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Transient behavior of a cylindrical adsorbent bed during the adsorption process

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HIGHLIGHTS

- Dynamic behavior of an adsorbent bed during the adsorption process is investigated.
- Silica gel–water pair is chosen to be an adsorbent–adsorbate working pair.
- A transient two dimensional local thermal non-equilibrium model is developed.
- Heat transfer resistances have a considerable influence on the adsorption dynamic.
- Cooling capacity increases with increasing P_{ev} and T_{ds} and decreasing P_{co} and T_c.

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ABSTRACT

A transient two dimensional local thermal non-equilibrium model is developed to investigate the influences of heat transfer and operating parameters on the dynamic behavior of a cylindrical adsorbent bed during the adsorption process. Local volume averaging method is used to drive the macro scale governing conservation equations from the micro scale ones. In the model, linear driving force model and Darcy's equation are considered to account for the resistances to internal and external mass transfer, respectively. Silica gel–water pair widely used in the adsorption cooling systems is chosen to be an adsorbent–adsorbate working pair. The parameters of interest are convective heat transfer coefficient, solid phase thermal conductivity, bed thickness, evaporator pressure, condenser pressure, driving heat source temperature and cooling source temperature. It is found that amount of refrigerant circulated through the system increases with increasing evaporator pressure-driving heat source temperature and decreasing condenser pressure-cooling source temperature. The duration of adsorption process is more sensitive to heat transfer resistances than to mass transfer resistances. The conductive and convective resistances need to be reduced to reach the equilibrium conditions in a short period of time and hence to have a better specific cooling power.

1. Introduction

Efforts on the development of a novel commercial cooling system have been extensively diverted to the thermally driven adsorption based cooling systems in the recent years since these systems are environmentally friendly and can be operated with a low-grade heat sources such as solar energy or waste heat [1–4]. However, still the thermal powered adsorption cooling systems do not seem a desired level to be able to compete with the traditional vapor compression cooling systems as far as their performances are concerned [5].

The performance comparison between an adsorption cooling system and a traditional vapor compression cooling system can be made by taking their coefficient of performances (COP) into consideration, at first glance. However, such a comparison between two different adsorption cooling systems using the different/same adsorbent–adsorbate working pairs may lead to unrealistic outcomes. Therefore, to make a more sensible performance comparison between the different adsorption cooling systems, their volumetric cooling power density (SCP_v, kW/m^3) and mass specific cooling power density (SCP_m, kW/kg) need to be taken into consideration as well as their coefficient of performances. The definitions of these parameters are given as follows [6];

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Nomenclature

α_v	area of gas–solid interface per unit volume, 1/m
C_p	specific heat, J/(kg K)
D_o	reference diffusivity, m^2/s
d_p	average diameter of the adsorbent particle, m
E_a	activation energy of surface diffusion, J/mol
h	convective heat transfer coefficient between the adsorbent bed and cooling fluid, W/(m^2 K)
h_{gs}	interfacial convective heat transfer coefficient, W/(m^2 K)
K	permeability, m^2
k	thermal conductivity, W/(m K)
L	length of the adsorbent bed, m
LH	latent heat of water, kJ/kg
m	mass, kg
Nu_d	Nusselt number
P	pressure, kPa
Pr	Prandtl number
Q	energy, kJ
Q_{ad}	heat of adsorption, J/kg_w
R	universal gas constant, J/(mol K)
Re_d	Reynolds number
r_i	inner diameter of the adsorbent bed, m
r_o	outer diameter of the adsorbent bed, m
r	radial coordinate, m
T	temperature, K
t	time, s
V	volume, m^3
v_r	gas phase velocity in radial direction, m/s
v_z	gas phase velocity in axial direction, m/s
X	adsorbate concentration, kg_w/kg_{ad}
X_∞	equilibrium adsorption capacity, kg_w/kg_{ad}
z	axial coordinate, m

Greek symbols

μ	viscosity, (Ns)/m^2
ρ	density, kg/m^3
ε_t	total porosity
ε_b	bed porosity
ε_p	particle porosity

