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Experimental evaluation of transient heat and mass transfer during regeneration in multilayer fixed-bed binder-free desiccant dehumidifier

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ABSTRACT

In this study, regeneration experiments were performed in a previously developed multilayer fixed-bed, binder-free desiccant dehumidifier (MFBDD) in order to investigate the transient heat and mass transfer characteristics during the desorption of condensed water from desiccant material inside the device. A microsphere silica gel (M.S.GEL manufactured by AGC Si-Tech. Co., Ltd., Japan) having a pore diameter of 2.7 nm was used as the desiccant, which was feasible for regeneration at a temperature slightly above 50 °C. To prevent heat loss during regeneration, the test section was placed inside a constant-temperature oven. Experiments were performed under several regeneration conditions to investigate the influence of temperature, humidity, and flow velocity of the regeneration air on the heat and mass transfer characteristics of the device. The influence of heat loss from the test section to the surroundings during regeneration was also determined by precisely controlling the oven temperature. The results revealed that the regeneration capacity of the device improved with an increase in the regeneration air temperature. However, the maximum temperature of regeneration air should be optimized for energy-efficient operation of the device according to the regeneration conditions.

1. Introduction

In our previous studies [1,2], we proposed a novel multilayer fixed-bed, binder-free desiccant dehumidifier (MFBDD) that can be feasibly integrated with conventional vapor-compression-based air-conditioners in order to reduce the primary energy consumption of the hybrid system We performed both experimental investigations [1] and numerical simulations [2] in these studies, and the results showed that the proposed device could be operated at a noticeably lower pressure drop and that a reasonably higher dehumidification capacity than that of a conventional desiccant wheel could be achieved. However, in addition to pressure drop and dehumidification capacity, another pivotal parameter—“regen eration” of desiccant particles subject to different conditions—needs to be assessed for effective integration of such devices with existing heating, ventilation, and air-conditioning (HVAC) facilities. Regeneration or drying of desiccant particles after their soaking with water vapor during adsorption is the most critical phase of an adsorption–desorption cycle, which determines the feasibility of integrating a desiccant dehumidifier in a hybrid air-conditioning system. A schematic diagram of how such a dehumidifier can be integrated with a vapor compression system is shown in Fig. 1. The heat sinks and heat source shown in Fig. 1 can be provided by the vapor compression system. It should be noted that unlike rotary desiccant wheel, the MFBDD will operate in a batch mode and a minimum of two MFBDDs will be required for a continuous operation: one in adsorption mode (unit 1) and the other in regeneration mode (unit 2) as shown in Fig. 1. The mode of operation between these two units can be interchanged by two-way valves V_1 and V_2.

Desiccant materials that require a high temperature and long time for regeneration are not suitable for practical desiccant-based evaporative air-conditioning applications. The amount of water vapor that can be desorbed within a specific time duration primarily depends on several factors such as the desorption isotherm of a particular desiccant material and the temperature, humidity, and flow velocity of the regeneration air. Therefore, study of these factors is crucial in order to clearly understand the regeneration characteristics of a desiccant material. While adsorption in solid desiccants has been the subject of many studies ranging from those on the fundamentals [3–8] to those on applications [9–16], limited studies have been conducted on the regeneration of solid desiccant materials in spite of the high relevance of this research topic to practical HVAC applications.

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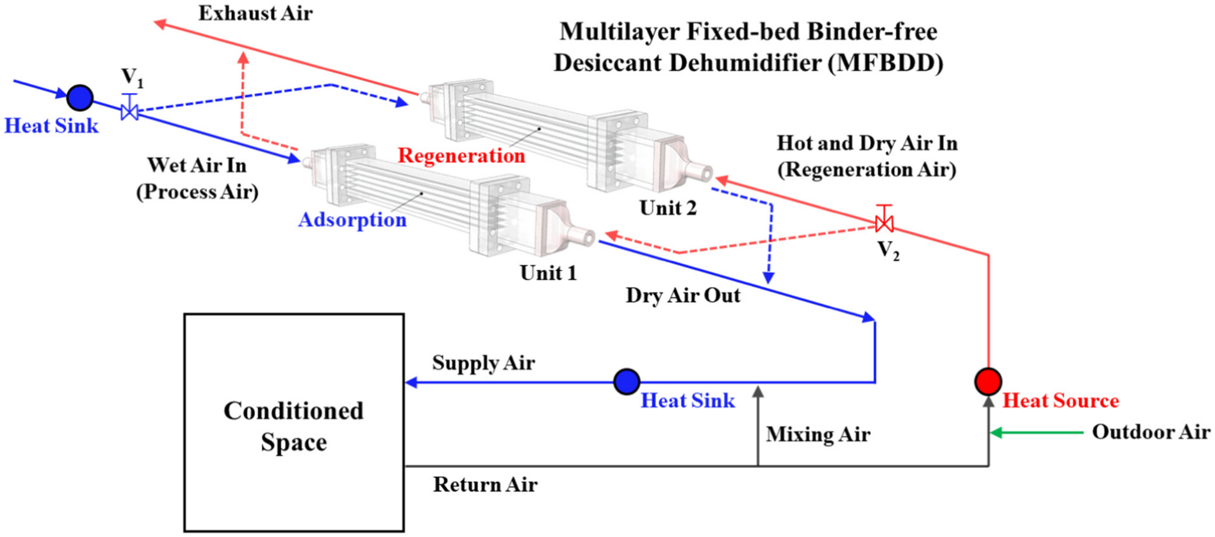

Fig. 1. Schematic diagram showing integration of MFBDD with vapor compression system. The heat sinks and heat source can be provided by a vapor compression system.

