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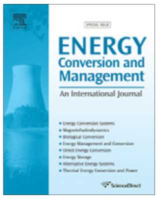

Performance study of silica gel coated fin-tube heat exchanger cooling system based on a developed mathematical model

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A B S T R A C T

Desiccant coated heat exchanger (DCHE) system can handle latent and sensible load simultaneously by removing the released adsorption heat in dehumidification process. The system can also be driven by low grade thermal energy such as solar energy. In this paper, a dynamic one-dimensional mathematical model validated by experimental data is established to predict the performance of DCHE system, using conventional silica gel as desiccant material. Cooling performance of DCHE system is calculated under ARI (American Air-conditioning and Refrigeration Institute) summer and humid conditions. Simulated results show that the operation time in dehumidification process is a crucial factor for cooling capacity of DCHE system, which can be enhanced by eliminating the initial period with higher outlet air temperature, the largest cooling power of DCHE system increase from 2.6 kW to 3.5 kW by eliminating first 50 s of operation time under ARI summer condition. The results also prove that the system can provide cooling power to indoor condition with selective operation time when regeneration temperature varies from 50 °C to 80 °C. Besides, the model is adopted to analyze the effects of some structural parameters on system performance under simulated condition. The system performs well in smaller cobber tube external diameter condition, while both transient heat and mass transfer capacity can be enhanced under the condition of smaller distance between the fins.

1. Introduction

With the rapid development of technology and society, energy crisis has become a global issue. According to latest statistics, energy consumption in buildings accounts for a large percentage of total consumption in developed countries. It is also revealed that conventional vapor compression cooling systems are the main contributor of electricity consumption in buildings. Therefore new types of heat driven cooling system have been proposed to eliminate the traditional energy consumption. As one of many thermal driven technologies, solid desiccant cooling technology has the merits of energy conservation and being environment-friendly because it can be driven by low grade thermal energy and adopts natural working fluid-water vapor as refrigerant. In the past decades, numerous researches have been conducted to improve the energy utilization efficiency of solid desiccant cooling system, including investigating novel desiccant material [1–4], developing novel system cycle [5–8] and optimizing system operation [9–13], etc. A new concept of "multi-stage" solid desiccant cooling system was proposed [14,15] recently and it was pointed out that if adsorption heat can be taken away from dehumidification process, overall performance of desiccant cooling system can be improved significantly. Therefore desiccant coated heat exchanger (DCHE), in which adsorbent desiccant material is coated on the surface of conventional fin-tube air-to-water heat exchanger, is proposed much more recently [16]. Cooling and hot water are pumped alternately into cobber tubes of DCHE, in one hand the side effect of released adsorption heat could be effectively overcome by pumping cooling water in dehumidification process, on another hand, the desiccant material can be regenerated by pumping hot water in regeneration process. Experimental results also showed that silica gel coated DCHE performs better than polymer coated DCHE [16]. In sum, it can be learnt from these results that, DCHE not only inherits the merits of solid desiccant cooling system but also can handle sensible and latent heat simultaneously.

Until now, there has been no quantitative data available about the air handling capacity (cooling capacity) of DCHE system, which is necessary and vital for system evaluation as well as system design. Meanwhile, obtaining all data via experiment is relatively time consuming and costs a lot. Therefore, establishment of accurate mathematic model to predict the performance of DCHE system become an urgent task and no related work can be referred mainly due to the fact that the heat and mass transfer process occurring within DCHE has two inner heat sources (one is hot/cooling water; another is adsorption/desorption heat), which is different from that of the conventional desiccant cooling equipment. To solve these problems, a dynamic heat and mass transfer mathematical

