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Effects of particle diameter on performance improvement of adsorption systems

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HIGHLIGHTS

- A transient 3D numerical modeling of an adsorbent bed is developed.
- The specific cooling power has a maximum value at a specific particle diameter.
- Effects of fin configurations and operational conditions on the optimum particle size are investigated.
- Maximum specific cooling power can be obtained at particle diameters between 0.2 and 0.3 mm.

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ABSTRACT

The adsorbent particle diameter is an influential parameter in the performance of an adsorption chiller since it affects both inter- and intra-particle mass transfer resistances. In this analysis, a plate finned-tube heat exchanger is considered with SWS-1L ($CaCl_2$ in mesoporous silica gel) and water as the working pair to investigate the particle diameter effects on the performance parameters of an adsorption system. As the effects of inter- and intra-particle mass transfer resistances are opposing, the optimum bed performance is expected to occur at a specific particle diameter. Furthermore, effects of fin height, fin spacing and cooling/heating temperatures of thermal fluid on the optimum particle diameter are examined in details. It has been found that the optimum performance for all fin configurations and thermal fluid inlet temperature variations, considered in the present study, is obtained for the particle sizes in the range of 0.2–0.3 mm.

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1. Introduction

Nowadays, improving energy efficiency is identified as an issue of great importance. In the field of refrigeration and air-conditioning, adsorption system is a promising technology since it incorporates environmentally benign refrigerants and the industrial waste heat or low grade solar energy instead of mechanical power. However, low values of performance parameters, which are the coefficient of performance (COP) and specific cooling power (SCP), are among the main factors that hinder the widespread application of these systems.

Among all attempts to overcome this drawback, improving the heat and mass transfer processes of the adsorber heat exchanger is one of the most attentive subjects of recent studies. In this regard, the adsorbent particle size is an effective parameter since it simultaneously affects the mass transfer resistances in the adsorbent bed of heat exchangers. Chang et al. [1] made an experimental study to investigate the effects of adsorbent layer and particle size of silica gel on the transfer processes of the adsorbent bed. They concluded that thinner layer of adsorbent made of larger sized particles improves the mass transfer performance. Glaznev and Aristov [2] proposed an experimental study using a metal plate covered with a monolayer of loose Fuji silica gel grains with different sizes to explore the grain size effect on water sorption dynamics. Recently, Aristov et al. [3] experimentally measured the effects of grain size and layer thickness on the isobaric water adsorption dynamics. Employing a large mass transfer surface and a thin layer to avoid the limitation of inter-particle mass transfer resistance, they found that the kinetics of isobaric ad-/desorption remains nearly unchanged under certain conditions.

To study the effects of particle size on the performance of adsorption systems numerically, the model must consider both inter-particle and intra-particle mass transfer resistances, since the particle size variation affects both resistances simultaneously. The uniform pressure distribution approach, which ignores the inter-particle mass transfer resistance, is employed by some

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Nomenclature

$\vec{A}$	area m^2
C_p	specific heat in constant pressure J kg^{-1} K^{-1}
CV	control volume m^3
CS	control surface m^2
COP	coefficient of performance –
D_i	internal radius of the metal tube m
D_o	external radius of the metal tube m
D_p	solid adsorbent particle diameter m
D_s	surface diffusivity m^2 s^{-1}
D_{so}	pre-exponent constant of surface diffusivity m^2 s^{-1}
E_a	activation energy of surface diffusion J mol^{-1}
f	friction factor –
F	free sorption energy J mol^{-1}
FH	fin height m
FS	fin spacing m
FT	fin thickness m
K_{app}	apparent permeability of adsorbent bed m^2
L_v	latent heat of vaporization J kg^{-1}
$\dot{m}$	mass flow rate kg s^{-1}
m_s	total mass of solid adsorbent kg
N	equilibrium uptake mol mol^{-1}
Nu	Nusselt number –
P	pressure Pa
Pr	Prandtl number –
Q	supplied heat J
R_g	gas constant J kg^{-1} K^{-1}
R_c	contact resistance m^2 K W^{-1}
R_p	particle radius m
R_u	universal gas constant J mol^{-1} K^{-1}
Re	Reynolds number –
SCP	Specific cooling power W kg^{-1}
t	time s
t_{cycle}	cycle time s
T	temperature K
TH	inlet thermal fluid heating temperature °C
TC	inlet thermal fluid cooling temperature °C
$\vec{u}$	velocity vector m s^{-1}
w	average adsorbate content $kg_{adsorbate}$ $kg^{-1}_{adsorbent}$
w^*	equilibrium uptake $kg_{adsorbate}$ $kg^{-1}_{adsorbent}$

