International Journal of Heat and Mass Transfer 127 (2018) 289–301

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Fluid flow and mass transfer in an industrial-scale hollow fiber membrane contactor scaled up with small elements

Kui He [a], Shunquan Chen [b], Chih-Ching Huang [c], Li-Zhi Zhang [a,d,*]

[a] Key Laboratory of Enhanced Heat Transfer and Energy Conservation of Education Ministry, School of Chemistry and Chemical Engineering, South China University of Technology, Guangzhou 510640, China
[b] Material and Membrane Separation, Guangzhou Institute of advanced Technology, Chinese Academy of Sciences, Guangzhou 511458, China
[c] Department of Bioscience and Biotechnology, National Taiwan Ocean University, Keelung 20224, Taiwan
[d] State Key Laboratory of Sub-tropical Building Science, South China University of Technology, Guangzhou 510640, China

ARTICLE INFO

Article history:
Received 26 March 2018
Received in revised form 9 August 2018
Accepted 12 August 2018

Keywords:
Membrane contactor
Hollow fiber membrane
Scaled up
Element
Heat and mass transfer

ABSTRACT

Current gas/liquid membrane contactors are classified into tubular hollow fiber contactors and tube-shell cross flow hollow fiber contactors. They are usually built with a closed and integrated structure, which reduces the maintainability of the contactor and makes the scaling-up of the contactor inconvenient. In this paper, a novel gas/liquid hollow fiber membrane contactor is proposed. It is consisted of many changeable and standard small contactors (elements), in which the fibers are randomly packed. These randomly packed small elements are then serially and orderly arranged to form the scaled up contactor for industrial applications. A two-dimensional predictive model is proposed to study the performance of the contactor, which is validated by air humidification experiments. The effects of inter-elements and intra-element flow maldistributions are investigated. Correlations are proposed to estimate the performance of the contactor from the parameters of the elements. It is found that for the contactors built with elements of high packing densities (0.5), the inter-elements effect is dominant for flow maldistribution, but for contactors built with elements of low packing densities (0.35), the collaborative effect of inter-elements and intra-element is dominant. It could maximally decrease the average air side Sherwood numbers by about 83%, with a pressure drop reduction of about 50%. The scaled up contactor has a comparable performance to the small elements when the elements are optimized, which shows the good scalability of this novel contactor.

1. Introduction

Membrane contactors or modules are devices that are used to conduct heat and mass transfer between two streams and to achieve mass separations, based on the selective transport features of the membranes. Two categories are typical: plate-frame membrane contactors [1] and hollow fiber membrane contactors [2,3]. As it is shown in Fig. 1a, the structure of a plate-frame membrane contactor is similar to that of a parallel plate heat exchanger, where metal plates are replaced by membranes. Two streams flow across both sides of the membrane respectively in a cross flow pattern. A hollow fiber membrane contactor is similar to a tube-shell heat exchanger, where the metal tube bank is replaced by a hollow fiber membrane bank. Fig. 1(b) and (c) depict a lab-scale hollow fiber membrane contactor and an application-scale hollow fiber membrane contactor respectively. The latter contactor contains several hundred times of membrane area of the former one.

Different membrane contactors are suitable to different applications. The plate-frame type is popularly used as total heat exchangers [4]. The latter one is more popular in liquid/liquid or liquid/gas contacting processes, such as, the forward/reverse-osmosis (FO, RO), membrane biology reactors [5] and etc. The hollow fiber membrane is self-supported so that it eliminates the need for spacers and the specific area can be enlarged to several thousand $m^2\,m^{-3}$. This facilitates the large scale production in industries. The gas/liquid membrane contactors will be the focus of this paper. They are mainly used in membrane distillation [6], air humidification/dehumidification [7,8] and other similar situations [9]. Polytetrafluoroethylene (PTFE), Polypro-pylene (PP) and Polyvinylidene (PVDF) are commonly used as the membrane material. In air dehumidification/humidification applications, these membranes show similar moisture permeability, in the order of $10^{-1}\,kg\,m^{-2}\,h^{-1}$ [9–11]. So in larger scale real applications, large

* Corresponding author at: South China University of Technology, School of Chemistry and Chemical Engineering, Key Laboratory of Enhanced Heat Transfer and Energy Conservation of Education Ministry, Wushan Road, Guangzhou 510640, China.

