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Experimental analysis of an internally-cooled/heated liquid desiccant dehumidifier/regenerator made of thermally conductive plastic

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ABSTRACT

Internally-cooled dehumidifiers that use liquid desiccant are supposed to be superior to the adiabatic type in terms of solution flow rate, device volume, etc. In the present study, an internally-cooled dehumidifier made of thermally conductive plastic was designed, and it achieved superior corrosion resistance. Its performance was investigated both experimentally and through simulation. An experimental chamber was built for this internally-cooled dehumidifier, and the experimental results in different working conditions were obtained using a lithium bromide (LiBr) aqueous solution. Performance indices including the moisture removal rate, dehumidification/regeneration efficiency, and volumetric mass transfer coefficient were analyzed in conjunction with the inlet parameters. Compared with the internally-cooled dehumidifiers made of metal materials described in the literature, the present analysis indicates that this plastic dehumidifier demonstrated comparable heat and mass transfer performance, providing a feasible approach for an internally-cooled process. In addition, with the help of the experimental results, a numerical model was built and validated for this internally-cooled dehumidifier using liquid desiccant.

1. Introduction

Indoor humidity control is one of the main tasks for air-conditioning systems, and reducing the energy consumed by the humid air handling process has a significant impact on the energy conservation of buildings [1]. In recent years, liquid desiccant has emerged as an efficient approach for controlling air humidity, and increasing attention has been paid to humid air handling processes that use liquid desiccant [2–8]. In contrast to conventional condensing dehumidification methods, liquid desiccant approaches can utilize renewable energy or low-grade energy [9]. Solar energy, industrial waste energy, and the condensing heat of a vapor compression cycle are all appropriate driving sources for liquid desiccant air handling processes. Both dehumidification and humidification requirements can be satisfied by the same air handling device using liquid desiccant. Another benefit of liquid desiccant methods is their ability to store latent heat using solution [10].

The dehumidifier/regenerator is one of the key components in liquid desiccant air-conditioning systems, which can be classified as either the adiabatic type or the internally cooled/heated type according to whether there is internal cooling/heating in the dehumidification/regeneration process. Currently, most of the air handling processes using liquid desiccant for both research and actual applications belong to the adiabatic type [3–8,11,12]. However, the internally cooled/heated process is believed to be superior to the adiabatic process in terms of reducing the circulating solution flow rate and device volume [13]. Scholars have paid increasing attention to internally-cooled/heated processes using liquid desiccant in recent years. Both theoretical and experimental analyses on internally-cooled dehumidifiers and internally-heated regenerators have been carried out [14–26].

Numerical and theoretical analyses on the internally-cooled/heated process and the entire air handling system have also been conducted [14–19]. Ren et al. [15] used one-dimensional differential equations to describe the coupled heat and mass transfer processes in internally-cooled systems, and both analytical solutions and numerical integrations were given for different flow arrangements. Khan et al. [16] proposed an internally-cooled dehumidifier using refrigerant to cool the sprayed solution; influencing factors related to dehumidification performance were then determined according to the simulation results. Qi et al. [17] established a system model for an internally-cooled liquid desiccant air handling device, and the energy performance of the novel system in a commercial building was simulated.

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Nomenclature

c_p	specific heat capacity (kJ/(kg °C))
d_o	outer diameter of the pipe (mm)
d_i	inner diameter of the pipe (mm)
F	heat and mass transfer area (m^2)
H	height of the device (m)
h	enthalpy (kJ/kg)
h_1	convective heat transfer coefficient between cooling/heating water and the internal surface of the pipe (W/(m^2 °C))
h_2	convective heat transfer coefficient between solution and the outside surface of the pipe (W/(m^2 °C))
K_h	heat transfer coefficient between air and desiccant (kW/(m^2 °C))
K_m	mass transfer coefficient between air and desiccant (kg/(m^2 s))
k_{mv}	volumetric mass transfer coefficient between air and desiccant (kg/(m^3 s))
L	length of the device (m)
m_w	moisture removal rate (g/s)
$\dot{m}$	mass flow rate (kg/s)
t	temperature (°C)
V	volume of the device (m^3)
X	concentration of liquid desiccant (mass ratio of desiccant to solution) (%)

