Chemical Engineering Science 64 (2009) 1154–1159

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

Analytical expressions for predicting permeability of bimodal fibrous porous media

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ARTICLE INFO

Article history:
Received 30 June 2008
Received in revised form 31 October 2008
Accepted 8 November 2008
Available online 24 November 2008

Keywords:
Bimodal media
Permeability modeling
Fibrous media
Filters

ABSTRACT

Pressure drop is one of the most important characteristics of a fibrous media. While numerous analytical, numerical, and experimental published works are available for predicting the permeability of media made up of fibers with a unimodal fiber diameter distribution (referred to as unimodal media here), there are almost no easy-to-use expressions available for media with a bimodal fiber diameter distribution (referred to as bimodal media). In the present work, the permeability of bimodal media is calculated by solving the Stokes flow governing equations in a series of 3-D virtual geometries that mimic the microstructure of fibrous materials. These simulations are designed to establish a unimodal equivalent diameter for the bimodal media thereby taking advantage of the existing expressions of unimodal materials for permeability prediction. We evaluated eight different methods of defining an equivalent diameter for bimodal media and concluded that the *area-weighted* average diameter of Brown and Thorpe [2001. Glass-fiber filters with bimodal fiber size distributions. Powder Technology 118, 3–9], *volume-weighted resistivity* model of Clague and Phillips [1997. A numerical calculation of the hydraulic permeability of three dimensional disordered fibrous media. Physics of Fluids 9 (6), 1562–1572], and the *cube root* relation of the current paper offer the best predictions for the entire range of mass (number) fractions, $0 \leqslant n_c \leqslant 1$, with fiber diameter ratios, $1 \leqslant R_{cf} \leqslant 5$, and solidities, $5 \leqslant \alpha \leqslant 15$.

1. Introduction

Pressure drop of fibrous media has been studied for many years and there exist many analytical, numerical, and/or empirical "easy-to-use" correlations available for determining their pressure drop. In almost all of these studies, a fibrous medium is assumed to be made up of fibers with a unimodal fiber diameter distribution, referred to as unimodal medium here. However, a great portion of the fibrous filters, for instance, are made up of blends of coarse and fine fibers with different average diameters (e.g., glass fiber media). In such filters fine fibers contribute to the high efficiency filtration (high collection efficiency for a given pressure drop) while the coarse fibers provide the mechanical rigidity. Despite their importance, pressure drop of fibrous media with bimodal (or multimodal) fiber diameter distributions has not been adequately studied in the literature and, unlike the case of unimodal media, there are no simple expressions/correlations that can be used to predict their pressure drop. This is probably because there are too many independent, but coupled, variables that need to be included in developing a model for predicting the pressure drop (or permeability) of bimodal or multimodal media.

There are few analytical/numerical studies dedicated to develop predictive models to estimate the permeability of a bimodal fibrous material. Most of these works, however, are limited to 2-D systems consisting of rows of fibers (in regular arrangements) perpendicular to the flow direction (Lundstrom and Gebart, 1995; Papathanasiou, 2001; Brown and Thorpe, 2001; Lebedev et al., 2003; Jaganathan et al., 2008a, Mattern and Deen, 2008; Dharmanolla and Chase, 2008). To our knowledge, there is only one modeling work that has considered disordered bimodal media in 3-D space (Clague and Phillips, 1997). The work of Clague and Phillips (1997), however, was limited to one specific set of parameters (fiber diameters, and species mass fractions) and did not discuss all influencing parameters. In this work, permeability of bimodal fibrous media is calculated by solving the air flow field in a series of 3-D virtual geometries. Our objective, here, is to find a unimodal equivalent diameter for each bimodal medium in such a way that it could be used with the existing unimodal expressions (see Eq. (2)) to predict the permeability of bimodal media. The current study is the first to consider anisotropic (layered) virtual 3-D geometries to emulate the microstructure of bimodal media and develop a criterion for choosing an equivalent average fiber diameter for them. In this paper we used a voxel-based computational fluid dynamics (CFD) code, GeoDict (from Fraunhofer

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doi:10.1016/j.ces.2008.11.013