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Study of heat and mass transfer in a dehumidifying desiccant bed with macro-encapsulated phase change materials

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ABSTRACT

The present article reports on the feasibility of using encapsulated phase change materials (EPCMs) in the dehumidifying bed of a desiccant cooling system. The mathematical model used to simulate the coupled non-equilibrium heat and moisture transfer processes in the porous composite structure containing the EPCM and desiccant particles is presented. Numerical investigations of heat and mass transfer in a desiccant dehumidifying bed composed of silica gel and EPCM particles have been carried out for different values of process parameters. Careful choices of EPCM volume fraction and thermo physical characteristics have been found to increase the overall effectiveness of the desiccant dehumidifier with negligible loss in the dehumidification efficiency. The air stream exits the desiccant/EPCM bed at relatively lower temperature and slightly higher moisture content than from purely desiccant bed. Desiccant cooling systems with less sensible heating and higher cooling capacity can be obtained by employing EPCM in the dehumidifier.

1. Introduction

Desiccant based air-conditioning systems offer a promising alternative to conventional air-conditioning systems using vapour compression refrigeration especially, under conditions involving high latent loads. This technique allows the use of low-temperature industrial waste heat or solar energy to drive the cooling cycle. Therefore, it attracted increased research attention during the last two decades [1,2].

In desiccant cooling systems, the process air is dehumidified and then cooled before being sent to the conditioned space. Desiccants remove moisture from the supply air until they reach equilibrium with it. The heat of absorption/adsorption released in the process heats the supply air. To make the system work continually, the adsorbed water vapour must be driven out of the desiccant material so that it can be dried enough to adsorb water vapour in the next cycle. This is done by heating the desiccant material to temperatures around 60–90 °C and exposing it to a regenerative air stream. The desiccant is then cooled so that it can adsorb moisture again.

A desiccant cooling system comprises three principal components, namely the regeneration heat source, the dehumidifier (desiccant material), and the cooling unit (sensible heat exchanger) (see Fig. 1). The actual configurations of each of the three components can vary according to the nature of the desiccant employed and the integration in the air-conditioning system. The desiccant can be used either in a stand-alone system or coupled judiciously with a vapour compression system to achieve high performance over a wide range of operating conditions.

Kang and Maclain-Cross [3] showed that the dehumidifier is the key component of a desiccant cooling system and the cooling COP (coefficient of performance) is significantly improved by enhancing the performance of this component. The research into desiccant materials that can be regenerated under low temperature (near-ambient) is the key element for augmenting the contribution that desiccant cooling can bring to the amelioration of comfort, energy and cost savings [1,4,5]. It is known that advanced desiccant materials may give improved sorption capacity, better moisture and heat diffusion rates, as well as favourable equilibrium isotherms.

Majumdar [4] investigated the performance of adsorption and desorption processes during a single blow operation in a dehumidifier made of a composite mixture of silica gel particles and inert particles with different compositions and thermo physical properties. Aristov et al. [6,7] have introduced hybrid selective water sorbent materials developed by impregnating a host porous desiccant material with hygroscopic salt. The product obtained has a sorption capacity which can be triple that of pure host material. Jia et al. [5] analysed the performance of a desiccant wheel fabricated with a new kind of composite desiccant that consists of a host matrix with open pores (silica gel) and a hygroscopic substance (lithium chloride) impregnated into its pores.

Since the adsorption process is exothermic, heat is released as the desiccant adsorbs water vapour in the dehumidifier. The heat of sorption dissipates through the desiccant felts and raises the

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Nomenclature

c_p	specific heat at constant pressure [J/(kg K)]
d_p	diameter of silica gel particle (m)
D_v	vapour/air mutual diffusivity (m^2/s)
EDS	system effectiveness
f_l	EPCM liquid fraction
G_γ	mass flux [kg/(m^2 s)]
h_γ	enthalpy of gas phase (J/kg)
$h_{\sigma\alpha}$, $h_{\sigma\gamma}$, $h_{\alpha\gamma}$	internal heat transfer coefficients [W/(m^2 K)]
H_{fg}	latent heat of condensation (J/kg)
H_f	PCM latent heat of fusion (J/kg)
J_d	Chilton and Colburn mass transfer factor
J_h	Chilton and Colburn heat convection factor
k	thermal conductivity [W/(m K)]
k_{eff}	effective thermal conductivity [W/(m K)]
k_g	internal mass transfer coefficient [kg/(m^2 Pa s)]
K	permeability (m^2)
L	bed height (m)
M_a	molecular weight of gas (g/mol)
$\dot{M}_v$	water vapour adsorption rate [kg/(m^3 s)]
P	pressure (Pa)
Pr	Prandtl number of gas
P_{vs}	partial pressure of the water vapour in a saturated mixture (Pa)
Q	heat of adsorption (J/kg)
r	particle radius (m)
r_h	hydraulic radius of porous medium (m)
R_a	gas constant for dry air (J/kg.K)
R_v	gas constant for water vapour (J/kg.K)
Re	Reynolds number
RH	relative humidity (%)
Sc	Schmidt number
S	volume specific surface area (m^2/m^3)
t	time (s)
T	temperature (K)
T_m	phase change temperature (K)
U_d	Darcy velocity (m/s)
W_v	humidity ratio of gas (kg/kg)
X	moisture content of the silica gel particles (%)
Z	distance along the bed height (m)

