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On the importance of the heat and mass transfer resistances in internally-cooled liquid desiccant dehumidifiers and regenerators

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A B S T R A C T

Liquid desiccant heat and mass exchangers are a promising technology for efficient humidity control in buildings. Many researchers have investigated these exchangers, often using numerical models to predict their performance. However, there is a lack of information in the literature on the magnitude of the heat and mass transfer resistances, both for the dehumidifier (which absorbs moisture from the air) and the regenerator (which heats the liquid desiccant to re-concentrate it). This article focuses on internally-cooled, 3-fluid exchangers in a parallel plate geometry. Water heats or cools a desiccant across a plate, and the desiccant absorbs or releases water into an airstream through a membrane. A sensitivity analysis was used to estimate the importance of each of the heat and mass transfer resistances (air, membrane, desiccant, plate, water), and how it changes with different design geometries. The results show that, for most designs, the latent and sensible heat transfer of the dehumidifier is dominated by the air mass transfer resistance and air heat transfer resistance, respectively. The air mass transfer resistance is also important for the regenerator, but much less so; the change in the desiccant equilibrium humidity ratio due to a change in either temperature or desiccant mass fraction is much higher at the regenerator's higher temperatures. This increases the importance of (1) getting heat from the water to the desiccant/membrane interface, and (2) diffusing salt ions quickly away from the desiccant/membrane interface. The membrane heat transfer and water heat transfer resistances were found to be the least important. These results can help inform decisions about what simplifying assumptions to make in numerical models, and can also help in designing these exchangers by understanding which resistances are most important.

1. Introduction

Achieving adequate comfort in buildings requires the control of both temperature and humidity. Vapor compression air conditioners remove humidity as a consequence of temperature control; air is cooled to meet the building's temperature setpoint, and water vapor is removed because of condensation on the cold evaporator surface. Removing more water vapor than is incidentally removed with this process requires colder air to reduce the humidity, and then re-heating of the air to maintain the desired temperature, which increases energy use.

This situation most commonly occurs during cool/humid conditions, and is becoming more prevalent in new efficient buildings. In these buildings, less sensible cooling is required because of lower ambient heat gains (improved insulation and windows) and lower internal heat generation (from more efficient equipment and lighting), while the latent loads (internal gains, ventilation) are nearly unchanged.

Liquid desiccants have been explored as one technology that could more efficiently and effectively meet these high-latent load conditions [1–3]. Liquid desiccants can be used within heat and mass exchangers to directly absorb water vapor from the air. Water is then removed from the desiccant solution in a regenerator, which often involves heat input. Thus, these exchangers are combined with hot and cold sources, with the cold side providing dehumidification and the hot side providing regeneration.

These hot and cold sources can come from a heat pump, such as a vapor-compression system [4–7], with the condenser providing hot water to the regenerator, and the evaporator providing chilled-water to the dehumidifier. Alternatively, a hot water source, such as a boiler, can be combined with an independent chilled-water source, such as evaporative cooling [8–10].

Many researchers have developed first-principles numerical models to predict the performance for 2-, 3-, and 4-fluid liquid desiccant heat and mass exchangers [9,11–22]. The internally-cooled

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Nomenclature

List of symbols

c_p	specific heat capacity (J kg^{-1} K^{-1})
d_h	hydraulic diameter (m)
D_K	Knudsen diffusion coefficient
D_M	molecular diffusion coefficient
D_{mem}	membrane effective diffusion coefficient
D_{va}	diffusion coefficient for water vapor in air
dx	node dimension in horizontal direction (m)
dy	node dimension in vertical direction (m)
dA	area of each node available for heat and/or mass transfer (m^2)
h	heat transfer coefficient (W m^{-2} K^{-1})
h_m	mass transfer coefficient (kg m^{-2} s^{-1})
J_v	water vapor flux (kg m^{-2} s^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
$\dot{m}$	mass flow rate (kg s^{-1})
mf_{LD}	mass fraction of liquid desiccant (kg$_{salt}$/kg$_{solution}$)
$N_{air\text{-}channels}$	number of air channels
Nu	Nusselt number
p	pressure (Pa)
Pr	Prandtl number, $\mu c_p/k$
q	heat flux (W m^{-2})
Re	Reynolds number, $\rho V d_h/\mu$
S_i	sensitivity of effectiveness to input I; sigma-normalized derivative
Sc	Schmidt number, $\mu/\rho D$
Sh	Sherwood number
T	temperature (°C)
V	velocity (m s^{-1})
x	distance in horizontal direction (m)
y	distance in vertical direction (m)

