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Performance analysis of a new kind of heat pump-driven outdoor air processor using solid desiccant

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ABSTRACT

A new type of outdoor air dehumidification processor using solid desiccant is proposed, in which a heat pump and square desiccant plates are combined. Each desiccant plate consists of an air channel with a honeycomb structure that is coated with desiccant material. The square desiccant plates change positions between the processed air duct for dehumidification and the regenerated air duct for regeneration. The cooling capacity of the heat pump is utilized to cool the processed air, and the exhaust heat of the heat pump is used to provide regenerative heat to the desiccant. Several stages can be combined together to gain higher efficiency. The proposed desiccant dehumidifier can achieve a low humidity ratio of the supplied air and provides low-temperature regeneration. A mathematical model is established to predict the performance of this desiccant processor, and the model shows good agreement with the experimental results. The factors that influence the performance of the processor are then analyzed in order to maximize performance. The simulation results show that the proposed desiccant processor provides regeneration at a low temperature (40–50 °C), and the COP can surpass 4.0 at different processed air inlet states.

1. Introduction

Along with condensation dehumidification, solid desiccant dehumidification is commonly used in industrial and commercial buildings. The latter method utilizes the adsorption characteristics of solid desiccants such as silica gel, molecular sieves, and activated alumina to dehumidify the processed air. After adsorbing the moisture from the processed air, the desiccant must be regenerated before being reused. The regenerative heat can come from solar energy, steam, etc. Solid desiccant devices are classified into two main types: rotary desiccant wheels [1–4] and desiccant beds [5–8].

A desiccant wheel is a rotor covered with solid desiccant material, which slowly rotates between the processed air and the regenerated air [9]. During the dehumidification process, the processed air operates close to an isenthalpic process; thus, the outlet temperature of the processed air will be very high, and assisted cooling must be implemented to cool down the dried processed air before it is introduced into occupied spaces. The cooling source involves a mechanical chiller [2,10] and direct or indirect evaporative cooling modes [2,11,12]. The advantage of desiccant wheels is that they can reach a lower and more constant humidity ratio of the supplied air compared to desiccant beds. However, the required regeneration temperature of desiccant wheels is very high (usually 80–130 °C), which hampers the utilization of waste heat. Jia et al. [11] adopted compound desiccant materials, which can absorb 20–40% more water than silica gel, to reduce the regeneration temperature to 80–90 °C. In two-stage desiccant wheel systems, cooling water from either direct cooling or indirect cooling systems is used to cool down the processed air after each stage of the desiccant wheel [13,14]. Two streams of regenerated air enter separately into each stage and are discharged to the outdoor environment. The regeneration temperature of these two-stage desiccant wheel systems can be reduced to below 90 °C. Due to the strength of the rotary structure, the thickness of the desiccant wheel is difficult to reduce, and multi-stage desiccant wheel systems described in previous research have been limited to two stages [13].

Desiccant beds represent another kind of desiccant dehumidification system in which a fixed bed is covered with desiccant materials. There are usually two beds, one for dehumidification mode and the other for regeneration mode, and the modes of dehumidification and regeneration alternate. The dehumidification process is discontinuous, and the humidity ratio of the supplied air

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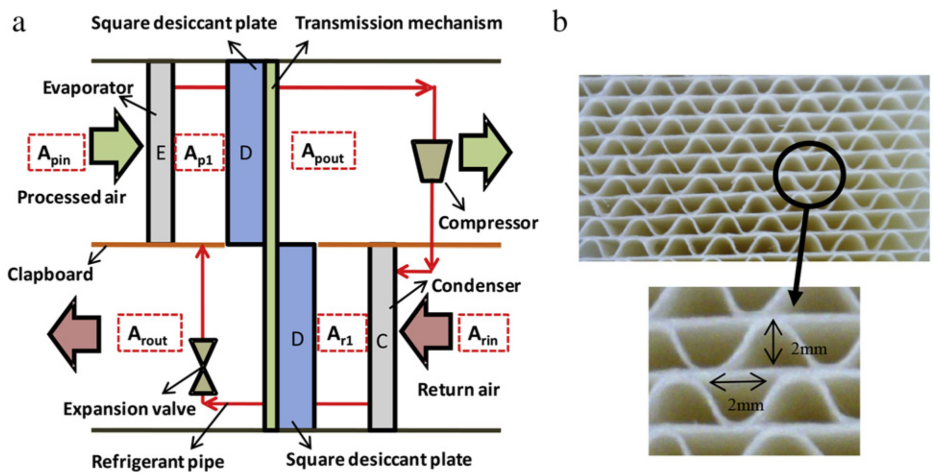

