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Desiccant-coated water-sorbing heat exchanger: Weakly-coupled heat and mass transfer

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ABSTRACT

Desiccant-coated, water-sorbing heat exchanger has been proposed and investigated which shows a great advantage to independently treat the sensible and latent heat load but without sacrificing compactness and comfort. Here, a theoretical and experimental study was made to investigate and predict its dynamic behaviors of heat and mass transfer in response to the step change of the operational mode switch which is essential to continuous operation but harmful to its sensible load capacity. The results show that it has a special feature of weakly-coupled heat and mass transfer, which opens up the possibility of adopting temperature and humidity loosely-coupled control strategy to independently control the temperature and humidity on a single exchanger at the same time. Both the outlet air temperature and humidity ratio of the evaporator in response to the step change of the operational mode switch can be described by two individual exponential functions of time, which indicates that the linear driving force model is possibly valid to describe the water uptake kinetics of the water-sorbing heat exchanger even if the real working conditions are non-isothermal and non-steady.

1. Introduction

Sensibly cooling loads must be dramatically reduced when designing highly energy efficient buildings and net-zero energy buildings, however, latent loads remain relatively constant [1]. This shift toward low sensible heat ratio (SHR) is a challenge for traditional heating, ventilation, and air-conditioning (HVAC) systems, particularly in humid climates [2]. To deal with the challenge, a novel concept of water-sorbing heat exchanger (WSHE) has been proposed by the authors [3], which shows a great potential to be a cost-effective, energy-saving and comfortable temperature and humidity control technology.

The main structure difference from conventional heat exchanger (such as fin-tube coil) is that there is a thin desiccant film on its outer surface, which can be achieved either by solid desiccant coating (Fig. 1a) or liquid desiccant spreading. Instead of cooling the air to condense its moisture for cooling-based dehumidifier, desiccant attracts moisture from the air by creating an area of low vapor pressure at the surface of the desiccant. Thus, it's believed that desiccant can dehumidify the air more efficiently. When low temperature heat transfer medium flows into WSHE, it operates as a cooler/adsorber to effect cooling and drying of the processing air flowing through it, meanwhile, the heat of adsorption will be taken away rightly but the removed water from the air stays in the desiccant thereon. After the desiccant gets saturated, it acts as a heater/desorber, the high temperature heat transfer medium warms the desiccant thereon which then desorbs water to the scavenging air that flows through it. In this case, latent load (dehumidification) and sensible load (cooling/heating) can be independently handled by the desiccant film and the heat transfer medium, respectively. In other words, the outlet air of WSHE can directly satisfy the supply air requirements (Fig. 1b). Thus, an essential characteristic is its ability to supply cool, dry air without reheat in summer season or warm, moist air without humidifier in winter season.

The device investigated in this article is a solid desiccant coated WSHE (Fig. 1a), on which water uptake happens at a low temperature (10–20 °C). This means the desiccant temperature is possibly close to or lower than the inlet air dew point and capillary condensation maybe occur. It not only effectively improves the water uptake capacity of the desiccant but also requires a relative low regeneration temperature (40–50 °C). In other words, the desiccants required for the WSHE are expected to have a larger water uptake capacity difference between high relative humidity (larger than 80%) and medium relative humidity (about 30%), which can be achieved for many desiccants, such as the mesoporous silica gel and the composite desiccants [4].

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Nomenclature

R	thermal resistance ($K\,W^{-1}$)
h_c	the moist air-side convection heat transfer coefficient ($W\,m^{-2}\,k^{-1}$)
η	fin efficiency (unitless)
A	area (m^2)
δ	thickness (m)
P_t	transverse tube pitch
P_l	longitudinal tube pitch
P_f	fin pitch
D_c	fin collar outside diameter (m)
r_i	inside fin radius for the equivalent circular area methodthat equal to the outside tube (include collar) radius (m)
r_o	outside fin radius for the Equivalent circular area method (m)
$C_{p,a}$	specific heat capacity of moist air ($kJ\,kg^{-1}\,K^{-1}$)
$C_{p,s}$	specific heat capacity of desiccant coated layer ($kJ\,kg^{-1}\,K^{-1}$)
$C_{p,hex}$	specific heat capacity of base heat exchanger ($kJ\,kg^{-1}\,K^{-1}$)
q_{st}	heat of adsorption ($kJ\,kg^{-1}$)
w	water content ($kg\,kg^{-1}$)
M	mass (kg)
G	flow rate ($kg\,s^{-1}$)
λ	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
T	temperature (°C)