Subscripts

ave	average
c	cooling
co	condenser
cy	cycle
ds	regeneration
eV	evaporator
g	gas phase
ge	effective gas phase
i	initial
s	solid phase
sat	saturation
se	effective solid phase

$$COP = \frac{Q_c}{Q_{in}} \tag{1}$$

where $Q_c = m_s LH_{@T_{eV}}(X_{max} - X_{min})$

$$SCP_v = \frac{Q_c}{t_{cy}V_s} = \frac{\rho_s LH_{@T_{eV}}(X_{max} - X_{min})}{t_{cy}} \tag{2}$$

$$SCP_m = \frac{Q_c}{t_{cy}m_s} = \frac{LH_{@T_{eV}}(X_{max} - X_{min})}{t_{cy}} \tag{3}$$

The cycle time involving durations of adsorption and desorption processes has a remarkable influence on both the SCP_v and SCP_m values of an adsorption cooling system. An improvement on the SCP of an adsorption cooling system can be achieved by decreasing the cooling cycle time or increasing the cooling capacity resulting in an increase in COP as well. Any attempt done to reduce the cooling cycle time and raise the cooling capacity can be successful if the effects of some design and operating parameters on the dynamic behavior of an adsorbent bed are understood fully.

Over the last two decades, as well as the experimental studies, various models have been used to numerically investigate the influences of design and operating parameters on the performance of adsorption cooling units. Rezk and Al-Dadah [7] proposed an empirical lumped analytical simulation model to investigate the influences of operating temperatures, fin spacing and cycle time on a silica gel/water adsorption chiller performance. Zhao et al. [8] developed a transient one dimensional local thermal equilibrium model with non-uniform pressure assumption to understand the dynamic behavior of an adsorption refrigeration tube during the adsorption process. Leong and Liu [5] presented a two-dimensional non-equilibrium numerical model with non-uniform pressure assumption to evaluate the effects of bed configuration and operating conditions on the values of COP and SCP of a zeolite-13X/water adsorption-cooling system. Ramji et al. [9] carried out a parametric study with a commercial CFD software package to present the influence of wall thickness on the desorption temperature, the cycle time and the cooling performance of an exhausted heat-powered activated carbon–methanol adsorption air-conditioning system. El Fadar et al. [10] numerically studied the effects of some important operating and design parameters such as adsorbent bed thickness and heat source temperature on the COP and SCP values of a parabolic trough solar collector-powered continuous adsorption refrigeration system. Leong and Liu [11] theoretically investigated the influences of bed dimensions, bed thermal conductivity, heat exchange fluid velocity, driven temperature and degree of heat recovery on the performance of combined heat and mass recovery adsorption cycle. Demir et al. [12] carried out a theoretical study for various parameters to understand the mechanisms of heat and mass transfer in an annular adsorbent bed. Gordeeva and Aristov [13] tried to find out the factors that have considerable importance on the adsorption and desorption dynamics in an adsorption cooling unit to make practical recommendations to optimize SCP. Miltkau and Dawoud [14] presented a one-dimensional model taking into account of combined heat and mass transfer to examine the influences of zeolite layer thickness and volume of vapor phase on the dynamics of a small scale zeolite–water adsorption heat pump. Sapienza et al. [15] constructed an experimental set up to investigate the effect of grain size of a SAPO-34 water adsorbent placed a flat plate HEX with a monolayer and multilayer configurations at variable and constant "heat transfer surface/adsorbent mass" ratios on the dynamic performance of an Ad-HEX (adsorbent + heat exchanger) and thus, on the SCP. Luo et al. [16] experimentally studied the effects of operating parameters such as solar hot water temperature, heating/cooling time, mass recovery time, and chilled water temperature on the coefficient of performance and the cooling power of a solar-powered adsorption chiller with heat and mass recovery cycle. Li et al. [17] conducted an experimental study to evaluate the performance of a zeolite FAM Z01-water adsorption chiller in terms of total heat input, cooling capacity, heat source temperature