International Journal of Heat and Mass Transfer 64 (2013) 162–172

Contents lists available at SciVerse ScienceDirect

International Journal of Heat and Mass Transfer

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

Turbulent heat and mass transfer across a hollow fiber membrane bundle considering interactions between neighboring fibers

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ARTICLE INFO

Article history:
Received 4 January 2012
Received in revised form 7 November 2012
Accepted 15 April 2013
Available online 13 May 2013

Keywords:
Turbulence
Heat and mass transfer
Hollow fiber membrane bundle
Cross-flow
In-line
Staggered

ABSTRACT

A cross flow hollow fiber membrane bundle is used for liquid desiccant air dehumidification. The turbulent fluid flow and conjugate heat and mass transfer across the bundle considering interactions between neighboring fibers are investigated. In the bundle, the process air flows across the fiber bundle and salt solution flows inside the fibers packed in the shell. Heat and moisture are exchanged through the membranes. Two structured arrangements: in-line and staggered, are considered. Due to the periodicity of the fluid flow and heat and mass transfer across the bundle, two representative periodic unit cells which include 2–3 neighboring fibers simultaneously, are selected as the calculation domains. Turbulence in the shell side is considered. The governing equations for fluid flow and heat and mass transfer in tube side, membrane side, and shell side are coupled together and solved numerically with a self-built code. The fundamental data of friction factor, Nusselt and Sherwood numbers on both the tube and the shell sides are then obtained and experimentally validated.

1. Introduction

Dehumidification of moist air is a key issue in HVAC (Heating, ventilating, and Air conditioning). Too much humidity can cause water condensation on walls, damage of materials like wood furniture, and growth of molds [1]. Indeed, molds can cause allergic reactions and make breathing difficult for some asthmatics [2].

Liquid desiccant air dehumidification has drawn much attention in these years [3–7]. However the traditional methods of packed columns have the problem of liquid droplets crossover, which has greatly limited the use of this technology. Recently hollow fiber membrane contactors have been used for liquid desiccant air dehumidification to replace the packed columns [8–12], to address this crossover problem. Such contactors can overcome the problem of solution droplets cross-over, since the solution and the air are separated apart by the membranes. The concept is like a cross-flow shell-and-tube heat exchanger where a bundle of fibers are packed in the shell. The solution flows in the fiber tubes, while the air flows across the fiber bundle. Heat and moisture are exchanged through the membranes.

The fibers arrangements can be either in-line or staggered, as shown in Fig. 1. As seen, the liquid desiccant flows inside the fiber tubes, while the process air flows across the fiber bank. The membrane is permeable to water vapor, but impermeable to salt solution. The air is dehumidified by the desiccant in the fibers, but solution is prevented from leaking to the air. Since the packing density can be very high and the air side heat and mass transfer is further intensified by the continuous disturbances from the numerous fibers, the dehumidification effectiveness with this cross flow module is very encouraging [8–11].

Heat and mass transfer in such a membrane bundle have been investigated. However previous studies were limited to free surface models with purely laminar flow assumptions [13–15]. The interactions between the neighboring fibers and the turbulent flow nature in shell side were not considered.

In this research, to account for these interactions between the neighboring fibers, the fluid in the fibers is modeled in combination with the neighboring fibers. The calculating domains are selected as the periodic area surrounded by the neighboring fibers, as shown in Fig. 1 the area surrounded by the dashed lines. On these representative cells, the fluid flow and the conjugate heat and mass transfer between the fluid and these surrounding fibers are investigated. To account for the turbulence in shell side generated by the impinging fibers, a low-*Re* k–ε turbulence model is used to describe the air flow in shell side. The Nusselt and Sherwood numbers in the bundle are obtained and analyzed. A hollow