Subscript

a	air
r	coolant
s	desiccant coated layer
hex	base heat exchanger
f	fin
t	tube
i	inlet
o	outlet

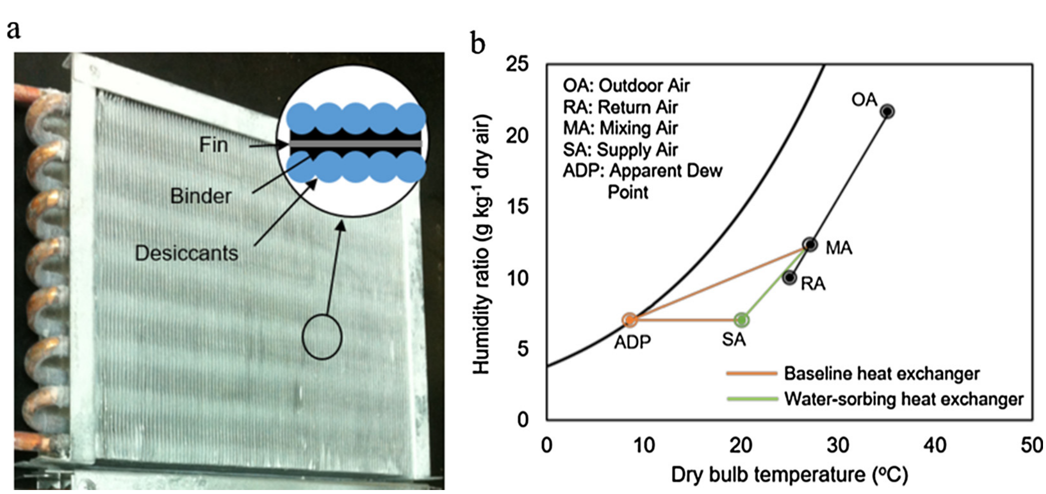

Fig. 1. The WSHE Photo (a) and tis air handling process shown in a psychrometric chart (b).

Similar concepts of solid desiccant-coated heat exchanger (DCHE) [5–13] (sometimes named adsorption heat exchanger [14–16]) or liquid desiccant-sprayed heat exchanger (DSHE) [17–20] have been reported in previous literatures, which are often used for adsorption refrigeration [6], heat pump [21], heat storage [22], desalination [8] and dehumidification [7,9–11,13,23,24]. The most common heat transfer mediums internally cooling the DCHEs and DSHEs are natural wind [10] and water from cooling tower [13,18], and the heat sources available are usually provided by solar heating [10,19,25] and other low-grade heat, such as industry waste heat. Thus, the water uptake often operates at high temperature (larger than 25 °C) and low relative humidity (lesser than 50% RH), which mainly relies on physical or chemical adsorption and results in a small water uptake capacity. To make the water uptake capacity difference at two-cycle conditions as large as possible, the temperature of regeneration must be high (usually greater than 75 °C [26]), which leads to a very low thermal coefficient of performance (typical 0.5–1.0 [27]). Meanwhile, considerable efforts have been made to screen the optimal desiccants [28], however, it has not achieved a breakthrough until now. Therefore, the so-called WSHE has a very clear distinction from before.

Besides, an inherent drawback of the previous DCHE used for dehumidification is the lack of sensible load capacity, which makes it only operate as an independent or assistant dehumidifier and lets the whole HVAC system bulk and costly [19]. Therefore, this kind of dehumidifier is generally used for industry applications, not suitable for commercial or residential buildings. To solve these problems, a new approach taking refrigerant as the heat transfer medium has been proposed and attracted more and more attention, which integrates two DCHEs [29–31] or DSHEs [32] with a vapor compression system. In this case, the adsorption temperature can be lower and the dependence on heat source available is moved away, which make the HVAC system more compact. Moreover, an obvious benefit is that its sensible load capacity can be improved slightly, however, the outlet air still can't meet the requirements of the supply air.

According to our knowledge, one of the main reasons is that sub-optimal design and operation of those desiccant systems amplify the negative effect of the thermal inertia on the transient