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Moisture uptake dynamics on desiccant-coated, water-sorbing heat exchanger

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ABSTRACT

Recently a novel concept of water-sorbing heat exchanger has been proposed, which can independently handle latent and sensible loads at the same time and provide a very promising high-efficient solution for temperature and humidity control. Obviously, moisture uptake behavior has great influence on heat exchanger's performance. Here, a series of experiments have been made to clarify whether the linear driving force (LDF) model could be used to describe this behavior and to investigate the water uptake mode at different times. Results show that the LDF model is valid for water-sorbing heat exchanger and the moisture uptake experiences four different modes in general, including non-isothermal adsorption, near-isothermal adsorption, capillary condensation and cooling-based condensation. This study also confirms that salts in porous matrix can accelerate moisture uptake and promote capillary condensation. These results in a great improvement of dehumidification capacity. Besides, an empirical and a semi-empirical framework were developed to evaluate the constant parameters in the LDF model. Meanwhile, a figure of merit of the desiccant, *Z*, was defined for engineering application, to simplify the LDF model in further.

1. Introduction

Recently, a novel concept of temperature and humidity loosely-coupled control has been proposed by the author, which shows a great potential to achieve a cost-effective, energy-saving and comfortable temperature and humidity control, its energy efficiency has been doubled in comparison with conventional air conditioner [1]. This technology relies on the so-called desiccant-coated, water-sorbing heat exchanger (WSHE), which is a bit like the previous adsorption heat exchanger (also named desiccant coated heat exchanger [2]) but has much greater abilities to independently handle the sensible load and latent load at the same time. In our previous studies [3], it is found that the water uptake of the desiccant on the WSHE, under non-isothermal and non-steady conditions, can be well described by the well-known linear driving force (LDF) model [4], $\{w(t) = w(0) + \Delta w_\infty[1 - \exp(-K_s t)]\}$, which is generally preferred to model the kinetics of the isothermal adsorption with the heat transfer effect neglected [5]. A somewhat similar situation has been reported by Aristov [6], he found that the adsorbate uptake *w*(*t*) in a closed system under conditions which were almost isobaric but strictly non-isothermal, could be described by a simple but quite reliable exponential dependence on time *t*. Actually, this equation can be directly derived from the LDF model.

The LDF model is first proposed by Gleuckauf and Coates (1947), which can be easily deduced from $dq/dt = K_s(q^* - q)$. It means that the rate of diffusion into the grains is essentially proportional to the amount still required to produce equilibrium [7–9]. Here K_s is a diffusion factor (the inverse of the time in which a grain adsorbent reaches 1/*e* of its equilibrium adsorption), q and q^* are the concentration (gas phase or solid phase) of that adsorbate at the outer surface of the particle and its average concentration in the interior of the particle or pellet, respectively. Furtherly, Gleuckauf (1955) [8] claimed that $K_s = 15D_{eff}/(R^2 \times S_l)$ should be applied for dimensionless time > 0.1 when the heat transfer effects on uptake can be ignored. Since then it is widely used to simulate the dynamic behavior of close systems, such as adsorption chiller [4,5], due to its simplicity, although it has limitations especially at short cycle times where it strongly underestimates adsorption uptake [4,5].

Meanwhile, Boyd et al. (1947) [9] proposed $K_s = 3h_m/(R \times S_l)$ if the diffusion is dominated by a resistance through a bounding liquid film around the adsorbent particle (h_m is the convective mass transfer coefficient, R is the radius of the grain and S_l is the slope of isotherm). Based on this, several simplified models have been proposed for an open system, such as Pseudo-gas-side (PGS) model [10], Solid-side resistance (SSR) model [10] and Gas and solid-side (GSSR) model [10]. Noted that the uptake rate in an open system is determined by both gas-side and solid-side diffusion resistance [10–14]. The basic idea behind these models is that the solid-side resistance can account for a fraction

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Nomenclature

A	Area (m^2)
Bi_m	mass transfer Biot number
D	Humidity ratio (kg/kg dry air)
D_{ap}	apparent diffusivity (Pa·s)
D_{eff}	effective diffusivity (Pa·s)
h_m	Gas-side mass transfer coefficient ($kg/m^2/s$)
K_s	the adsorption rate constant (/s)
M	Mass (kg)
P	Pressure (Pa)
P_b	Ambient pressure (Pa)
R	the radius of the grain size (m)
RH	Relative humidity (%)
RH_c	The inlet *RH* of evaporator/adsorber
RH_h	The inlet *RH* of condenser/desorber
RH_{cr}	The critical transition relative humidity
S_l	$=\partial x/\partial c$, the slope of the isotherm
T	Temperature (°C)
V	Velocity (m/s)
W	Water content (kg/kg desiccant)
$\dot{w}$	($=dw/dt$)Water uptake rate (kg/kg/s)
x	Equilibrium uptake capacity, kg/kg
Z	Figure of merit of desiccant

Greek symbols

Δ	difference
ΔH	the heat of adsorption (kJ/kg)
ΔT_{cr}	The temperature difference between the heat exchanger surface and the heat transfer fluid
Δw_∞	the maximum potential uptake capacity of the desiccant (kg/kg desiccant)
δ_{s*}	the equivalent radium of the grain size (m)
ρ	Density (kg/m^3)
τ	Duration of adsorption process (s)

Subscripts

a	air
c	cold fluid
dp	dew point
f	means fin in Eq. (4)
h	hot fluid
i	inlet
o	outlet
s	desiccant
sat	saturated
w	water

of gas-side resistance and vice versa. A more general method presents $[3h_m/(R \times S_l)]/[15D_{eff}/(R^2 \times S_l)] = 0.2Bi_m$ [15], where the mass transfer Biot number is defined by $Bi_m = h_m R/D_{eff}$ [16].