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2013.04.035

Nomenclature

a	contactor shell width (m)
A	area (m^2)
A_m	fiber membrane area in the air stream side (m^2)
b	contactor shell height (m)
D	diffusivity (m^2/s)
D_h	hydrodynamic diameter (m)
f	friction factor
h_{abs}	absorption heat (kJ/kg)
k_{ai}	turbulent kinetic energy for the approaching air stream (m^2/s^2)
L	contactor length (m)
m_v	moisture flux (kg m^{-2} s^{-1})
Nu	Nusselt number
P	pressure (Pa)
Pr	Prandtl number
r	radius (m)
Re	Reynolds number
Sc	Schmidt number
Sh	Sherwood number
S_L	longitudinal pitch
S_T	transverse pitch
T	time averaged temperature for the air stream, temperature for the solution stream (K)
U	dimensionless velocity coefficient
u	time averaged velocity for the air stream, velocity for the solution stream (m/s)
V_{ai}	approaching velocity for the air stream (m/s)
x, y, z	coordinates in physical plane (m)
X_s	mass fraction of water in solution (kg water/kg solution)

Greek letters

ρ	density (kg/m^3)
μ	dynamic viscosity (Pa s)
δ	membrane thickness (m)
φ	packing fraction
θ	dimensionless temperature
ξ	dimensionless humidity
ψ	variable
Θ	dimensionless mass fraction of solution
Γ	diffusion coefficient
Λ	heat conductivity (W m^{-1} K^{-1})
ω	time averaged humidity for the air stream, humidity for the solution stream (kg moisture/kg dry air)
ε_{ai}	turbulence dissipation rate for the approaching air stream (m^2/s^3)
ε, η	transversal coordinates in computational plane

Superscripts

*	dimensionless
′	fluctuation

Subscripts

a	air
ave	average (mean)
b	bulk
C	fully developed under naturally formed boundaries
e	equilibrium
H	uniform heat flux (mass flux) condition
h	heat
i	inlet, inner
L	axially local
Lat	latent, moisture
m	mass, membrane
o	outlet, outer
s	solution
T	uniform temperature (concentration) condition, heat dissipation rate
t	turbulent
v	vapor
w	wall, water vapor
x	x axis direction
y	y axis direction

fiber membrane-based liquid desiccant air dehumidification experiment is performed to validate the results.

2. Mathematical model

2.1. Governing equations

In the hollow fiber membrane bundle, the two streams flow in a cross-flow arrangement. The air flow and the heat and mass transfer across the bundle show periodic features [16,17]. For reasons of symmetry and simplicity in calculations, two unit cells, as shown in Fig. 1(a) and (b) for the in-line and the staggered respectively, are selected as the calculation domains. The packing fraction of the whole bundle is equal to that of the unit cell, which can be calculated by

$$\varphi = \frac{\pi r_o^2}{S_T S_L} \tag{1}$$

where r_o is fiber outer radius (m); S_L and S_T are longitudinal and transverse pitches (m) as shown in Fig. 2, respectively.

Due to the complex geometry of the unit cell, a boundary-fitted coordinate transformation technology is used in calculations. The physical planes shown in Fig. 2(a) and (c) are transformed to the computational planes as shown in Fig. 2(b) and (d), respectively. The fibers are oriented normal to the air flow. The solution stream flows along the z axis in the circular fiber tubes (two round channels for the in-line, three round channels for the staggered), while the air stream flows over the fibers. Heat and moisture can be exchanged through the membrane between the air and the solution streams. When water vapor is absorbed by the solution, absorption heat is released on the interface between the solution and the membrane.

In practical applications, Reynolds number for the solution stream in the inner circular channel is below 10 (much less than 2300), so laminar flow is assumed. However, for the shell side air stream, the flow conditions are different. Though the Reynolds number for the air stream is still below 2300 (around 200–600), it has been found that the flow tends to become turbulent due to the continuous disturbances from the numerous fine fibers [15,18]. The laminar model is not suitable for the air stream when the Reynolds number is larger than 300 [15,18]. Certainly a turbulence model is required. However, the local turbulent Reynolds numbers ($Re_t = \rho k^2/\mu\varepsilon$) are less than 150. In this case, the near wall flow cannot be accurately modeled by a standard k–ε turbulence model [19,20]. To address this problem, a low-Re k–ε model [19,20] is used for the air stream. Other assumptions are:

(1). The air and the solution streams are Newtonian with constant thermal properties.
(2). The air stream is two-dimensional [16,17], meaning the velocities are functions of x and y only.