Applied Energy 141 (2015) 1–11

Contents lists available at ScienceDirect

Applied Energy

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

Performance characteristics of cross-flow membrane contactors for liquid desiccant systems

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HIGHLIGHTS

- Different types of flat plate membrane contactors developed to eliminate carryover in liquid desiccant systems.
- Two-dimensional steady-state model developed to predict performance of contactors.
- The simulated results are found to be in good agreement with experimental findings.
- Performance of the contactors depends significantly on the membrane characteristics.
- Parametric analysis carried out to select best operating ranges of design parameters.

ARTICLE INFO

Article history:
Received 7 June 2014
Received in revised form 26 October 2014
Accepted 7 December 2014
Available online 23 December 2014

Keywords:
Hydrophobic membranes
Membrane contactors
Liquid desiccants
Dehumidification

ABSTRACT

Membrane based indirect contact liquid desiccant dehumidification technology subsides the serious concern of liquid desiccant droplet carryover observed in conventional direct contact liquid desiccant systems. In the membrane contactor the air and liquid desiccant streams flow in alternate channels in cross-flow arrangement, separated by micro-porous semi-permeable hydrophobic membranes. Only water vapor can pass through the membranes but liquid desiccant cannot permeate. A two-dimensional steady-state mathematical model for semipermeable membrane based indirect contactors as dehumidifiers for liquid desiccant dehumidification applications has been developed. The model can predict the air and desiccant parameters inside the dehumidifier and the outlet parameters for a given input parameters. Five different membrane contactors have been fabricated and series of experiments have been conducted to validate the mathematical model. Aqueous solution of lithium chloride has been used as desiccant. The maximum deviations between experimental and predicted values are within ±10% for outlet specific humidity and outlet enthalpy of air, ±15% deviation in dehumidification effectiveness and ±20% deviation in enthalpy effectiveness. The distributions of major parameters viz. temperature, humidity, concentration, etc., within the contactor have been presented. Parametric analysis has been carried out to study the effects of membrane characteristics, contactor design, fluid flow rates, ambient conditions and desiccant concentration on the performance of the contactors.

1. Introduction

The dehumidification of air is of great importance in hospitals, industries, offices and households to maintain thermal comfort and indoor air quality (IAQ) mainly in hot and humid climate like in New Delhi. In conventional air-conditioning systems, air is dehumidified by cooling it below its dew point temperature and then heating the dry air to desired supply temperature. This process however is energy intensive and the damp condition caused by water condensation over the cooling tubes or coils invites mold to breed, thus deteriorating the IAQ. Liquid desiccant dehumidification systems, which involve the use of a liquid desiccant to absorb the moisture/water vapor from the air, have gained popularity due to the advantages of low grade energy consumption, zero water droplet condensation (hence no frost formation), sterilizing effect, etc.

Dehumidification using liquid desiccants can be achieved in two ways – (a) direct contact in which the moisture is absorbed from the air through direct contact with the liquid desiccant [1–4] and (b) indirect contact where a micro-porous membrane is used between the air and the desiccant [5–12]. The direct contact process allows for a larger exchange of moisture when compared to the indirect contact process, due to the additional resistance provided by the

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http://dx.doi.org/10.1016/j.apenergy.2014.12.014

Nomenclature

A	surface area (m^2)
a	thermodynamic activity
B	breadth of the contactor (m)
C	concentration (kmole/m^3)
$C_{lm,so}$	logarithmic mean solute concentration difference (kmole/m^3)
C_t	total concentration of the solution (kmole/m^3)
c_p	specific heat capacity (J/kg K)
D	diffusion coefficient (m^2/s)
D_h	hydraulic diameter (m)
d_a	width of air channel
d_h	hydraulic diameter (m)
d_p	pore diameter (m)
H	height of the contactor (m)
h_t	heat transfer coefficient (W/m^2 K)
h	enthalpy (kJ/kg)
h_{T_d}	latent heat of vaporization (W/m^2 K) at temperature T_d
J	mass flux (kg/m^2 s)
K	mass transfer coefficient (m/s)
Kn	Knudsen number
k	thermal conductivity (W/m K)
L	length of contactor (m)
Le	Lewis number
M_w	molecular mass of water (kg/kmole)
$\dot{m}$	mass flow rate (kg/s)
m_h	Henry's constant (kg m^2/K mole s^2)
NTU	number of transfer unit
Nu	Nusselt number
n	number
P	pressure (Pa)
P_l	partial pressure of solution (Pa)
Pr	Prandtl number
R	heat transfer resistance (m^2 K/W)
R_u	universal gas constant (8.314 kJ/kmole K)
Re	Reynolds number
Sc	Schmidt number
Sh	Sherwood number
T	temperature (K)
U_h	overall heat transfer coefficient (W/m^2 K)
U_m	overall mass transfer coefficient
w	specific humidity (kg/kg of dry air)

Greek letters

δ	membrane thickness (m)
ϵ	membrane porosity
ε	effectiveness
ξ	desiccant concentration
ρ	density (kg/m^3)
μ	dynamic viscosity (N s/m^2)
λ	mean free path (m)
ϕ	mass transfer resistance (m^2 s/kg)
τ	membrane tortuosity

Subscripts

a	air
atm	atmosphere
d	desiccant
e	equilibrium
in	inlet
k	Knudsen
lm	logarithmic mean
lam	laminar
mem	membrane
o	ordinary
out	outlet
p	pore
sen	sensible
lat	latent
tot	total
$turb$	turbulent
v	water vapor
w	water

Superscripts

$'$	with reference to liquid membrane interface

membrane during water vapor transfer in the latter case. However, the major disadvantage of direct contact has been the carryover of the desiccant droplets in the downstream supply air, resulting in harmful and toxic effects to the humans and materials. The indirect membrane contactors eliminate carryover by employing a microporous semi-permeable hydrophobic membrane in between the desiccant and the air which allows only the water vapor to pass through it. The research on heat and moisture transfer using membranes has been reviewed in literature [13–15]. Hydrophobic semi-permeable microporous membranes like polypropylene (PP), polyvinylidenefluoride (PVDF), polytetrafluoroethylene (PTFE), polyether sulfone (PES), polyethylene (PE), etc. and hydrophilic membrane like cellulose acetate (CA) have been used by researchers in indirect contact liquid desiccant systems.

Experimental studies on membrane based liquid desiccant dehumidification systems have been carried out by various authors [5–12]. Most of the numerical studies [16–22] on membrane contactors have been carried out using models which solve continuity and momentum equation to find velocity fields, and solves the energy and mass balances to get the concentration and temperature fields within dehumidifier. In the present a two-dimensional steady-state mathematical model has been developed for studying the performance of flat-plate cross flow membrane contactors working as dehumidifiers in liquid desiccant dehumidification systems. The model has been validated through experimental data collected on five membrane contactors. A test facility has been created at Refrigeration and Air-conditioning Laboratory for obtaining the performance of these contactors. Aqueous solution of lithium chloride has been used as desiccant. In the present work, the solution flow is laminar and the air flow covers the laminar and the transition regime. Zhang and co-workers [16,19–22] first proposed the heat and mass transfer model for a parallel-plate and hollow fiber membrane dehumidifier. Most of the previous studies have focussed on laminar regime only. Appropriate correlations have been used in the present study to take care of the transition regime. The model developed in this study has been used to investigate the temperature, humidity and concentration fields within the membrane contactor. Parametric studies have been carried out to investigate the effect of membrane characteristics, contactor design variables, air and desiccant conditions on the performance of the contactor. The