International Journal of Heat and Mass Transfer 52 (2009) 751–759

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Coupled heat and mass transfer through asymmetric porous membranes with finger-like macrovoids structure

Li-Zhi Zhang *

Key Laboratory of Enhanced Heat Transfer and Energy Conservation of Education Ministry, School of Chemical and Energy Engineering, South China University of Technology, Guangzhou 510640, China

ARTICLE INFO

Article history:
Received 12 December 2007
Received in revised form 14 July 2008
Available online 15 September 2008

Keywords:
Heat transfer
Mass transfer
Asymmetric membranes
Finger-like macrovoids

ABSTRACT

Asymmetric porous membranes with finger-like macrovoids have been extensively used in various processes, either directly as the transfer media or indirectly as the substrate for active layer. Heat and mass transfer through such membranes are the key parameters influencing system performance. However, previous studies on heat and mass transport only treated these membranes as a black box of homogeneous porous media by neglecting their asymmetric nature in structure, which fails to disclose the relations between the membrane structure and system performance. To solve this problem, this study gives a more detailed investigation of the thermal and mass diffusion through these membranes, with the help of scanning electron microscope (SEM) observations of membrane surface and cross-sectional structures. In the model setup, the whole membrane is classified into three layers: a sponge-like porous support layer, a layer of porous media with finger-like macrovoids, and a thin denser skin layer with smaller pores. The model is then incorporated into the analysis of coupled heat and mass transfer in a membrane exchanger for moisture permeations. Results show that the effective diffusivity of the membrane has been dramatically improved due to the existence of more than 70,000 per meter large finger-like voids inside.

1. Introduction

Porous membranes have been extensively used in various processes such as membrane distillation [1,2], pervaporation [3], gas separation [4], membrane reactors [5,6], fuel cells [7], and enthalpy recovery [8,9]. They are used either directly as the transfer media, or indirectly as the substrate support for the permselective active layer.

Phase-inversion method has been the widely used technology for membrane preparation since it was successfully used by Loeb and Sourirajan to develop cellulose acetate membranes for seawater desalination in 1960s [10]. According to this method, the formation of membrane structure is controlled by both the thermodynamics of the casting solution and the kinetics of transport process. Usually, depending on the rate of phase separation, two different structures, namely a symmetric sponge-like (from delayed phase demixing) or an asymmetric finger-like structure (from instantaneous phase demixing) can be expected [10–12]. Fig. 1 shows a typical symmetric sponge-like membrane structure and Fig. 2 shows a typical asymmetric finger-like structure. They are the scanning electron microscope (SEM) of the cross-sections of a polyether sulphone (PES) and a polyvinylidene fluoride (PVDF) membrane, respectively. Fig. 2 is actually an upside down graph of a real asymmetric membrane which is composed of three parts from bottom to top: a sponge-like porous support, a porous media with finger-like and nearly parallel macrovoids, and finally a very thin skin layer with rather small pores. This denser skin layer usually acts as the permselective active layer to separate substances. Due to the existence of large finger-like macrovoids, it is qualitatively believed that the asymmetric membranes have less resistance than symmetric membranes, and thus are beneficial for permeation performance. As a result, asymmetric membranes with finger-like macrovoids have been used more extensively than symmetric membranes [10–14].

Heat and mass transfer through the membranes are the key factors influencing system performance of various aforementioned membrane-related processes. Traditionally, the membranes were treated as a black box, by assuming them a homogeneous porous media and neglecting their structural non-uniformity in thickness [6–12]. The methodology is reasonable in that it is simple in modeling. However, it fails to predict the relations between the membrane structure and the heat mass transfer properties, especially for the widely used asymmetric membranes that have finger-like macrovoids.

In this study, coupled heat and mass transfer in a membrane exchanger in which two air streams exchange heat and moisture simultaneously is investigated. The unit simulates an air to air heat mass exchanger. Emphasis is on the detailed modeling of heat and mass transfer through the asymmetric membranes, based on the

* Tel./fax: +86 20 87114268.
E-mail address: Lzzhang@scut.edu.cn

0017-9310/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijheatmasstransfer.2008.07.029

Nomenclature

c_p	specific heat (kJ kg^{-1} K^{-1})
D	diffusivity (m^2/s)
D_h	hydrodynamic diameter (m)
d_p	pore diameter (m)
h	convective heat transfer coefficient (kW m^{-2}K^{-1})
$\dot{m}_v$	emission rate (kg m^{-2} s^{-1})
k	convective mass transfer coefficient (m/s)
l_f	finger void length (m)
Le	Lewis number
M	molecule weight (kg/mol)
NTU	number of transfer units
Nu	Nusselt number
n_f	number of finger voids (1/m)
P	Atmospheric pressure (Pa)
q	heat flux (kW m^{-2})
R	gas constant, 8.314 J/(mol K); resistance (s/m)
Sh	Sherwood number
T	temperature (K)
u_a	air bulk velocity (m/s)
v	molecular diffusion volume
x	coordinate (m)

