Chemical Engineering Science 175 (2018) 1–11

Contents lists available at ScienceDirect

Chemical Engineering Science

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

Effects of pore size distribution and coordination number on filtration coefficients for straining-dominant deep bed filtration from percolation theory with 3D networks

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HIGHLIGHTS

- A straining-dominant deep bed filtration model based 3D network is proposed.
- The effects of simulation parameters on the deep bed filtration are illuminated.
- The simulated results based on 3D networks agree with the experimental results.

ARTICLE INFO

Article history:
Received 26 April 2017
Received in revised form 19 August 2017
Accepted 16 September 2017
Available online 19 September 2017

Keywords:
Straining
Pore size distribution
Percolation
Coordination number

ABSTRACT

A power law relation between the filtration coefficients of straining and flux through small pores has been reported. The effluent concentrations of the colloidal particles and the exponents derived from the experiment are inconsistent with those obtained from 2D network models simulation in their researches. In this study, a straining-dominant deep bed filtration (DBF) model is proposed based on 3D network simulation. The effects of simulation parameters such as lattice type, lattice coordination number z, pore size distribution (PSD), and particle capture scheme on DBF were investigated. Consistent with the power law formula and the normalized effluent concentrations (Ce/C_0), simulation results indicate that the exponents increase with increasing coordination number z. The change in the PSD parameters alters the flux and weight of path type linked to node, thereby influencing the numerical simulation of staining-dominate DBF on 3D networks. The effects of capture scheme and coordination number on the simulated normalized effluent concentration could be due to variations in the total capture probability for different lattices with the same PSD. The results were obtained from simulation on hexagonal close packing (HCP) and 2D triangular lattices under the optimal conditions. The simulated Ce/C_0 and exponents of the HCP lattice are similar to those of 2D triangular lattice and consistent with the experimental data.

1. Introduction

Colloidal suspension transport in porous media is an essential feature of various natural and industrial processes, such as petroleum production (Civan, 2015; Ding, 2010), ultrafiltration (Shi et al., 2011; Ruthven, 2009; Madaeni et al., 2006), microfiltration (Sun et al., 2016; Vicente et al., 2013), packed bed filtration (Islam et al., 2011; Chi and Payatakes, 1979), microbial transport in porous media (Bai et al., 2016; Tufenkji, 2007; Harvey et al., 1993), and formation of riverbeds (Battin and Sengschmitt, 1999). Simulation of filtration is important in various industrial applications to optimize the operation conditions and minimize costs. Study of colloidal suspension transport in porous media requires a model that describes the porous matrix. Colloidal particles can be removed from porous media through gravity segregation, diffusion, straining, bridging, and electrical forces. The migration and deposition of colloidal particles can be analyzed through several models, such as Classic Models (Ives, 1980; Heertjes and Lerk, 1967; Maroudas and Eisenklam, 1965) and Trajectory analysis model (O'Melia, 1985; Tien and Payatakes, 1979; Yao et al., 1971). The Classic Models are mainly based on the deposition of suspended particles in the pore space of the filter media and used to establish a macro empirical formula of effluent

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https://doi.org/10.1016/j.ces.2017.09.033

Nomenclature

C_e	effluent concentration
C_0	influent concentration
f	pore size distribution density
f_{ns}	flow fraction via the inaccessible small pores
$f_a + f_{nl}$	fractional flow via large pores
f_l	probability of a pore being larger than the injected particle
f_l^*	average probability of particle flow through larger pores
f_c	conventional percolation threshold
f_c^*	flow-biased percolation threshold
q_l	flow in the capillary
l	length of a capillary (m)
l_w	distance between two neighboring branches
$f_{\inf}^*$	fraction of flow through infinite cluster
B	fraction of flow through the backbones of the infinite clusters
L_0	medium or network length (m)
N_l	minimum number of capillaries connecting the inlet and the outlet
Δp	pressure difference between nodes (Pa)
ρ	density of suspension
g	gravitational acceleration
r_n	node radius (m)
r_p	capillary radius (m)
r_s	spherical particle radius (m)
r_{sc}	particle radius at the threshold