Greek symbols

α	specific surface area (m^2/m^3)
β	rib effect coefficient (dimensionless)
η	total fin efficiency (dimensionless)
η_m	dehumidification/regeneration efficiency (dimensionless)
λ	heat conductivity coefficient of the pipe wall (W/(m °C))
ω	humidity ratio (g/kg)
$\Delta\omega$	logarithmic mean humidity ratio difference between air and solution (g/kg)

Subscripts

a	air
e	air in equilibrium with desiccant
h	heat transfer process
m	mass transfer process
in	inlet
out	outlet
s	liquid desiccant
w	water

Experimental methods have also been used to examine the performance of internally-cooled or heated processes [20–26]; different experimental devices have been set up to investigate the operating performance. Queiroz et al. [20] tested the performance of an evaporative condenser-based internally-cooled dehumidifier made of copper pipes using triethylene glycol. Zhang et al. [21] proposed a fin coil-based internally-cooled dehumidifier made of stainless steel and tested the influence of different parameters (e.g., solution flow rate and cooling water flow rate) on the performance of the device. Yin et al. [23] investigated both the dehumidification performance and regeneration performance of an internally-cooled/heated device using a plate-fin heat exchanger (PFHE) made of stainless steel. Bansal et al. [24] tested the performance of the dehumidification process in a packed tower internally-cooled dehumidifier with cooling tubes.

In an internally-cooled dehumidifier, the performance of the heat transfer process between the solution and cooling media will significantly influence the structure and material of the device. For an adiabatic device, both a large specific surface area and a satisfactory wetting effect between the air and solution are required to guarantee an adequate operating performance. For an internally-cooled dehumidifier, in addition to the specific surface area and the wetting effect between the air and solution, the thermal conductivity of the material is expected to be high enough to achieve a satisfactory heat transfer effect between the solution and cooling media. Metal materials are generally used for the sensible heat exchangers between two liquids. Because the spray medium in an internally-cooled liquid dehumidifier is saline solution, most metal heat exchangers cannot be adopted in actual buildings due to their lack of resistance to corrosion, despite the fact that their high heat conductivity could improve the performance of the heat transfer process. As such, the problem of corrosion prevents the long-term stable operation of these devices.

Considering the corrosion problem, producing internally-cooled dehumidifiers made of different materials is a feasible approach for researchers. Some experimental analyses of internally-cooled dehumidifiers made of stainless steel or other corrosion-resistant metals have been carried out [10,20,23,24]. Plastic has good corrosion resistance, also with benefits in ease of manufacture, maintenance and lowering the cost [27,28]. Heat exchanger made of plastic has been applied in many areas such as sea water desalination and flue gas recovery [29,30] due to its superior anti-corrosion performance, and thus plastic could therefore be selected as the material for an internally-cooled dehumidifier. Kessling et al. [10] and Saman et al. [26] designed plastic plate internally-cooled dehumidifiers and tested their performance. However, the heat conductivity of common plastic material is much lower than that of metal material; as a result, the overall operating performance of the internally-cooled device will be limited by the unsatisfactory heat conductivity. In the present study, a new type of internally-cooled dehumidifier made of thermally conductive plastic was designed. An experimental chamber was set up, and the effects of the inlet and operating parameters on both the dehumidification performance and regeneration performance of the device were investigated.

2. Internally-cooled dehumidification module and experimental conditions

2.1. Internally-cooled dehumidification module

An internally-cooled/heated dehumidifier/regenerator made of thermally conductive plastic was designed; the façade of this module is shown in Fig. 1(a). Tubes with fins are adopted in the device to increase the specific surface area of this component and to enhance the mass transfer performance between the air and solution. The module is an eight-row heat exchanger, and there are eight parallel channels in each row. The specific area (α) of the module is 342 m^2/m^3. Fig. 1(b) shows the schematic of the flow pattern. The flow direction of solution to cooling water is counter-flow, and those of air to solution and air to cooling water are both cross-flow. Solution is sprayed from the top of the device. The cooling water flows in from a water separator at the bottom of the device and flows out through a water collector at the top of the device, while air flows through the device from the front side.

The base material of the plastic is polypropylene, with a thermal conductivity of 16.5 W/(m K). Physical property parameters of common metal materials and plastics are listed in Table 1, including thermal conductivities, melting point and strength of extension. The main influence of the different materials is on the heat conductivity performance of the internally-cooled dehumidifier. As