A simple review as mentioned above reveals that the validity of the LDF model relies on two points. Firstly, the adsorbent temperature is constant, or say the heat transfer effects can be neglected. Secondly, the value of K_s must be constant during adsorption process, which is determined by four parameters, R, h_m, D_{eff}, and S_l. Considering that D_{eff} and S_l are functions of adsorbent temperature [17,18], it is reasonable to infer that the LDF model will be valid as long as the adsorbent temperature is near-constant in general. For example, in a closed system, the gas-side mass transfer resistance is ignorable [19] and the adsorbent temperature is relatively steady excluding the very beginning. In this case, the findings in Refs. [3,6] can be explained very well. Of course, more research is needed to verify whether the LDF model is solid under any conditions for WSHE. Meanwhile, the LDF model is usually only used to explain the experimental data, not to predict the uptake behavior for forwarding design in an open system, because a reliable method to evaluate the values of Δw_∞ and K_s is still absent. In the theory, Δw_∞ can be estimated by the water content difference according to the isotherms at two cycle conditions, but it is hard to know the final air states around the desiccant because the WSHE will be switched into desorption mode before the desiccant gets saturation to avoid the occurrence of cooling-based condensation [1].

In order to fill the research gaps of this area, here, a series of experimental studies under various working conditions are conducted to further verify the reliability of the LDF model used to describe the water uptake kinetics of a WSHE. Based on these, effective methods to evaluate the two parameters Δw_∞ and k in the LDF model will be introduced, which are very important to the designers and researchers who expect this tool available not only explain the behaviors of the WSHE but also to predict its performance.

2. Experiment

2.1. Experiment descriptions

The experimental setup is shown in Fig. 1a and b and the tested heat exchangers are illustrated in Fig. 1c. One quadrate air channel with a cross-section area of 280 mm × 200 mm is adopted as air duct and the WSHE is installed in the middle. An axial flow fan is installed at the outlet to drive air flow. In addition, the air duct, water and the rubber tubes connecting the thermostatic bath with WSHE are wrapped with heat insulation foam to reduce heat loss. Each test lasted more than 1 h after the test system approached a steady state, which included several cycles. Every cycle experienced two operational modes: the cooling/adsorption operation and the heating/desorption operation. For the cooling/adsorption operation, cold water (eg. 15 °C) would flow through the tested heat exchanger and the moist air was cooled and dried. After the cooling mode, the tested heat exchanger turned into the heating/desorption mode, where cold water would be replaced by hot water (eg. 50 °C) and the moist air would be heated and humidified. Two thermostatic baths are utilized to provide cold water and hot water, which have a volume of 30 L, control accuracy of ± 0.05 °C and volume flow rate of 15 L min^{-1} by the internal water pump. Two connected constant temperature and humidity chambers were adopted to simulate various outdoor and indoor air conditions. Temperature and humidity ratio of the air is measured by high accuracy and multi-functional digital Thermo/Hygrometer (type: TH110-PNA produced by KIMO Instruments). The measurement range of temperature is 20–80 °C with an accuracy of ± 0.2 °C and the measurement range of relative humidity is 0–100%RH with an accuracy of ± 1.7%RH. A thermo-electric anemometer (Kelong-VA40) is adapted to measure the airflow velocity and then the air flow rate can be calculated. Its measurement range and accuracy are 0–50 ms^{-1} and ± 0.015 ms^{-1}. Other temperatures are measured by PT-100 RTD, with an accuracy of ± 0.15 °C.

In our previous studies [4], only the inlet cold water temperatures T_{wi} were variable. Actually, the factors influencing the water uptake rate of the desiccant-coated layer still have a lot, such as the inlet air relative humidity RH_{ai} and the frontal air velocity V_a. Thus, three groups of experiments under different T_{wi}, $RH_{ai,}$ and V_a have been made on the test setup described in Refs. [1,3]. To raise the credibility of experimental conclusions, two kinds of WSHE have been tested, one is silica-gel-coated WSHE (SG WSHE) (Fig. 1) fabricated by coating mesoporous silica gel onto the surfaces of conventional fin-tube heat exchangers according to the common procedure described in Ref. [20]; the other is composite silica-gel support LiCl (CSGL) desiccant-coated WSHE (FH WSHE) (Fig. 3) was achieved based on SG WSHE according