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Flows past arrays of hollow fiber membranes – Gas separation

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ABSTRACT

Computational fluid dynamics simulations are conducted for binary fluid flows over banks of hollow fiber membranes. Separation of carbon dioxide (CO_2) from methane (CH_4) is studied using hollow fiber membranes structured in different arrangements. The membrane is considered as a functional surface where the mass flux and concentration of each species are coupled and determined as a function of the local partial pressures, the permeability, and the selectivity of the membrane. k–ω Shear Stress Transport (k–ω SST) turbulent model is employed to study steady flow over banks of hollow fiber membrane for values of the Reynolds number up to 1000. Lattice Boltzmann method is used to study transient flow pass an array of diamond shaped hollow fiber membranes. The flow structure around the hollow fiber membranes has strong influence on the separation performance. This study demonstrates that good mixing in the bank of hollow fiber membranes enhances separation. The results show that hollow fiber membrane module with staggered arrangements performs much better than that with inline arrangements. It is also demonstrated here that the transient nature of flows has significant influence on the membrane performance.

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1. Introduction

Membrane based gas separation has been successfully employed in various industrial applications since it offers several advantages. It is cost effective, easy to implement, and energy efficient compared to conventional separation processes [1]. There are different types of flows in these membrane modules: countercurrent flows; concurrent flows; and radial crossflows [2]. The present study investigates the spatial and temporal characteristics of the radial crossflows in the hollow fiber membrane modules and their effects on the membrane performances.

Several investigators considered only the mass balance in the hollow fiber membrane to examine system performance for gas separation applications [1–4]. The effect of flow in the feed channel on the membrane performance in a spiral wound membrane module containing spacers has been studied for desalination and food processes [5–9]. Membrane surface is treated as an impermeable wall by Al-Sharif et al. [5] and Shakaib et al. [8] while Guillen and Hoek [6], Pal et al. [7] and Subramani et al. [9] considered permeable membrane surface in their studies. Anqi et al. [10] study steady and transient two dimensional flows in a feed channel containing circular shaped spacers with different arrangements. The mass flux through the membrane is modeled as a function of the osmosis pressure and the concentration. The k–ω Shear Stress Transport (SST) turbulence model was employed to obtain the pressure, the concentration, and the velocity fields. Anqi et al. [10] demonstrated that the membrane performance is enhanced strongly by the presence of spacers in a desalination process. Sohrabi et al. [11] consider the effect of flow over banks of hollow fiber membrane in a process separating liquid from gas. They have used predetermined velocity profile and solved only the mass transport equation to study membrane performance. Kaya et al. [12] used the k–ε turbulence model to capture the flow over banks of hollow fiber membrane for water desalination. They concluded that characterizing flow in the feed channel should be considered in membrane simulations. However, these investigators neglect mass flux through the membrane by considering membrane surfaces as impermeable boundary. Similarly, Huang and his co-workers [13–18] conducted experiments and numerical simulations to study humidification and dehumidification processes. They have examined the characteristics of the flow and temperature fields over banks of hollow fiber membranes. Membranes are treated as impermeable surface in these studies. Real separation process