E-mail address: lzzhang@scut.edu.cn (L.-Z. Zhang).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.08.039
0017-9310/

Nomenclature

A	area (m^2), contactor name
B	contactor name
C	constants in correlations
D	length scale (m)
D_{va}	moisture diffusivity in air ($m^2\ s^{-1}$)
D_{vm}	effective moisture diffusivity in membrane ($m^2\ s^{-1}$)
d	outer diameter of fiber (m)
$\bar{d}$	mean diameter (m)
f	friction factor
k	convective mass transfer coefficient ($m\ s^{-1}$)
m	constants in correlations, mass source
N_f	total number of fibers in the core
Nu	Nusselt number
p	pressure (Pa)
Pr	Prandtl number
P_T	transverse fiber pitch (m)
R	radius (m)
RH	relativity humidity
Re	Reynolds number
S	source term, length scale (m)
Sc	Schmidt number
Sh	Sherwood number
T	temperature (K)
u	velocity ($m\ s^{-1}$)
V	velocity ($m\ s^{-1}$)
W	volume velocity ($L\ h^{-1}$)

Greek letters

α	specific area ($m^2\ m^{-3}$), constants in correlations
β	packing density
δ	membrane thickness (m)
Δ	differential
ε	humidity efficiency
ρ	density ($kg\ m^{-3}$)
γ	correction factor
φ	correction factor
μ	dynamic viscosity (Pa s)
ω	humidity ($kg\ kg^{-1}$)

Subscripts

a	air
con	contactor
ef, em	effective, element
f	fiber
hum	humidity
m	membrane, mean
max	maximum
in	inlet of sub-channel
out	outlet of sub-channel
t	total
s	solid, superficial
T	transverse
v	vapor
w	width, water, wall
x, y, z	streamwise, normalwise, spanwise

membrane areas should be packed or connected together to form large contactors [12–15].

In this paper a novel membrane contactor is proposed, as shown in Fig. 2. The contactor is assembled with many small yet standard contactors, which are named as elements. The placement of the standard elements are well designed. They can be arranged in inline, staggered, or in other arrangements. So in macro scale, the contactor is orderly placed, to have the uniform and designed flow field. In micro scale, each element is randomly packed. So they can be easily manufactured in large scale. The scale up of the contactor is straightforward by plugging these small elements into a pre-made frame. The design is a balance between performance and maintenance (cost). Most importantly, if a fiber breaks, the element having the broken fiber can be easily replaced. So the maintenance is easy. The novel contactors are promising in many industries. Performance studies and system optimization with this contactor will be of interest. As a pre-requisite step, flow and heat mass transfer properties in this contactor should be known.

In subsequent sections, the detailed fluid flow and mass transfer characteristics will be investigated. Since heat transfer coefficients can be obtained from mass transfer coefficients with heat mass transfer analogy, flow and mass transfer phenomena will be studied here with a contactor used in air humidification. The flow maldistribution and its influences will be discussed and compared to traditional contactors.

2. Experiment and numerical model

2.1. Experiment

Fig. 3 shows the geometric configurations of the contactor and two consecutive elements inside the contactor. In order to save the space inside the contactor and to prevent the air leakage through the spaces among the elements, it is found that inline arrangement is the best arrangement to distribute the small elements in the contactor. So for the scaled up contactor, only inline arrangement is considered. It is shown in this case that 5 elements are aligned in series to form a channel, and five channels are placed in parallel to form the contactor. There are also 5 channels in the depth direction. In the gaps between the channels, plates are inserted to separate the channels apart and to block the large cavities between the channels to reduce fluid leaking. The characteristic lengths of the contactor are: length $L_x = 200$ mm; height $L_y = 180$ mm; width $L_z = 340$ mm. Totally two contactors are fabricated, with elements of different packing densities. Contactor A is built with elements of a packing density of 0.35, and contactor B is built with elements of a packing density of 0.5. The geometrical and physical characteristics of the two tested contactors are summarized in Table 1. The membrane is made from PVDF by wet spinning. The structural features of PVDF hollow fiber membrane are shown in Fig. 4. Fig. 4(a) and (b) show the SEM (Scanning Electron Microscope) graphs of the hollow fiber membrane, which illustrate the cross sectional view of the membrane. It shows that the membrane is a typical asymmetric membrane with non-uniform macrovoids. The SEM graph (Fig. 4(c)) of the membrane surface shows that there are few visible pores on the surface. Sketched in Fig. 4 (d), it shows a five layers porous structures. The surface layer (δ_1) is less than 2 μm. The thickness of layers with macrovoids ($\delta_2 + \delta_4$) occupies more than 70% of the total thickness, which is about 100 μm. Other properties of the membrane under operating conditions are listed in Table 2. The porosity and nominal mean pore size of the membrane are measured by Ture Density Analyzer (BeiShiDe Instrument Technology, 3H-2000TD) and Membrane Pore Size Analyzer (BeiShiDe Instrument Technology, 3H-2000