Fig. 1. Operating principle of the dehumidifier using solid desiccant: (a) single-stage dehumidifier; and (b) square desiccant plate material.

always varies as the dehumidification process moves forward. The performance of inner cooling/heating desiccant beds appears to be superior to that of adiabatic desiccant beds. In inner cooling/heating desiccant beds, cooling fluid is supplied into the dehumidification bed, and hot fluid (50–70 °C) is supplied into the regeneration bed [15]. The desiccant bed can be combined with a heat pump, in which the evaporator and condenser are coated with solid desiccant and serve as the dehumidification bed and the regeneration bed, respectively.

A product that utilizes a heat pump system has been developed for home use [16], and its COP can exceed 4.0 using indoor exhaust air as regenerated air. However, the processed air duct and the regeneration duct have to alternate every 3–5 min, as do the evaporator and the condenser in the heat pump with four-way valves. This makes the system complex, and it suffers from the cooling-heating offset of the refrigerant inside the heat pump cycle as well.

A new type of solid desiccant dehumidification processor combined with a heat pump is proposed in this paper. In this system, the square desiccant plates change positions between the processed air duct and the regenerated air duct. The cooling capacity of the heat pump is utilized to cool the processed air before it enters the desiccant plates, and the exhaust heat of the heat pump is used to provide regenerative heat to the desiccant. Multiple stages can therefore be combined together. The proposed desiccant dehumidifier can be operated easily, and a low regeneration temperature can be achieved. The heat pump system does not need to change its refrigerant direction or air ducts to meet the alternation demand of the dehumidification and regeneration modes, and it avoids the cooling-heating offset of the refrigerant inside the heat pump cycle. In this paper, the performance of this desiccant dehumidifier is experimentally and numerically analyzed, and the main factors that influence its performance are discussed.

2. Operating principle of the new desiccant processor

The proposed desiccant processor is composed of two parts: a desiccant bed system and a heat pump system, as shown in Fig. 1. The desiccant bed system is composed of square desiccant plates, whose honeycomb structure is similar to that of a desiccant rotary wheel. There are two square desiccant plates, one each in the processed air duct and the regenerated air duct. The two desiccant plates change positions every few minutes so the wet desiccant bed can be regenerated and the dried desiccant bed can dehumidify the processed air. The processed air and regenerated air flow in their own ducts and in reverse directions. Several stages of square desiccant plates can be linked together in a line to enhance performance, with evaporators and condensers inserted between each plate. Fig. 2 shows a two-stage desiccant dehumidifier combined with a two-stage refrigeration cooling system.

The air handling process of this multi-stage desiccant dehumidifier is different from that of a desiccant wheel. For desiccant wheels, processed air cools down the desiccant material, removes the heat of adsorption, and operates close to an isentropic process, as shown in Fig. 3. Since the change in humidity of the processed air is very large, the outlet temperature is very high, so the inlet temperature of the regenerated air needs to be around 90–130 °C. When the air handling processes of the processed air and the

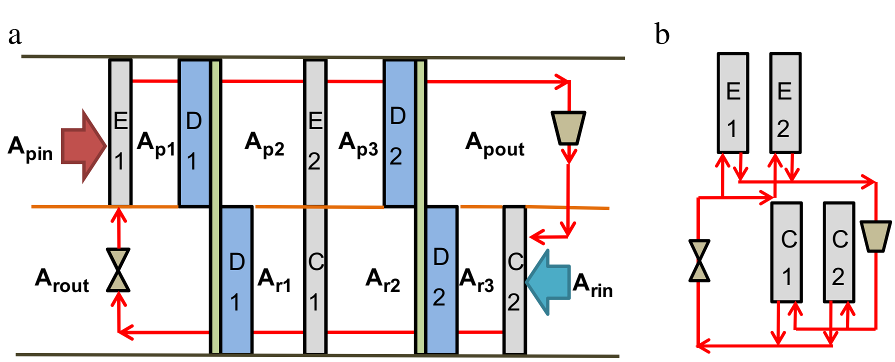

Fig. 2. Operating principle of the multi-stage desiccant dehumidifier: (a) operating principle; and (b) pipeline connection of the heat pump.