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Bed configuration effects on the finned flat-tube adsorption heat exchanger performance: Numerical modeling and experimental validation

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HIGHLIGHTS

- Finned flat-tube heat exchangers are promising in adsorption cooling applications.
- Bed lengths larger than 20 mm are not recommended for grain sizes of 0.3 mm.
- Rectangular beds produce higher *SCP* than their corresponding trapezoidal beds.
- An effective adsorption heat exchanger designing procedure is proposed.

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ABSTRACT

A three dimensional numerical scheme has been developed to examine geometrical configuration effects on the performance of a single bed adsorption chiller with a trapezoidal aluminum finned flat-tube heat exchanger (FFT HEx). A mathematical distributed model along with the linear driving force (LDF) model and Darcy's law have been considered to take into account the effects of heat and both intra/inter-grain mass transfer resistances. The developed numerical scheme has also been validated experimentally by using a composite sorbent SWS-1L and water as a working pair. Additionally, rectangular beds with identical working conditions and bed dimensions as the tested trapezoidal beds have been examined in similar details to identify, which type of the fin geometry provides a superior performance. It was found that in this particular HEx, the heat transfer resistance is mainly influenced by both of the fin pitch and height, while the inter-grain mass transfer resistance is independently controlled by the bed length. This fact makes the role of the fin pitch and fin height almost interchangeable with respect to the cycle time and specific cooling power (*SCP*) especially in rectangular beds. However, the coefficient of performance (*COP*) is more influenced by the fin height than the fin pitch. In addition, higher *SCP* can be achieved at smaller bed dimensions at the expense of lower *COP*. Moreover, it was found that using rectangular bed is more appropriate, since its *SCP* is either the same or higher than its corresponding trapezoidal bed especially at shorter bed lengths, while *COP* remains almost the same for both bed types in all considered ranges of bed dimensions. Finally, a bed designing procedure has been proposed for proper designing of effective adsorption HExs based on the performed parametric studies.

1. Introduction

Exploring new ways of producing cooling energy based on renewable energies or low-grade heat sources is of great need and interest. Adsorption cooling systems (ACS) due to their thermal compression, environmental friendly refrigerants, non-corrosive fluids, and the absence of crystallization problems have particularly attracted researchers in the past few decades. However, the main drawback of ACS in comparison with conventional cooling systems, is the adsorbent relatively limited heat and mass transfer properties, which lead to the low specific cooling power (*SCP*) and consequently large system sizes.

Evidently, using high performance heat exchangers can partially compensate for the weak transport properties of the adsorbent materials. In general, a well-designed adsorption heat exchanger (Ads-HEx) should consider both heat and mass transfer properties. In a sense that adsorbent bed must be capable of being heated and cooled in the shortest possible time, while providing the shortest passage for the refrigerant vapor to flow through the adsorbent particles. Therefore, proper choice of the Ads-HEx geometrical specifications becomes of great practical importance. Computational modeling of the quite

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Nomenclature

A	area, m^2
ACS	adsorption cooling system
BL	bed length, m
C_p	specific heat in constant pressure, J/(kg K)
COP	coefficient of performance, –
CS	control surface, m^2
CV	control volume, m^3
D_h	hydraulic diameter, m
d_p	particle diameter, m
D_{eff}	effective diffusivity, m^2/s
D_{so}	pre-exponent constant of surface diffusivity, m^2/s
E_a	activation energy of surface diffusion, J/mol
FFT	finned flat-tube
FH	fin height, m
FP	fin pitch, m
FT	fin thickness, m
FTH	flat-tube height, m
FTT	flat-tube thickness, m
h	convective heat transfer coefficient, $W/(m^2 K)$
HEx	heat exchanger
k	thermal conductivity, W/(m K)
K_0	LDF constant, –
K_d	bed permeability, m^2
L_v	latent heat of vaporization, J/kg
m	mass, kg
$\dot{m}$	mass flow rate, kg/s
Nu	Nusselt number, –
P	pressure, Pa
Q	heat, J
R_g	gas constant, J/(kg K)
R_p	particle radius, m
R_u	universal gas constant, J/(mol K)
S	source term or heat transfer surface, W or m^2
SCP	specific cooling power, W/kg
STP	supplied thermal power, W
t	time, s
T	temperature, K
STP	total cooling power, W
$\vec{u}$	velocity vector, m/s
VCP	volumetric cooling power, W/m^3
w	uptake, $kg_{adsorbate}/kg_{adsorbent}$
w^*	equilibrium uptake, $kg_{adsorbate}/kg_{adsorbent}$

