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Studying the heat and mass transfer process of liquid desiccant for dehumidification and cooling

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HIGHLIGHTS

- Simple mathematical model is developed for liquid desiccant dehumidifiers.
- Linear relationship between equilibrium temperature and concentration of desiccant.
- Flow rate of solution and temperature of coolant are most sensitive parameters.
- Performance of dehumidifiers is evaluated using three performance indexes.
- Integration with chiller systems results in performance improvement of about 25%.

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ABSTRACT

Desiccant-based dehumidification has gained significant attention in recent years to develop the energy efficient hybrid air-conditioning systems particularly for the tropical climate. Thus far, complex and tedious theoretical models have been developed to analyze the heat and mass transfer phenomena involved in liquid desiccant dehumidification processes. In the present study, a simple theoretical model has been presented to quantify the heat and mass transfer rates of the water-cooled liquid desiccant dehumidification and cooling processes for air-conditioning applications. Seven coupled ordinary differential equations have been developed to describe the complex heat and mass transfer processes. As far as the solution approach and practical application are concerned, the governing equations are solved simultaneously using the numerically stable 4th order Runge-Kutta scheme while preserving its accuracy to 6% in construct to full-scale model simulation. The developed model is rationally modified to study the performance of adiabatic dehumidifiers. The dehumidification and cooling performances of the adiabatic and water-cooled dehumidifiers are analyzed over a wide range of operating conditions. Finally, the energy performance enhancement potentials of the hybrid liquid desiccant air-conditioning system have been demonstrated. By analyzing the dehumidification and cooling performance, an energy saving of up to 25% can be achieved using the hybrid air-conditioning systems.

1. Introduction

Air-conditioning and mechanical ventilation (ACMV) systems consume about 60% of the total energy consumption of commercial buildings in the tropical region. Researchers have made significant attempts to reduce the energy consumption of the ACMV systems by developing the energy efficient alternative air-conditioning machines which include desiccant assisted air-conditioning systems, latent and sensible cooling load decoupling systems, direct evaporative cooling systems, indirect evaporative cooling systems etc. In hot and humid areas, desiccant assisted air-conditioning systems are considered as potential alternatives to the traditional vapor compression systems due to their advantage in removing the latent load of spaces. The liquid desiccant system possesses several advantages [1] including (a) Good dehumidification performance, (b) Low-grade energy sources can be used for regeneration, (c) Lower pressure drop of the process air stream, (d) Multiple liquid desiccant cooling systems can conveniently be connected by pumping, and (e) Ability to filter different bacteria, microbial contamination, viruses, and molds.

Researchers have examined the performance of different adiabatic and water-cooled liquid dehumidifiers by both experiments and simulations. Mohammad et al. [2,3] conducted a detailed review of liquid desiccant dehumidification systems as well as the principle of operation for liquid desiccants and classification of hybrid liquid desiccant

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Nomenclature

A	heat transfer area, m^2
c_p	specific heat capacity, $J\,kg^{-1}\,K^{-1}$
d_h	hydraulic diameter, m
D_s	diffusivity of water in desiccant solution, $m^2\,s^{-1}$
D_a	diffusivity of vapor in air, $m^2\,s^{-1}$
g	acceleration due to gravity, $m\,s^{-2}$
h_a	convective heat transfer coefficient of air, $W\,m^{-2}\,K^{-1}$
h_i	convective heat transfer coefficient between solution bulk and wall, $W\,m^{-2}\,K^{-1}$
h_o	convective heat transfer coefficient between interface and solution bulk, $W\,m^{-2}\,K^{-1}$
h_w	convective heat transfer coefficient of coolant, $W\,m^{-2}\,K^{-1}$
i	specific enthalpy, $J\,kg^{-1}$
i_{st}	specific enthalpy of moisture at the exposed surface of desiccant film, $J\,kg^{-1}$
$i_{par,w}$	partial enthalpy of absorbed moisture at the exposed surface of desiccant film, $J\,kg^{-1}$
Ja_s	Jacobs number of liquid desiccant, dimensionless
$k_{m,a}$	mass transfer coefficient of air, $kg\,m^{-2}\,s^{-1}$
$k_{m,s}$	mass transfer coefficient of solution, $m\,s^{-1}$
k	Thermal conductivity, $W\,m^{-1}\,K^{-1}$
Ka_s	Kapitza Number of solution, dimensionless
LHR	latent heat ratio, dimensionless
$m_{v,a}$	mass fraction of vapor at a-surface, dimensionless
$m_{v,s}$	mass fraction of vapor at s-surface, dimensionless
M	mass flow rate, $kg\,s^{-1}$
$\overline{M}$	molecular weight, kg/kmol
MMR	moisture removal rate, $kg\,m^{-2}\,h^{-1}$
Nu	Nusselt number, dimensionless
P	pressure, bar
P_o	reference pressure, 1 bar
Pr	Prandtl number, dimensionless
Q_a	rate of heat transfer from interface to air, W
Q_i	rate of heat transfer from solution bulk to water, W
Q_{lat}	latent energy transfer rate, W
Q_o	rate of heat transfer from interface to solution bulk, W
Q_{sen}	sensible energy transfer rate, W
Re	Reynolds number, dimensionless
Sc	Schmidt number, dimensionless
Sh	Sherwood number, dimensionless
T	temperature, °C
U_{b-w}	overall energy transfer coefficient from desiccant solution to water, $W\,m^{-2}\,K^{-1}$
X	length segment along the direction of the channel, m
W	width of plate, m