Greek letters

ρ	density (kg/m^3)
λ	heat conductivity (W m^{-1} K^{-1})
ω	humidity ratio (kg moisture/kg air)
τ	pore tortuosity
ε	porosity
δ	thickness (μm)
α	skew angle (°)

Superscript

*	dimensionless

Subscripts

a	air
e	equivalent, exhaust air
f	finger, fresh air
i	inlet
k	Knudsen
m	membrane
o	outlet, ordinary
s	sensible, solid
tot	total
v	vapor

SEM observations of membrane surface and cross-sectional structures. The reason for an increased effective diffusivity with finger-like macrovoids will be quantitatively analyzed.

2. Experimental work

2.1. Test rig

An experimental setup has been built to study the simultaneous heat and moisture transport through an asymmetric porous membrane. The whole test rig is shown in Fig. 3. Ambient air is humidified and is driven to a heating/cooling coil in a hot/cool water bath. The cooling coil can also act as dehumidifier when necessary. After the temperature and humidity reach test conditions, the air is then sucked through the exchanger for heat and moisture exchange. This flow is denoted as the hot and humid fresh stream. Another flow is driven directly from ambient to the exchanger. It is denoted as the cool and dry exhaust flow. The membrane, which is developed in the laboratory, is sandwiched by two stainless steel rectangular shells. Two parallel rectangular air passages on both sides of membrane are formed, which is like a one-plate plate-and-shell heat exchanger. The flow is arranged in a counter flow configuration, to have maximum exchange effectiveness, as shown in Fig. 4. In the test, a 10 mm thick insulation layer is placed on the inner surface of the shell to prevent heat dissipation from the shell to the surroundings. Moisture dissipation from air stream to the surroundings is negligible. After the exchanger and pipes are installed, additional insulation is added on the outside surfaces to minimize heat losses from the unit. The PVDF made is highly hydrophobic, so the vapor condensation and blocking in the pores are prevented.

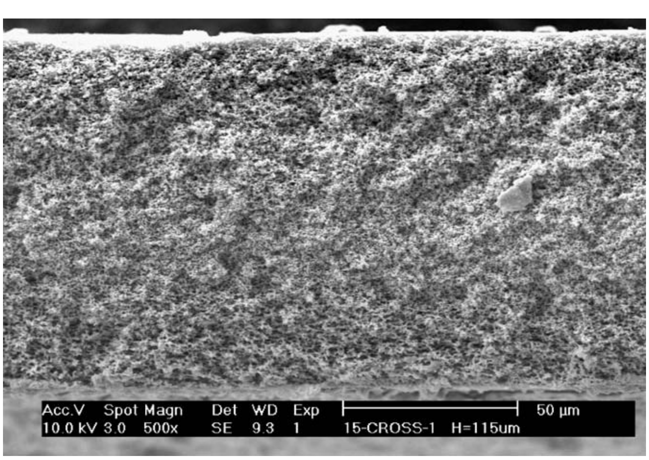

Fig. 1. SEM graph of the cross-section of a symmetric porous membrane.

The nominal operating conditions: fresh air inlet 35 °C and 0.021 kg/kg; exhaust air inlet 25 °C and 0.010 kg/kg. The corresponding inlet relative humidity (RH) is 59% and 51% for fresh air and exhaust air, respectively. During the experiment, air flow rate is changed by variable frequency pumps, to have different air velocities. Humidity, temperature, and volumetric flow rates are monitored at the inlet and outlet of the exchanger. To have a balanced flow, equal air flow rates are kept for the two air streams. Volumetric air flow rates are varied from 1.2 to 7.2 L/min, corresponding to air velocities from 0.5 to 3 m/s which are typical for commercial total heat mass exchangers. Air flow under such conditions is laminar, with Reynolds numbers not exceeding 500. The uncertainties are: temperature ±0.1 °C; humidity ±2%; volumetric flow rate ±1%. The final uncertainty for effectiveness and heat transfer coefficients is ±4.5%. The uncertainties of sensors are defined by the manufacturers. The uncertainties for the deduced value are estimated by uncertainty transfer equations, as introduced in [15,16].

2.2. Membrane materials

Industrial grade PVDF supplied by Guangzhou Tianma Co. Ltd. is used as the membrane raw material. The membrane is fabricated through following steps: (1) 15 g PVDF powder is weighted and placed into a vessel with 100 g *N*,*N*-dimethylformamide (DMF) at about 90 °C. The solution is heated and stirred until it is completely dissolved. It took about 2 h. (2) 3 g polyethylene glycol (PEG) and