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A comparative study of permeable and semipermeable membranes constructed multiple layer water filters by non-dimensional lattice Boltzmann simulations

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ABSTRACT

A Non-Dimensional Lattice Boltzmann Method (NDLBM) based on a multiple zone porous medium model is extended to simulate fluid flow and mass transfer inside multiple layer water filters. Comparative studies based on two basic design models (permeable and semipermeable membrane model) are carried out to investigate the flow and mass transport inside cylindrical multiple layer water filters. In the permeable membrane design model, the water is purified by passing multiple units with sandwich like structures. In the semipermeable membrane model, macromolecules such as suspended particulates cannot pass the semipermeable membranes, while micromolecules can pass the porous semipermeable membranes. The quasi-steady state velocity distributions are obtained. The transient concentrations of suspended particulates captured by porous solid structures and left in water are compared for the two design models. Different dimensionless governing parameters and the porosities for the membranes are studied to understand the underlying mechanism of the purification procedure and to compare performance of the two models.

1. Introduction

Fluid flow and mass transfer in water filters have various engineering applications such as air cleaner, water purification, and petroleum purification [1–4]. It is one of the challenging problems in fluid flow and mass transfer for a long time due to complex microscopic geometries of water filters. Early work for numerical study of flow and mass transfer for filters are limited on simplified calculations based on the outlet concentrations [5]. To get a better understanding of the underline mechanism and provide a tool for comparison of different design types, simulations on the transient flow and convective mass transfer fields inside filters are necessary. Very limited studies for flow and mass transfer fields inside filters are available in literatures due to the computational costs for simulations of transient flow and mass transfer fields by using the conventional numerical methods based on the Navier-Stokes equations [6]. A porous medium model based on a geometry factor was developed to build a uniform model between the microscopic and the macroscopic drag forces in a representative element volume (REV) [7]. The macroscopic scale flow and heat transfer, i.e. the Darcy velocity and volume averaged temperature in a REV, could be obtained by solving the volume averaged governing equations.

In the past two decades, the Lattice Boltzmann Method (LBM) has been introduced to speed up simulations of fluid flow and heat transfer problems in complex geometry domains and multi-phase flows [8–11]. Also, the conjugate heat transfer in a complex structure was able to be solved with LBM method by modifying the relaxation time in the energy equation [12,13]. Different domains are identified by a relaxation time matrix rather than separated by space domains, which makes the applications more convenient comparing to the conventional method based on Navier–Stokes equations. However, in the above simulations with LBM, the relationships of the governing parameters for LBM and the governing parameters for flow and mass transfer processes were not clearly related in macroscopic, microscopic, and mesoscopic scales, respectively. Previous LBM based porous medium studies need to adjust velocities through some empirical coefficients [14], so as to match the LBM simulation predicted results with real physic fields due to the different time scales in LBM simulations and in the real physical problems. Recently, a Non-Dimensional Lattice Boltzmann Method (NDLBM) was developed by Su et al. [15] to simulate the conjugate mixed convection inside a concentrated

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Nomenclature

A	area, m^2
d	diameter of the tube, m
c_s	lattice speed of sound, m/s
$\mathbf{c}$	lattice velocity vector
dt	time step, s
D	mass diffusion coefficient, m^2/s
$\mathbf{e}$	unit vector
f	density distribution function
F	body force term, N/m^3
g	temperature distribution function
g	gravity acceleration
H	inside height of the tank
L	macroscopic length scale, m
Q	mass source term, W/m^3
Re	Reynolds number
Sc	Schmidt number
Sh	Sherwood number
t	time, s
$\mathbf{v_f}$	fluid velocity vector, m/s
U	macroscopic velocity scale, m/s
$\mathbf{v}$	Darcy velocity, m/s
w	weighting factor
r, x	cylindrical coordinates
r_{sf}	interface reaction rate

Greek symbols

Δt	time scale
$\Delta\omega$	concentration scale
ℓ	lattice length scale
Δx	lattice size in x direction
Δr	lattice size in r direction
ω	concentration, mol/m^3
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
τ	relaxation time

Subscripts

d	microscopic length scale
f	fluid
ℓ	lattice length scale
L	macroscopic length scale
in	inlet
k	the index of the 9 directions
od	opposite direction
out	outlet
w	wall
s	solid
0	initial time

Superscripts

$\wedge$	volume averaged value
$*$	dimensionless variables

photovoltaic thermal receiver. Based on the scale analysis, the dimensionless relaxation time used in the NDLBM is strictly related to the mesoscopic Reynolds number and the mesoscopic Peclet number for flow and heat transfer, respectively. Also, the NDLBM for both direct and porous medium model simulations have been developed by Su and Davidson [16]. This porous medium model which directly connects macroscopic drag with microscopic drag coefficients by a geometry factor [7] was extended in the present NDLBM to avoid limitations of the valid range of the permeability and the Forcheimer coefficient [17–19] used by previous LBM porous medium models [20–25]. And there is no need for further adjustment of the velocity based on empirical coefficients.

In the present study, we would like to simulate the transient fluid flow and mass transfer of the suspended particulates inside multiple layer water filters. Two typical design models of water filters will be simulated, including the permeable membrane model and the semipermeable membrane model. In the first design model, the water is purified by passing multiple units of sandwich like structures. In the second design model, suspended particulates cannot pass the semipermeable membranes, while water molecules can pass the porous semipermeable membranes. Comparative studies based on these two basic models will be carried out to investigate the underlying mechanism of the transient mass transport inside a multiple layer water filter. An extended NDLBM with the uniform form porous medium model [16] will be developed to simulate the transient fluid flow and mass transfer in porous structures with different microscopic geometries and materials inside filters.

2. Computational models and numerical method

The permeable and semipermeable membrane models, denoted as models A and B, are shown in Fig. 1(a) and (b), respectively. For both models, the impermeable walls are denoted in black. Outer impermeable walls are the outside enclosures of the filters. Inner impermeable walls are applied to constrain the direction of flow entering the core domains of the filers. The core domains of the filters are constructed by units of the sandwich like porous structures. Each of the unit consists of three layers: the water induced layer, the membrane layer, and the mixture layer. As shown in Fig. 1(a), water is purified by passing each units of the sandwich like porous structures from outer layer to centerline layer in the permeable membranes model. However, in the semipermeable model, water can enter each unit through the induced layer and mixture layer at almost the same time for all units, and then is purified simultaneously by each of the units, as shown in Fig. 1(b). Clearly, the permeable membrane layers in model (A) allow the suspended particulates to enter the membrane domain, which are captured by the solid structures of the permeable membranes. In contrast, the semipermeable membranes in model B don't allow the suspended particulates to enter the membrane domain, which isolates the suspended particulates at the front surface of the semipermeable membranes. That is, in model B, water can enter each unit through the water induced layer and mixture layer. However, the suspended particulates cannot pass the semipermeable membrane, and will partially be captured in the water induce and mixture layers.

The main objective of the present study is to investigate the underlying mechanism and to compare the purification capacity of the two kinds of multiple layer filters constructed by permeable and semipermeable membranes. For micromolecules such as water molecules, the membranes for both models are treated as porous medium. The porosities of the three layers in each units are equivalent for the two models. The difference is that the permeable membranes of model A are treated as absorptive mass sink for macromolecules such as suspended particulates, while the