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An analysis of the heat and mass transfer roles in air dehumidification by solid desiccants

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ABSTRACT

Although Passive and active solid desiccant dehumidification have been increasingly investigated and applied in modern air-conditioning design, some discrepancies regarding the effectiveness and the psychrometric representation of the two processes can be found in the literature. Passive desiccant wheels are usually applied as an energy saving technique for vapor-compression cooling systems, unburdening the cooling coil from handling the humidity of outside ventilation air stream. In contrast, active desiccant wheels are designed to promote a thorough dehumidification of outside ventilation air, many times allowing for the use of an evaporative cooler and achieving an appreciable cooling effect, using only water as the refrigerant. The present work is comprised of a comparative study of the roles played by heat and mass transfer in passive and active adsorptive air dehumidification. The adequate definition of effectiveness for desiccant wheels is also discussed.

1. Introduction

The careful control of ambient air moisture content is of concern in many industrial processes, with diverse applications such as in metallurgic or pharmaceutical production. In the air-conditioning field, the increasingly concern with sick building syndrome has brought the humidity control into a new perspective. Underestimated ventilation rates usually result in poor indoor air quality, with a high concentration of volatile organic compounds, smoke, bacteria and other contaminants [1]. Epidemiological studies indicate a direct connection between inadequate levels of moisture and the incidence of allergies, in addition to infectious respiratory diseases. Events such as the outbreak of Legionella in 1976 and the more recent SARS (severe acute respiratory syndrome) shed a new light over indoor air quality control and regulations [2].

The standard procedure for reducing the concentration of contaminants is to increase the flow of fresh air, known as ventilation rate. In fact, the required fresh air volume per occupant/hour imposed by indoor air-quality standards has typically doubled over the last three decades [3,4]. However, since the outside fresh air has to be brought to the thermal comfort condition, increased ventilation rates also imply increased thermal loads, which in turn will demand air chillers with increased cooling capacity. Accordingly, there is a trade-off between indoor air quality and energy consumption, which is also of main concern of private and public sectors.

All-air systems usually employ multi-zone air-conditioning equipment, with individual reheat coils. Separate single ducts from the air-handling unit are distributed to each room, which is individually controlled. When the room air humidity exceeds a limit value, the humidistat takes control of the cooling coil, calling for additional cooling so as to dehumidify the air to the desired level. At this point, the air is excessively cold to be supplied to the room, which causes the thermostat to set off the reheat coil, with the objective of bringing the air temperature back to the comfort condition, as depicted in Fig. 1. The steepness of the room sensible heating ratio, represented by the dashed line, prevents the fan-coil process (curve EA–LA) to intersect it, which can only be accomplished by the reheat process. Although it provides a satisfactory individual control of each zone, this constitutes a very energy wasteful design, since the air is continuously cooled and reheated. Moreover, it requires both temperature and humidity sensors and controls, which might represent a significant increase to the total cost of the system.

In addition, the different kinematics of heat and mass transfer makes it very difficult for the humidistat to respond as fast as the thermostat, many times resulting in an ineffective control. The strategy of bringing the air temperature value forth and back is an evidence of the cooling coil inability to simultaneously handle the sensible and the latent components of the thermal load [5].

The previous reasoning expresses a favorable scenario for the application of air dryers, particularly solid sorbent dryers. Adsorption is primarily used for component separation from a gaseous

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Nomenclature

a	constant
c	constant
C_{wr}	wall specific heat (kJ/kg K)
d	constant
f	desiccant mass fraction
F_i	characteristic potential
h	convective heat transfer coefficient (kW/m^2)
h_y	convective mass transfer coefficient (kg/m^2 s)
h_v	heat of vaporization (kJ/kg)
H	enthalpy of air (kJ/kg)
L	length of the wheel (m)
$\dot{m}$	air mass flow rate (kg/s)
m_w	mass of the wall (kg)
P_{atm}	atmospheric pressure (Pa)
P_{ws}	saturation pressure (Pa)
P_{wt}	wetted perimeter of flow channel (m)
Q	heat of adsorption (kJ/kg)
t	time (s)
T	temperature (°C)
u	air flow velocity (m/s)
Y	air absolute humidity (kg H_2O/kg air)
Y_L	adsorbed air layer absolute humidity (kg/kg air)
W	desiccant humidity (kg of moisture/kg of desiccant)
x	coordinate (m)