Greek symbols

δ	thickness (m)
$\varepsilon_{sensible}$	sensible effectiveness
ε_{latent}	latent effectiveness
ΔH_{dil}	enthalpy of dilution (J kg^{-1})
ΔH_v	enthalpy of vaporization (J kg^{-1})
μ	dynamic viscosity (kg m^{-1} s^{-1})
Θ	porosity
ρ	density (kg m^{-3})
ω	humidity ratio

Subscripts

a	air
i	nodal subscript for finite difference model (x-direction)
j	nodal subscript for finite difference model (y-direction)
LD	liquid desiccant
$LD\text{-}M$	liquid desiccant membrane interface
LM	log-mean difference

heat and mass exchangers (3- and 4-fluid) have some advantages over 2-fluid designs by allowing a lower flow of liquid desiccant. This difference means less heat is transferred between the regenerator and dehumidifier, which improves efficiency, and they can provide a lower supply humidity for a given desiccant concentration [23].

The focus of this paper is on 3-fluid heat and mass exchangers in a parallel-plate construction. It also includes membranes for containing the liquid desiccant. Hydrophobic membranes prevent droplets of liquid desiccant from entering the airstream, but allow vapor transport between the air and desiccant. Parallel-plate designs are suitable for internal cooling and for using membrane-contained desiccant films. Two other geometries are also relevant for liquid desiccant systems, but not discussed in this paper: hollow-fiber membrane module designs [4], and finned-tube designs [24–26]. The former is not amenable to internal cooling, and the latter does not include membrane containment of the desiccant.

One plate-and-membrane assembly from a 3-fluid desiccant exchanger is shown in Fig. 1. These assemblies can be made differently, but generally accept air, water, and liquid desiccant in some way, and then ensure even distribution along the plates for all three fluids. The example in Fig. 1 has horizontal air and water flow and vertical desiccant flow behind the membrane.

The numerical models of these components require assumptions for the heat and mass transfer coefficients between the three fluids. Researchers have explored some of these assumptions in isolation [27], but have mainly used these models to study the effect of flow rates and other operating conditions on performance [20,22,23,28,29]. Others briefly investigated the effects of design parameters through the number of transfer units, but did not link these parameters to the actual design geometry [13,14]. Some studies briefly investigated the effects of design parameters, but they were on 2-fluid exchangers or tube designs [15,30].

This research was motivated by a lack of information in the literature on two related questions: (1) what is the relative importance of the heat and mass transfer resistances for 3-fluid parallel plate desiccant dehumidifiers and regenerator, and (2) how is the performance of these heat and mass exchangers

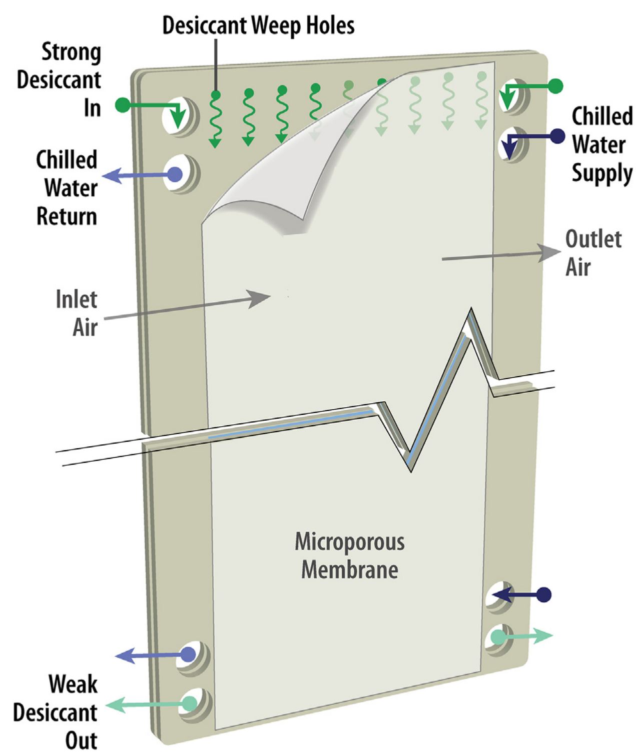

Fig. 1. One plate-and-membrane assembly from a 3-fluid desiccant exchanger, showing water, air, and desiccant flow directions. This is for dehumidification (using chilled water).