V_n	volume of each node
V_b	volume of each bond (capillary)
z	coordination number
λ	filtration coefficient, capture probability per unit length (m^{-1})
λ_l	network filtration coefficient, capture probability per pore
η	suspension dynamic viscosity (Pa·s)
μ	location parameter forpore size distribution
σ_{trans}	transition from smooth deposition to blocking type deposition
σ	scale parameter for pore size distribution
θ	angle between a capillary and horizontal direction
θ_a	average angle between a pore and flow direction
α	exponent of power-law
β	exponent of power-law
γ	exponent of power-law

Abbreviations

HCP	Hexagonal Close Packing
BCC	Body Center Cubic
PSD	Porous Size Distribution
MINCAP	Minimum Capture Scheme
MAXCAP	Maximum Capture Scheme
PTM	Parallel Tube Model
DBF	Deep Bed Filtration

turbidity. The Classic Model is a simple empirical model and does not provide significant insights into the physics of deposition. The trajectory analysis model cannot accurately predict permeability changes due to Deep Bed Filtration (DBF). Some model parameters (critical interstitial velocity, and porosity of deposits σ_{trans}) must be approximated based on previous experimental data (Rege and Fogler, 1988). Both models exhibit limitations in study of DBF.

The pore blockage of filter media in DBF by suspended particles is similar to cluster growth in percolation model. Percolation (Broadbent and Hammersley, 1957) is originally derived from filtration, and both processes are similar in many aspects. Therefore, percolation model can be applied to study filtration and obtain accurate results (Bell et al., 1996; Allen, 2009; Golden, 1997; Ewing and Gupta, 1993). Percolation model can also be used to predict the properties of medium (Perrier et al., 2010; Berkowitz and Ewing, 1998; Selyakov and Kadet, 1997) and is associated with network modeling of transport in porous media. Network models can describe the effects of pore scale physics, whereas percolation theory can reflect the effects of randomness on macroscopic properties (Berkowitz and Balberg, 1992), fluid properties, and their interplay. Kaiser (Kaiser, 1997) established a microscopic model of directed percolation to describe the clogging of a porous medium caused by colloidal suspension. Yuan et al. (2012) applied percolation theory and random walk in a 2D square network to study staining-dominate DBF; this study proposed two particle capture mechanisms and two power-laws that describe the relationship between the fractions of flow through the small pores and the filtration coefficient. The trend of simulation agrees with that of laboratory test data. However, the normalized effluent concentrations (Ce/C_0) and the exponents calculated from the experimental data are inconsistent with the simulation results on the 2D network.

Our previous studies (Ding et al., 2015a,b; Ding and Chaolin, 2015) investigated the effects of coordination number, capture scheme, and pore size distribution (PSD) on simulation of straining-dominant DBF in 2D networks. The results verify that the two parameters of PSD significantly influence the simulation of power law and the experimental calculation of exponents. The simulated data are consistent with the laboratory test results when proper simulation conditions are used even in 2D networks.

The structure of 2D networks differs from that of actual 3D filter media. In actual filtration, the influence of gravity should be considered. Moreover, the coordination number and capillary length of the actual filter media vary up to a certain range but are constant in a 2D regular network.

In this study, a numerical simulation model of staining-dominate DBF was established to verify the power law and investigate the role and mechanism of microscopic parameters in the process. The effects of simulation parameters such as lattice type, lattice coordination number z, PSD, and particle capture scheme were determined to optimize the simulation conditions. Finally, the Ce/C_0 obtained from the simulation of filtration on the 3D network under the optimal conditions was compared with the laboratory test data in the literature.

2. Experimental section

For model validation, a small-scale experimental data set of staining-dominate DBF was selected. The data set refers to injection of various monodispersed colloidal particle suspensions into a porous matrix (laboratory test data of the medium 30/125 (Yuan et al., 2012)) that consists of packing glass bead with monitored inlet and breakthrough particle concentrations. In this work, we briefly review the experiment, where a plastic column with packing space of 47 mm in diameter and 50 mm in length was constructed to simulate the porous media. Spherical glass granules (size: 30–125 μm) for packing were acquired from Ballotini Bead, Potters Industries Pty. Ltd. (Australia). Monodisperse suspensions of yellow–green fluorescent carboxyl polystyrene latex microspheres of different sizes were used in the experiments. These carboxyl groups provided the net negative charge in the alkaline solution, resulting in mutual particle repulsion, as indicated by the calculation of the interaction energy using Derjaguin–Landa