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Mathematical modeling and parametric study of liquid desiccant system with internally-cooled dehumidifier

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ABSTRACT

In this study, liquid desiccant system equipped with an internal cooling part has been modeled mathematically, and its efficiency has been investigated in different geometrical, physical and environmental conditions. The system uses a plate heat exchanger with co-current flow pattern, and liquid desiccant solution exchanges heat with cool water in adjacent channels. The results show that, if the effect of air humidity on changes in process air temperature is taken into account, the results of mathematical modeling error reduces in comparison with experimental results. If the height and width of the heat exchanger increases, system efficiency is improved, and at the best condition, the humidity ratio of intake air reduces up to 50%. In addition, although by increasing the air and desiccant flow rates entering the heat exchanger, humidity ratio of outlet air increases, the amount of humidity absorbsion increases as the water flow rate rises. When the temperature and relative humidity of ambient air increases, the amount of humidity absorbed will increase. Liquid desiccant system decreases ambient air humidity at 40 °C in both relative humidity of 100% and 40% in the same conditions specified by 43.4% and 10.1%, respectively. It is found that an increase in the temperature of the water flow and liquid desiccant solution at system input reduces the amount of moisture absorbed, and the effect of prior on humidity absorbtion is higher than the latter. When water and desiccant inlet temperatures rise 10 °C, the humidity ratio of outlet air increases 10.0% and 40.0%, respectively.

1. Introduction

The use of air conditioning systems is increasing day by day, and a large share of the energy produced in the world is consumed in the equipment. In recent years, the use of desiccant systems has increased to absorb humidity from the air flow. Using desiccant systems, air flow humidity is absorbed before entering a cooling system. Thus, energy consumption in cooling systems is reduced and appropriate and conditioning air is provided.

Humidity-absorbing systems due to low energy consumption in the regeneration process of the absorbent are considered as low-cost systems. Energy needed in them can be supplied using different energy sources available, such as steam generated in power plants and refineries, solar energy, geothermal energy, or other energy sources supply [1]. Desiccant absorbs humidity from the air flow, and this process is accompanied by the release of latent heat. So far, various systems have been introduced with a variety of liquid and solid desiccants. Liquid desiccants due to operational flexibility and the ability to absorb pollution and bacteria in the air are more used. Moreover, liquid desiccant compared with solid desiccant is regenerated at a lower temperature, and air pressure drop is less in such systems. However, in the liquid desiccant systems, usually a small amount of desiccant solution is transferred to outside in the form of droplets with air flow. Nevertheless, liquid desiccants are more used in industrial applications, and high volume of humidity will be absorbed by them.

In the liquid desiccant systems in which spray method is used, cooling of dehumidification and heating of the regeneration are performed out of the system. However, in the moisture-absorbing systems in which the liquid desiccant is used, there are some channels that warm or cool water are used for heating and cooling of liquid desiccant film. In this situation, a solution of liquid desiccant and air flow in a channel are connected indirectly with another adjacent channel in which the cooling or heating fluid flows with parallel, counter or cross flow pattern. In such systems, the temperature difference between air and liquid desiccant solution during dehumidification and regeneration processes has always kept at high rate so that the system can be used with the proper efficiency. In the process of absorption, humidity in the air is absorbed based on vapor partial pressure difference between liquid desiccant and air flow [2]. When the vapor partial pressure in the desiccant is lower than the vapor partial pressure in air flow, humidity

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Nomenclature

C_p	specific heat (kJ/kg.K)
d	depth of channel (m)
d_H	hydraulic diameter (m)
D	diffusion coefficient (m^2/s)
f	coefficient (Dimensionless)
m	mass flow rate (kg/s)
H	height of channel (m)
h_a	enthalpy of air (kJ/kg)
h_c	heat transfer coefficient between air and desiccant (W/m^2/K)
h_D	mass transfer coefficient (kg/m^2.s)
k	thermal Conductivity (kW/m.K)
L	thickness of wall (m)
$q_{1,2}$	heat transfer (kJ/kg)
q_v	latent heat of vaporization (kJ/kg)
T	temperature (K)
v	velocity of the fluid (m/s)
W	width of channel (m)
X_s	desiccant concentration (%)
z	direction (m)
Pahr	percentage of air humidity ratio reduction (−)
Patr	percentage of air temperature reduction (−)

Dimensionless number

Le	Lewis number (Dimensionless)
Re	Reynolds number (Dimensionless)
Sc	Schmidt number (Dimensionless)
Sh	Sherwood number (Dimensionless)