Greek letters

λ_1	auxiliary parameter
λ_2	auxiliary parameter
H	desiccant wheel characteristic potential effectiveness
ϕ_w	relative humidity of air layer
ε	effectiveness

Subscripts

1	air
ci	cold inlet
co	cold outlet
dw	desiccant wheel
EA	Entering Apparatus (fan-coil)
er	enthalpy recovery
EXH	exhaust stream
hi	hot inlet
ho	hot outlet
IA	Insufflated Air
in	inlet
LA	leaving apparatus (fan-coil)
OA	outside air stream
out	outlet
RA	room air
sat	saturation
w	wall

Superscript

*	non-dimensional

mixture, and is widely employed in the chemical industry. The main advantage is that the material pore size can be designed for selective adsorption of a given component, allowing even trace amounts to be removed. In air-conditioning systems, silica-gel has been used to remove the air humidity to an acceptable level, unburdening the cooling coil from the dehumidification task. Silica-gel is a form of silicon dioxide derived from sodium silicate and sulfuric acid, which has good affinity to water vapor and an adsorbing capacity of as much as 40% of its own weight. It can be manufactured as a substrate, and applied as a coating to a cylindrical drum, fitted with a micro-channel mesh. This equipment is often referred to as a desiccant wheel. The air dehumidification can be passive or thermally activated, as explained in the next section.

Although the modeling of desiccant wheels has been addressed by many publications [6–18], the discussion about the definition of efficiency for desiccant wheels is yet to be settled [19]. The mathematical modeling used to simulate the dynamic behavior of the desiccant wheel [16–18] is briefly described in the next section.

2. The mathematical modeling of air drying by solid desiccants

The modeling of the desiccant wheel is described by the following system of partial differential equations. The first and second equations account for mass balances within the flow channel and the desiccant layer, respectively. Similarly, the third and fourth equations represent energy balances within the flow channel and the desiccant layer, respectively.

$$\begin{cases} \dfrac{\partial Y}{\partial x^*} = Y_L - Y \\ \dfrac{\partial W}{\partial t^*} = \lambda_2 (Y - Y_L) \\ \dfrac{\partial T_1}{\partial x^*} = T_w - T_1 \\ \dfrac{\partial T_w}{\partial t^*} = (T_1 - T_w) + \lambda_1 (Y - Y_L) \end{cases} \tag{1}$$

The independent variables are the non-dimensional position

$$x^* = \frac{2h\,P_{wt}x}{\dot{m}(\partial H_1/\partial T_1)} \tag{2}$$

and the non-dimensional time

$$t^* = \frac{2hP_{wt}Lt}{m_w C_{wr}} \tag{3}$$

with the auxiliary parameters given by

$$\lambda_2 = \frac{C_{wr}}{f(\partial H_1/\partial T_1)} \tag{4}$$

$$\lambda_1 = \frac{((\partial H_1/\partial w) - (1/f)\partial H_w/\partial W)}{(\partial H_1/\partial T_1)} = \frac{Q}{(\partial H_1/\partial T_1)} \tag{5}$$

Q is the heat of adsorption, given by [20],

$$Q = h_v(1.0 + 0.284\mathrm{e}^{-10.28\,W}) \tag{6}$$

and the enthalpy of the air H_1 can be written as [21]

$$H_1 = aT_1 + Y(d + cT_1) \tag{7}$$

where

$a = 1.00$ kJ/kg °C
$d = 2501$ kJ/kg
$c = 1.86$ kJ/kg °C

There are four equations to be solved [1], and five unknowns, T_1, T_w, W, Y and Y_L. The equation that relates the absolute humidity of the air in equilibrium Y_L (or its relative humidity) to the moisture content and the temperature of the solid is the adsorption isotherm, and for silica gel RD is given by [22]

$$\phi_w = 0.0078 - 0.0579\ W + 24.16554\,W^2 - 124.78\,W^3 + 204.2264\,W^4 \tag{8}$$