Greek symbols

ΔH	heat of adsorption, J/kg
ε	porosity, –
μ	viscosity, $(N s)/m^2$
τ	characteristic time, s
ρ	density, kg/m^3
$\forall$	volume, m^3

Subscripts

ads	adsorption or adsorbent
b	bed
cham	chamber
chan	channel
cond	condenser
des	desorption
evap	evaporator
f	thermal fluid
fin	fin
g	gaseous phase
p	particle

complex adsorbent bed transport phenomena can serve as a proper tool in identifying the more efficient HExs among the industrially available ones. There are relatively limited numerical studies that considered the effects of adsorption bed geometrical parameters on its cooling performance. One can refer to the non-finned Ads-bed studies such as Alam et al. [1] on a tube adsorber, as well as Leong and Leo [2] and Solmus et al. [3,4] on two different types of cylindrical adsorbers. Whereas, for the finned bed types investigations the study of Niazmand and Dabzadeh [5] on the annular finned adsorber, Mahdavikhah and Niazmand [6], Chakraborty et al. [7], and Rezk et al. [8,9] on a plate finned adsorber as well as the comparative study of Niazmand et al. [10] on adsorbent beds with square and annular plate fins, can be mentioned among others. More details regarding the above mentioned studies are provided in Table 1. One of the central findings of these investigations is the importance of the adsorber geometrical configuration especially the adsorbent bed thickness in an ACS performance.

A particular kind of heat exchangers is the finned flat-tube (FFT) type, which due to its extensive heat transfer surfaces has attracted especial attention. The available ones in the market, which are made of aluminum have the advantages of low weight and thermal capacity as compared to other materials [11]. Nevertheless, as indicated by Sharafian et al. [12] they have not been yet properly sized and optimized as an adsorber for waste heat driven ACS.

Previous experimental and numerical investigations employing the FFT HExs as an adsorber bed examine the performance of the bed from different aspects such as the cycle time [13–21], operating temperatures [13–15,17–19,21–24], working pair [18,19,24,25], and HEx configuration [18,19,21–24,26,27]. In the following, the literature review is limited to the studies related to the FFT Ads-HEx configuration.

More efficient heat transfer can be obtained by reducing the thermal contact resistance between the adsorbent and the HEx surface. As reported by Freni et al. [27] using the coated FFT Ads-HEx enhances the *SCP* in comparison with a granular adsorber, which is also associated with a lower volumetric cooling power (*VCP*). Evidently, a hybrid solution, where loose grains of adsorbent are placed inside the coated HEx is one the most efficient configurations with respect to the *VCP* [19,21].

Isobaric desorption and adsorption dynamics of water by employing 0.15–1.18 mm AQSOA FAM Z02 grain sizes loaded into aluminum FFT HExs were measured experimentally by Santamaria et al. [26]. For this purpose, the HExs with a given fin height (*FH*) of 8 mm and fin pitch (*FP*) of 1.5 mm, but different bed lengths of 22, 40, and 85 mm were tested. It was found that longer beds can be as efficient as shorter ones for relatively larger grain sizes. However, using smaller grain sizes (e.g. 0.3–0.35 mm) in longer beds can lead to the longer adsorption time, while the desorption time is almost independent of the bed length (*BL*).

Gordeeva et al. [22] has conducted a similar study by employing the LiBr/silica-ethanol working pair. In contrast to [26], the authors indicated that regardless of the grain size in the range of 0.2–1.0 mm, adsorption rate is always slower at longer beds and hence, bed lengths larger than 22 mm are not recommended. Frazzica et al. [18] by using the activated carbon/ethanol working pair in a FFT Ads-HEx with the fixed bed length of 22 mm, experimentally observed a similar adsorption rate behavior for different grain sizes in the range of 0.425–1.18 mm, while non-monotonous behaviors are reported by [22,26].

Verde et al. [24] employed an analytical lumped model based on the thermal resistance network, to examine the effects of bed geometrical parameters of a silica gel/water cooling system on the specific cooling