International Journal of Heat and Mass Transfer 55 (2012) 8061–8072

Contents lists available at SciVerse ScienceDirect

International Journal of Heat and Mass Transfer

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

Conjugate heat and mass transfer in a cross-flow hollow fiber membrane contactor for liquid desiccant air dehumidification

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ARTICLE INFO

Article history:
Received 25 May 2011
Received in revised form 20 July 2012
Accepted 18 August 2012
Available online 17 September 2012

Keywords:
Heat transfer
Mass transfer
Liquid desiccant
Cross-flow
Hollow fiber membrane contactor

ABSTRACT

The fluid flow and conjugate heat and mass transfer in a cross-flow hollow fiber membrane contactor are investigated. The shell-and-tube like contactor is used for liquid desiccant air dehumidification, where numerous fibers are packed into the shell and air flows across the fiber bank. To overcome the difficulties in the direct modeling of the whole contactor, a representative cell, which comprises of a single fiber, a liquid solution inside the fiber, and an air stream across the fiber, is selected as the calculation domain. The air stream in the cell is surrounded by an assumed outer free surface. The equations governing the fluid flow and heat and mass transfer in the two cross-flow streams are solved together with the heat and mass diffusion equations in the membrane. The friction factor and the Nusselt and Sherwood numbers on the air and stream sides are then calculated and experimentally validated.

1. Introduction

Recently, hollow fiber membrane contactors have been used in liquid desiccant air dehumidification to overcome the problem of liquid solution droplets cross-over [1–4]. According to this concept, numerous membrane fibers selectively permeable to water vapor are packed into a shell to form a shell-and-tube like contactor. The liquid desiccant flows inside the fibers, while the air flows outside the fibers [1–4]. The air is dehumidified by the desiccant in the fibers. Since the packing density can be very high, the dehumidification effectiveness is very encouraging [1–4]. The other benefit with this technology is that the process air is not in a direct contact with the liquid solution, so solution droplets cross-over is prevented.

Counter flow is the most commonly used arrangement for membrane contactors. Heat and mass transfer in such contactors have been thoroughly investigated [5–8]. However this structure has a shortcoming: the air pressure drops are high, especially for air conditioning applications where air flow rates are high. To address this problem, a cross-flow membrane contactor, as depicted in Fig. 1, is proposed and investigated for liquid desiccant air dehumidification.

The fundamental data on Nusselt and Sherwood numbers in the contactor is of interest. The structure is similar to a cross-flow shell-and-tube heat exchanger, which has been well-studied. The resistance and Nusselt numbers for a cross-flow tube bank under uniform temperature or uniform heat flux boundary conditions can be found in several well-known textbooks [9–11]. However these data and correlations are not suitable for the membrane contactor for air dehumidification because the boundary conditions are different. The boundary conditions here are neither uniform heat flux nor uniform temperature. Rather, it's a conjugate problem. At last, the heat and mass transfer are strongly coupled because of vapor condensation on membrane surface.

In this research, the fluid flow and the coupled heat and mass transfer in the cross-flow hollow fiber membrane contactor is investigated. To overcome the difficulties in the direct modeling of the numerous fibers, the Happel's free surface model is employed to simplify the analysis and to build the calculation domain. The governing equations for heat and mass transfer in the cell are proposed and solved. The Nusselt and Sherwood numbers under naturally formed boundary conditions are obtained and analyzed. An experiment is conducted to validate the results. The obtained transport data is useful for future component design and structural optimization.

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0017-9310/$ - see front matter
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2012.08.041

Nomenclature

a	contactor shell width (m)
b	contactor shell height (m)
A_c	cross-section area (m^2)
C	drag coefficient
D	diffusivity (m^2/s)
D_h	hydrodynamic diameter (m)
f	friction factor
h_{abs}	absorption heat (kJ/kg)
L	contactor length (m)
Le	Lewis number
m	mass flow rate (kg/h)
m_v	moisture emission rate (kg m^{-2} s^{-1})
n	normal direction
n_{fiber}	number of fibers
Nu	Nusselt number
p	pressure (Pa)
Pe	Peclet number
Pr	Prandtl number
r	radius (m)
Re	Reynolds number
Sc	Schmidt number
Sh	Sherwood number
T	temperature (K)
u	velocity (m/s)
V_a	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
τ	shear stress (Pa)
ψ	variable
θ	dimensionless temperature
β	angle as shown in Fig. 2(b)
ξ	dimensionless humidity
Θ	dimensionless mass fraction of solution
λ	heat conductivity (Wm^{-1} K^{-1})
ω	humidity ratio (kg moisture/kg dry air)
ε η	transversal coordinates in computational plane

Superscripts

*	dimensionless

Subscripts

1	membrane surface on air side
2	membrane surface on solution side
a	air
ave	average (mean)
b	bulk
C	fully developd under naturally formed boundaries
cal	calculated
e	equilibrium
exp	experimental
f	free surface
G	geometric
H	uniform heat flux (mass flux) condition
h	heat
i	inlet, inner
L	axially local
Lat	latent, moisture
m	mass, membrane
o	outlet, outer
r	radial direction
β	tangential direction, angularly local
s	solution
T	uniform temperature (concentration) condition
v	vapor
w	wall, water vapor
x	x axis direction
y	y axis direction

2. Mathematical model

2.1. Free surface model

A cross-flow hollow fiber membrane contactor as shown in Fig. 1 is used for liquid desiccant air dehumidification. The solution stream flows inside the fibers, while the air stream flows across a bundle of fibers in the shell side. A direct modeling of the whole bundle on a fiber-to-fiber basis is difficult to perform since the fibers are numerous, usually 2000 to 12,000 in a contactor 20 × 20 cm in cross section. To solve this problem, Happel's free surface model [12–14] is employed. According to this approach, the bundle is assumed to be comprised of a series of frictionless free surface cells. Each cell has only one fiber in the center and is surrounded by an air envelope [12–14]. The cross sections of the conjugated tube channel and air flow channel (separated and coupled by the membrane) are a circle and an annulus respectively, as depicted in Fig. 1(b). The free surface radius of a cell can be obtained by [12–14]

$$r_f = r_o \cdot \left(\frac{1}{\phi}\right)^{1/2} \tag{1}$$

where r_o is fiber outer radius (m); φ is packing fraction of the contactor, which is equal to

$$\phi = \frac{n_{fiber}\pi r_o^2}{ab} \tag{2}$$

where n_{fiber} is the number of fibers; a is the contactor shell width (m); b is the contactor shell height (m).

2.2. Governing equations in the cell

In the hollow fiber membrane contactor, the two flows are in a cross-flow arrangement. For reasons of symmetry and simplicity in calculation, only half a cell is selected as the calculation domain [13,14]. The coordinate system of the unit cell is shown in Fig. 2(a). Here the solution stream flows along the z axis in the inner circular channel, while the air stream flows over the fiber which is oriented normal to the air flow. The air stream approaches the fiber with a uniform velocity V_a, at a uniform temperature T_{ai} and a uniform humidity ω_{ai} [13,14]. 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 numbers for both the air and the solution streams are less than 500, therefore laminar flows are assumed. The fluids are Newtonian with constant thermal-physical