Greek symbols

δ_{wall}	thickness of wall, m
μ	dynamic viscosity, Pa s
ρ	density, $kg\,m^{-3}$
ϕ	relative humidity of air, percentage
ω_a	absolute humidity of air, $kg\,kg^{-1}$
ω_s	concentration of desiccant in the solution, $kg\,kg^{-1}$

Subscripts

a	air, a-surface
b	bulk
if	solution interface
in	inlet condition
l	desiccant
out	outlet conditions
s	desiccant aqueous solution, s-surface
v	vapor, moisture
w	water
wall	wall

systems. They reported that the coefficient of performance (COP) of the hybrid liquid desiccant cooling is better than the vapor compression system by 23.1–73.8% especially when the dehumidification unit and evaporative cooling are used in tandem with the vapor compression system. Lithium chloride, lithium bromide, calcium chloride, tri-ethylene glycol and a mixture of them are identified as the commonly used liquid desiccants. Thu et al. [4] recently evaluated the feasibility of hybrid dehumidification – mechanical vapor compression systems using classical Carnot, endoreversible and experimental approaches. They demonstrated that the break-even COP for the dehumidifier spans 4 to 7; depending on the requirement of the outdoor air ratio and the temperature of the supply air. Chua et al. [5] presented an integrated composite desiccant and nano-woven non-regenerative membrane system for the dehumidification of air. They tested the performance and reported the improvement of energy efficiency by up to 40% compared to the best grade commercial silica-gel desiccant. Wu et al. [6] developed a control strategy for the intermittent supply of the concentrated desiccant solution to multiple dehumidifiers based on their required dehumidification rates. They demonstrated that the proposed strategy can supply the concentrated solution with less energy consumption. Yin et al. [7] summarized several recent advancements in dehumidification technologies using liquid desiccants. Rafique et al. [1] presented different commercially available liquid desiccants and their composites which combine the properties of two or more desiccant materials to achieve better performance.

As far as experimental studies are concerned, researchers have conducted experimental investigations on dehumidification and regeneration using different structures. Luo et al. [8] investigated the performance of a cross-flow water-cooled dehumidifier made of fin-tube heat exchangers with high corrosion resistance. Zhang et al. [9] designed a stainless steel water-cooled dehumidifier and analyzed the performance of the system using the exhaust heat from a heat pump. Yin et al. [10] tested the performance of a water-cooled countercurrent plate-fin heat dehumidifier. Bansal et al. [11] compared the performance of a water-cooled structured packed bed tower with a similar absorber without internal cooling. Qi et al. [12] investigated key influencing factors that affect the wetted area and film thickness of the falling film liquid desiccant system. Gao et al. [13] studied the heat and mass transfer between air and liquid desiccant in a cross-flow dehumidifier. Keniar et al. [14] studied the feasibility of using a liquid desiccant membrane system to remove humidity from an office space. The dehumidifier comprises a set of permeable vertical tubes placed in the indoor space with liquid desiccant flowing through them.

A number of theoretical models of different levels of complexities have been developed by researchers to study the heat and mass transfer behaviors of liquid desiccant systems. Luo et al. [15] conducted a detailed review of various mathematical models for modeling the simultaneous heat and mass transfer process of a liquid desiccant dehumidifier. They reported that finite difference model, effectiveness Number of Transfer Unit (NTU) model and simplified models are mainly employed to study the adiabatic dehumidifier. On the other hand, variable as well as uniform liquid films of different thicknesses are generally considered for the water-cooled dehumidifiers.

Ren et al. [16] developed a set of one-dimensional differential equations to describe the heat and mass transfer process of liquid desiccants. The equilibrium humidity ratio of the desiccant solution was