Greek letters

β	wetness coefficient (Dimensionless)
μ	dynamic viscosity of the fluid (kg/(m.s))
ρ	density of the fluid (kg/m^3)
ω	humidity ratio of the air (humidity) (kg of water vapor/kg of dry air)

Subscripts

1	channel (I)
2	channel (II)
a	air
in	inlet
s	solution
sat	saturation status
v	vaporization
w	water

in the air is absorbed by the desiccant, and this process continues until a balance is established and desiccant reaches to saturation mode. After the desiccant material reaches to saturation mode, no longer able to absorb humidity and must be regenerated for reuse. In the regeneration process, desiccant is exposed to the airflow with higher temperature. The vapor partial pressure in a warmer air is lower than its amount in the surface of desiccant. Under this condition, due to the vapor partial pressure difference at the interface of air and desiccant, humidity is transferred from absorbent material to warm air, and thus the desiccant material is regenerated [3].

Many researchers have conducted study on the use of liquid desiccant systems. For example, laboratory design of hybrid solar air conditioning system including vapor compression system and liquid desiccant cycle was introduced by Yadav [4]. In this system, the liquid desiccant was used to dehumidify the air and reduce the amount of latent heat. Also, heat output from the condenser was used to regenerate the desiccant to increase system efficiency factor. He showed that, due to the low temperature required to regenerate the desiccant, solar thermal energy can be used. Kinsara et al. [3] studied the air conditioning system equipped with liquid desiccant system. They used a solution of calcium chloride as a liquid desiccant. In this study, the effect of inlet desiccant solution temperature and efficiency of the heat exchanger on absorbtion of humidity was evaluated. The results showed that, with increasing inlet desiccant solution temperature, system efficiency is improved. In addition, system efficiency is strongly dependent on the efficiency of the heat exchanger, and the absorption of humidity can be substantially increased using a good design. Khan and Martinez [5] used a mathematical model to predict the behavior of an evaporative cooling system equipped with a liquid desiccant system. The finite difference scheme was used to solve the governing equations. The results showed that, when a solution of lithium chloride is used as a liquid desiccant, thermal efficiency of the system depends on the concentration of desiccant solution and mass flow rate of process air. Saman and Alizadeh [6] studied the performance of liquid desiccant system in which a plate heat exchanger with cross flow pattern was used. In this study, the finite difference method was used to solve the governing equations. The results of this study in which calcium chloride was used as desiccant solution showed that the performance of the system depends on the amount of heat and mass transfer, initial concentration of the desiccant solution and secondary air mass flow rate to primary mass flow rate ratio. Ali and Vafai [7] studied heat and mass transfer processes between air flow and liquid desiccant film in two modes of inclined parallel flow and inclined counter flow theoretically. They examined the effect of plates slope in desiccant system on the amount of air humidity absorbed and regenerated. The results showed that, when the Reynolds number for the air flow decreases, the amount of humidity absorbed by the system increases. Also, it was concluded that, when inlet air temperature and the concentration of liquid desiccant increases and decreases, respectively, the dehumidification - process is improved. In addition, when the desiccant solution flow rate decreases, the desiccant regeneration process is done better. Chen et al. [8] studied the desiccant system with packed bed type using a mathematical model. They assumed that the desiccant concentration in output is constant, and solved the governing equations using an analytical solution. The results of analytical solution were consistent with the experimental results of previous studies. They also calculated the optimal flow rate of the working fluids using this method. Yin et al. [9] studied air conditioning system equipped with evaporative cooling and liquid desiccant systems. Experimental model used in this study was packed-bed type, and a solution of lithium chloride-water was used as a liquid desiccant system. The proposed system could be operated using heat sources which have the temperature between 60 and 80 °C such as solar energy and industrial waste heat. They examined the impact of heat source temperature, relative humidity and ambient air temperature, temperature and initial concentration of desiccant solution on dehumidification and regeneration rates. Laboratory results showed that, Mass transfer coefficient in the regeneration process is equal to 4 g/m^2s. Liu et al. [10] theoretically studied heat and mass transfer in dehumidifier and regeneration parts of liquid desiccant system using a two-dimensional mathematical model. In this study, it was assumed that flow pattern in the heat exchanger of the system is in form of Cross-flow. In addition, the Lewis and NTU dimensionless numbers were used as input parameters. The values of these parameters were obtained from experimental results. In this study, the changes in concentration of liquid desiccant during the regeneration and dehumidify process were ignored. Alizadeh [11] studied the air-conditioning system with liquid