (BC). This paper analyzes a fibrous microfilter, including the construction of the geometric model from scanning electron microscope (SEM) images, and the comparison with experimental results and macroscopic approach modeling. A slip condition was implemented in open-source code OpenLB, based on specular reflections of the populations. The validation of the proposed boundary condition was carried out by simulations in a 2D channel, disposed at 45 and 90 degrees, and simple cases of a flow around an octagon. The experimental order of convergence (EOC) was evaluated for all cases and the results of the pressure drop around the octagon were compared to data obtained by a macroscopic approach. A good agreement between the pressure drop through the filter media and the results obtained numerically and experimentally was observed. These findings endorse the accuracy of the implemented slip BC and the importance in considering this phenomenon in microscale systems.

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1 Introduction

Fibrous filter media are largely used in air purification, such as mining and cement industries, and in indoor rooms that require the control of airborne particles. However, a high-efficiency filter has significant energy penalties associated with its use. Accurate prediction of the performance of fibrous air filter media from basic considerations (the geometry of the fiber mat and the characteristics of the gas flow through it) is a long-pursued goal. Simulations of the flow fields in filter media of necessity require rather drastic simplification of the actual geometry of the filter media, which is a complex 3D tangle of fibers.

Analytical studies made before the availability of computational fluid dynamics (CFD) were surprisingly effective in predicting the dependence of filter media resistance and particle capture efficiency on the fiber diameter and fractional solids of the media, using relatively simple geometries. Kuwabara [26] and Happel [16] used a 2D geometry containing a single round fiber; Spielman and Goren [49], Yeh and Liu [63], Sangani and Acrivos [44], Brown [4] and Ingham et al. [19] used regular arrays of uniform-diameter fibers. Kirsch et al. [24] used non-uniform spacing of uniform diameter fibers, while Kirsch et al. [25] used arrays of fibers with more than one diameter. Mölter et al. [36] developed a concept to extend single-fiber geometry to any diameter distribution, by assigning a portion of the total void fraction of the filter medium to small ranges of fiber diameters in the distribution.

The development of CFD allowed analysis of more complex 2D geometries, and also more accurate representation of boundary conditions at the simulated fiber surfaces. Fardi and Liu [12] used CFD to analyze a geometry having fibers with rectangular cross-sections, which to some degree simulated filters made of electric fibers. Jordan and Fissan [21] simulated particle capture by a single fiber (apparently in 2D) with particle diffusion and electrostatic forces included. Pedras and Lemos [39] analyzed regular arrays of ellipses, while Liu and Wang [30] used arrays of circles, but removed some of the boundary-condition restrictions made in analytic solutions. Shamsuddin and Douglas [46] used the full time-dependent Navier-Stokes equations and an explicit finite-difference scheme to analyze the drag of a single fiber and particle capture at high Reynolds Numbers, better matching conditions for this case. Lücke et al. [33] simulated randomly-located uniform fibers. Tronville and Rivers [54, 55] used randomly-located fibers with log-normal distribution in a 2D analysis. Their papers included the effect of slip on the fine fibers modeled, and described how computational problems for small-dimension geometries were overcome. Herman, Lehmann and Velu [18] followed much the same procedures as Tronville and Rivers [54, 55], but since the paper dealt only with coarser, nonwoven textile-diameter fibers, it did not deal with slip at fiber boundaries.