Several researchers investigated how changes in the regeneration air temperature, regeneration air humidity, or flow rate ratio of the regeneration air to the process air (here the term "process air" refers to humid outside air supplied to the inlet of the adsorption section of a desiccant wheel) influence the adsorption capacity of a desiccant system. Eicker et al. [17] investigated the dehumidification capacity of several commercially available desiccant wheels under different regeneration conditions. Their results revealed that both the dehumidification capacity and the energy efficiency increased with an increase in the regeneration air temperature as well as the ratio of the regeneration air flow rate to the process air flow rate up to a certain limit. For example, when the regeneration air temperature of a commercial silica-gel Hexcore wheel was increased from 60 °C to 75 °C, the dehumidification capacity increased from 4.0 g/kg$_{DA}$ to 5.1 g/kg$_{DA}$ without any significant increase in the enthalpy (from 1.4 kJ/kg to 2.7 kJ/kg) of the supply air (here the term "supply air" refers to dehumidified air supplied from the outlet of the adsorption section of a desiccant wheel). However, with a further increase in the regeneration air temperature from 75 °C to 90 °C, the enthalpy of the supply air increased significantly (by 10.9 kJ/kg) whereas the dehumidification capacity increased only slightly, from 5.1 g/kg$_{DA}$ to 5.7 g/kg$_{DA}$. Similar results were also observed for different volume flow ratios of the regeneration air to the process air (hereafter referred to as "volume flow ratio"). When the volume flow ratio was increased from 0.5 to 0.75, the dehumidification capacity increased noticeably, from 3.8 g/kg$_{DA}$ to 5.1 g/kg$_{DA}$, but the enthalpy of the supply air increased only slightly, from 2.7 kJ/kg to 3.2 kJ/kg, at a regeneration air temperature of 75 °C. However, a further increment of the volume flow ratio from 0.75 to 1.0 significantly increased the enthalpy of supply air (12.3 kJ/kg) without any improvement in the dehumidification capacity. These results suggest that there exists an optimum limit for the regeneration air temperature and volume flow ratio beyond which the energy efficiency degrades and the enthalpy of the supply air increases noticeably which is unfavorable for evaporative cooling in the next stage. They also investigated the influence of the regeneration air relative humidity on adsorption capacity, and found that the dehumidification capacity of the desiccant wheel could be augmented by using regeneration air with lower relative humidity.

White and coworkers [18] evaluated the effects of varying the ratio of the face velocity of process air to that of regeneration air (hereafter referred to as "face velocity ratio") on the dehumidification capacities of three different desiccant wheels: those made of silica gel, polymer, and zeolite. In their experiment, the process air was supplied at a constant temperature and velocity of 30 °C and 2.5 m/s, respectively. The velocity of the regeneration air was varied between 2.5 m/s and 1.5 m/s keeping the temperature of regeneration air constant at 50 °C. Their results revealed that with a decrease in the velocity of the regeneration air (i.e. with an increase in the face velocity ratio), the dehumidification capacity of all the three wheels decreased. However, when the face velocity ratio was equal to 1.0, the dehumidification capacity of the polymer-coated wheel was doubled. The zeolite-coated wheel was found to be the most insensitive to the flow rate of the regeneration air over the entire considered range of process air humidities.

Angrisani et al. [19] investigated the possibility of regenerating a silica-gel-coated desiccant wheel by using thermal energy from a microgenerator. In their experiment, the desiccant wheel was coupled to an electric chiller, a natural-gas-fired boiler, and a small-scale cogenerator. They adopted a maximum regeneration temperature of 65 °C during the experiment and found that higher dehumidification effectiveness could be achieved by increasing the regeneration temperature. However, at a higher regeneration temperature, the heat loss also became dominant and resulted in lower regeneration effectiveness. Abou-Ziyan et al. [20] also investigated the effects of increasing regeneration temperature on the performance of a thin-multilayer activated alumina bed and reported that at a higher regeneration temperature, a shorter regeneration time was required and a higher moisture removal capacity could be achieved. Chung et al. [21] optimized the area ratio of a desiccant wheel between the regeneration airflow passage and the process airflow passage and concluded that at a lower temperature, a larger regeneration portion was needed for the wheel.

In addition to evaluating different regeneration conditions, several studies in the literature focused on the different regeneration methods, such as combining solar radiation [22–24], microwaves [25–27], or ultrasound [28–30] with hot air in order to further reduce the primary energy consumption for regeneration. In this regard, Yang et al. [31] proposed an interesting concept of regenerating the desiccant materials under the combined effect of microwaves and solar radiation. They experimentally showed that a higher degree of regeneration (defined as the mass ratio of the water desorbed in a certain time during the regeneration to water contained in the saturated silica gel) as well as better energy effi-