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Nomenclature

A	cross-sectional area, m^2
C	perimeter of air flow passage, m
c_p	constant pressure specific heat, kJ/(kg K)
D	moisture removal, kg/kg
f	mass per unit length, kg/m
H	enthalpy, kJ/kg
h	thermal conductivity between air and desiccant layer, W/m K
k	thermal conductivity, W/m K
K_y	coefficient of mass convection kg/(m^2 s)
M	number of the layers inside heat exchanger
m	mass, kg
N	number of tube passes in x direction
N_1	number of tube passes (in z direction)
Nu	Nusselt number
P	pressure, Pa
q_{st}	heat of sorption kJ/kg adsorbate
R_{de}	equivalent diameter, m
r_i	inside radius of the tubes, m
r_o	outside radius of the tubes m
RH	relative humidity ratio%
S_{ad}	contact surface between the air and desiccant layer, m^2
S_{wd}	contact surface between the water and desiccant layer, m^2
Sh	Sherwood number
T	temperature, K
t	time
u	velocity m/s
V	latent heat of condensation (water vapor), kJ/kg
v	kinetic viscosity m^2/s
W	extent of adsorption kg adsorbate/kg adsorbent
X	length of heat exchanger in x direction, m
Y	absolute humidity ratio of the air kg water vapor/kg dry air
L	length of heat exchanger in y direction, m
Z	length of heat exchanger in z direction, m
Greek	
ρ_{md}	desiccant density per unit area, kg/m^2
δ	thickness of the fins m
γ	distance between the fins, m
ε	porosity
Φ	volume ratio of desiccant material in layer (without desiccant $\Phi = 0$)
Subscript	
a	air
c	cooling water
d	desiccant layer
h	hot water/regeneration water
in	inlet
l	liquid water
m	matrix
out	outlet
sg	silica-gel desiccant
v	water vapor
w	cooling/regeneration water

model taking into account of two inner heat sources is established. The main objectives are to investigate the feasibility of DCHE system under standard ARI (American Air-conditioning and Refrigeration Institute) summer and humid condition, to analyze the operation control strategy and to evaluate cooling capacity. Besides, effects of some structural parameters on system performance, which cannot be easily changed in the experimental setup, are discussed.

2. Establishment of mathematical model

Components in DCHE system include silica gel coated DCHE, thermal source, cooling source and pipelines, etc. as shown in Fig. 1. DCHE is core component in the system, in which ambient air can be handled to different supply air states. Here thermal source stands for the origin of hot water, such as the thermo bath or solar water collector. Similarly, cooling source represents underground water or evaporative cooler which can provide cooling water. Pipelines are used to bridge different components. Emphasis should be placed on the facts that: (1) like in most of solid desiccant cooling systems, an evaporative cooler can be regarded as backup following DCHE in dehumidification side. If enthalpy of outlet process air meets the requirement of supply air but of high temperature, required supply air can be produced using evaporative cooler. (2) Heat losses in the thermal source as well as in the cooling source can be neglected, therefore temperature of hot water and cooling water are equal to the corresponding source temperature. In other words, whole system model can be established by directly combining the temperature of heat and cooling source with the mathematical model of DCHE. Therefore dynamic heat and mass transfer model of DCHE is established in following part.

Schematic figure of DCHE, which is located in three dimensional Cartesian coordinate system, is shown in Fig. 2a. Introduced by Ge et al. [16], DCHE is fabricated by coating desiccant material on the surface of conventional fin-tube heat exchanger. Due to the hygroscopic characteristic of the desiccant material, heat and mass transfer occurs simultaneously in DCHE. In order to simplify the mathematical model setup, numerical analysis in this paper is based on the following assumptions:

(1) The temperature and moisture content gradients in "x" and "y" direction are negligible.
(2) Heat exchanger is with an ideal structure, which means the flow channels for the air or for the water are identical.
(3) Molecules of desiccant material are evenly distributed in heat exchanger surface.
(4) Heat transfer consistence of the cobber tube is negligible and its temperature is assumed to be equal to that of the desiccant material.
(5) Heat conduction as well as the mass diffusion within both air stream and desiccant material is negligible.
(6) The heat and mass transfer coefficients between the air stream and the desiccant wall, as well as the heat transfer coefficient between the desiccant material and water are constant over the entire DCHE.
(7) Adsorption heat is released to the desiccant layer only; however it is transferred to the air and water by convective method.
(8) The inlet conditions of air and water are uniform in space, but may vary with time.
(9) Thermodynamic properties of the air and water are assumed to be constant.
(10) The pressure loss of the air stream in axial direction is negligible.