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Nomenclature

A	surface area (m^2)
c	lattice speed (lu/ts)
C	concentration (mol/m^3)
C_D	drag coefficient (–)
d	hydraulic diameter (m)
D	diffusion coefficient (m^2/s)
D_t	eddy diffusion coefficient (m^2/s)
e	discrete velocity vector
f	density distribution function
fr_i	friction factor in an inline geometry
fr_s	friction factor in a staggered geometry
fr	average friction factor
F_D	drag force (N)
F_1, F_2	blending functions
g	concentration distribution function
h	height (m)
h_m	mass transfer coefficient (m/s)
J	molar flux (mol/m^2)
K	turbulent kinetic energy (J/kg)
l	membrane thickness (m)
L	membrane length (m)
m	mass flux (kg/m^2 s)
M	molecular weight (g/mol)
n	vortex shedding frequency (1/s)
N	mole fraction (–)
N_m	bulk mole fraction (–)
p	pressure (Pa)
Δp	pressure difference (Pa)
P	permeance (mol/m^2 s Pa)
tot	total properties
$\ddot{P}$	permeability (mol/m s Pa)
Re	Reynolds number (–)
S	spacing (m)
Sc	Schmidt number (–)
Sc_t	turbulent Schmidt number (–)
Sh	Sherwood number (–)
St	Strouhal number (–)
t	time (s)
u_i	flow velocity vector
U	average velocity (m/s)
V_w	suction rate (m/s)
w	weight coefficient
x_i	position vector
α	mass selectivity (–)
$\beta^*, \beta 1, \beta$	turbulent model parameters (–)
γ	rate of strain tensor
δx	lattice width (lu)
δt	time step (ts)
θ	angle (rad)
κ	membrane flux parameter (–)
μ	dynamic viscosity (kg/m s)
μ_t	eddy viscosity ((kg/m s)
ν	kinematic viscosity (m^2/s)
ν_t	eddy kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
σ, λ	turbulent model parameters (–)
τ_f	hydrodynamic relaxation time
τ_g	mass relaxation time
ω	specific dissipation rate (1/s)

Subscripts and superscripts

a and b	species: CO_2 or CH_4
i and j	index notation
CH_4	properties of CH_4
m	discrete direction
w	properties at the membrane surface
t	eddy properties
CO_2	properties of CO_2
a/b	ratio of properties of a to properties of b

in hollow fiber membrane modules requires a proper mass flux model through the membrane. Mass fluxes through the membrane should be determined as a function of the local pressure and mass fraction and membrane properties.

Alkhamis et al. [19] introduced a unique model for the mass flux through the membrane for gas separation process. The membrane wall is treated as a functional surface, where the mass fluxes of species are calculated based on the local pressure, membrane permeability and the selectivity. Alkhamis et al. [19] studied the separation CO_2 from CH_4 in a spiral wound membrane module containing spacers and concluded that separation process can be enhanced significantly by the presence of spacers in the membrane system. It has been demonstrated by these investigators that spacers should be an integral part of the membrane system design and optimization in the application of gas–gas separation. Alkhamis et al. [20] conducted computational simulations to study a gas separation process in a hollow fiber membrane containing a porous support layer. They employed the same flux model described above to investigate the effect of the porous support layer on the separation process of CO_2 in a CO_2/CH_4 mixture. It has been demonstrated that the presence of the porous layer has profound adverse effects on the hollow fiber membrane performance. Mass flux of both CH_4 and CO_2 is reduced by the presence of the porous layer. Alkhamis et al. [21] showed that flow restricting devices such as orifices can be utilized to alleviate undesirable effects of the porous support layer on the membrane performance.

The membrane flux model proposed by the present authors [19–21] is employed here to study membrane performance in a separation module containing bundles of hollow fiber membranes. The present work utilizes CFX commercial software to simulate steady two dimensional velocity and concentration fields to investigate the effect of momentum mixing in the feed channel on the hollow fiber membrane performance. A binary mixture of methane (CH_4) and carbon dioxide (CO_2) is considered as fluid flowing over hollow fiber membrane banks. Flow simulations are conducted for a wide range the Reynolds numbers, $200 \leqslant Re \leqslant 1000$. Spatial characteristics of the radial cross flow over a bank of hollow fiber membrane with an inline and staggered arrangements are simulated using the k–ω Shear Stress Transport (k–ω SST) turbulence models. Turbulence model and the numerical method are validated by comparing the predicted values of the drag coefficient and the Strouhal number for flows past a cylinder against those documented in the literature. Lattice Boltzmann method is used to determine the influence of transient effects on the membrane performance. The present study is the first in implementing membrane flux boundary conditions using lattice Boltzmann method to study separation process with membranes.

2. Governing equations

The schematic of the flow geometry is illustrated in Fig. 1. It consists of arrays of hollow fiber membrane with an inline and a

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