Greeks

ΔF	adsorption potential J mol^{-1}
ΔH	heat of adsorption J kg^{-1}
$\vec{\nabla}$	delta operator m^{-1}
ε_t	total porosity –
ε_b	bed porosity –
ε_p	particle porosity –
λ	effective bed thermal conductivity W m^{-1} K^{-1}
μ	viscosity N s m^{-2}
ρ	density kg m
$\forall$	volume m^3

Subscript

0	initial condition
a	adsorbate
b	adsorbent bed
cond	condenser
evap	evaporator
fluid	thermal fluid
g	gaseous phase
in	inlet
out	outlet
max	maximum
min	minimum
s	solid adsorbent
sat	saturation

researchers in order to simplify the governing equations and to decrease the computational cost [4–6]. This approximation, however, is acceptable only for adsorbent beds with small thicknesses or large-sized particles [7]. The intra-particle mass transfer resistance, which is controlled by the particle porosity and the particle diameter, can be neglected only for very small-sized particles [8,9]. Otherwise the linear driving force model is an appropriate choice to account for intra-particle diffusion in the modeling procedure [10,11].

Taking into account both mass transfer resistances, Leong and Liu [12] numerically investigated the effects of particle diameter, bed thickness, bed porosity, and heating temperature of thermal fluid on SCP and COP of an adsorption chiller. However, no fins were used to enhance the transfer processes and the effect of particle diameter on the system performance was not examined for different bed thicknesses, thermal fluid temperatures or porosities. In another numerical study, Niazmand and Dabzadeh [13] studied the effects of particle diameter on the COP and SCP of an annular finned tube heat exchanger. They indicated that SCP has an optimum value with respect to particle diameter, while COP is basically independent of particle size. However, their study is limited to a specified working condition as far as fin configurations and thermal fluid temperature are concerned. Raymond [14] presented a one-dimensional adsorbent layer model to determine the optimum particle diameter for two values of bed thicknesses. It was shown that the optimum diameter corresponding to the minimum adsorption time increases for larger bed thicknesses.

As the conductivity of adsorbent particles is relatively low, using extended surfaces can improve the heat transfer rate and consequently speed up the adsorption and desorption processes. Although the effects of fin height and spacing on the chiller performance have been investigated earlier [13,15–18], the variations of SCP and COP with particle diameter at different fin height and spacing are still remained to be examined.

Another influential parameter in designing the adsorbent bed is the thermal fluid heating and cooling temperatures. Previous experimental studies [19–23] showed that increasing the heating temperature and decreasing the cooling temperature of thermal fluid both increase COP and SCP of the system. Riffel et al. [24] numerically studied the effects of hot/cold water inlet temperature as well as chilled water inlet temperature on the performance of annular finned tube adsorbent bed with assumptions that temperature has no variation in radial direction of the bed and pressure is uniform throughout the bed.

This literature survey indicates the shortage of information with regards to the effects of thermal fluid inlet temperature on the particle diameter as related to the optimum performance of the system. Although it has been clarified that the particle size affects the cycle time and the SCP of an adsorption chiller, the trend of these variations for different geometrical specifications and operational conditions has not been studied yet. Consequently, the present study investigates the effects of particle size on the adsorption chiller performance for different fin heights, fin spaces and heating/cooling temperatures of thermal fluid in search for the particle diameter corresponding to the optimum performance of the system.

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