Greek symbols

ε	porosity; volume fraction
μ	air dynamic viscosity (kg/m s)
η	dehumidification efficiency
ν	air kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
τ	tortuosity
φ	relative humidity of the gas at certain point in the bed
φ_w	relative humidity on the aqueous solution/air interface

Subscripts

a	dry air
e	outlet conditions
i	inlet conditions
0	initial
s	(solid + liquid + EPCM) phase
v	water vapour
α	EPCM
$\alpha\gamma$	transfer between EPCM and gas phase
β	liquid phase
γ	gas (dry air + water vapour)
σ	solid desiccant
$\sigma\gamma$	transfer between solid and gas phase
$\sigma\beta$	(solid + liquid) phase

temperature of the felts and the exit temperature of the process air stream. Also, as the temperature of the felt increases, the sorption capacity of the desiccant decreases. This change causes an increased exit process-stream humidity ratio. Also owing to the higher exit temperature, the sensible heat exchanger has to remove this excess heat from the air stream. These changes result in a reduced cooling capacity in the adsorption process and lead to the requirement of an increased capacity of the sensible heat exchanger. One would, therefore, like to achieve processes that give dehumidification at constant or minimum increase in temperature in the dehumidifier.

The objective of the present study is to investigate the feasibility of achieving (or approaching) such processes by using a composite felt structure made of mixed solid desiccant particles and PCMs of different compositions and thermo physical properties. The concept of introducing phase change materials (as a heat sink for the exothermic heat generation during adsorption) in the composite structure shall be investigated. Encapsulated PCMs are proposed to be used in the present study. They are now produced industrially by different manufacturers in the form of heat storage granulate in which a phase change material (PCM) is contained within a secondary supporting structure. The encapsulation process ensures that the PCM, when in the liquid form, does not leak out of the granulate. The result is that the bound PCM is always a solid in its macroscopic form. The mathematical model used to simulate the coupled non-equilibrium heat and moisture transfer processes in the porous composite structure containing the PCM is presented. The coupled nonlinear differential equations are solved using the finite volume method. Simulations have been carried out using silica gel particles and PCMs of different compositions. The effects of process parameters on the performance of the desiccant bed are analysed.

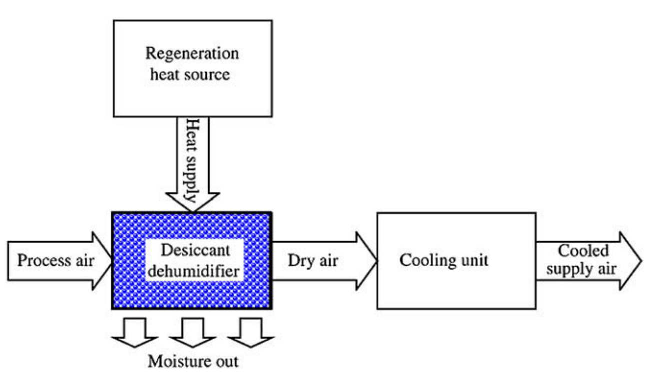

Fig. 1. Principle of desiccant cooling.

2. Candidate materials

In general, the chosen adsorbent used in desiccant cooling systems should have both high hygroscopic capacity and saturated adsorption rate. The ideal desiccant for a particular application depends on the range of water vapour pressures likely to occur in the air, the temperature level of the regeneration heat source, and the moisture sorption and desorption characteristics of the desiccant within those constraints. The greater the difference between the air and desiccant surface vapour pressures, the greater the ability of the material to adsorb water vapour from the air at that moisture content.