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Performance investigation of finned tube type adsorber for different fin specifications

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Abstract
In this study, 2D axisymmetric heat and mass transfer simulation of finned tube type adsorber bed employing activated carbon-ethanol working pair has been performed. The model uses mass, momentum, and energy conservation equations as well as adsorption equilibrium and adsorption rate equations. Moreover, almost identical experimental conditions have been provided for the simulation to validate the simulation results. In the result section, temperature and pressure profiles are presented and validated by comparing with the experimental results. Specific cooling power and COP were evaluated and found 210.63 W/kg and 0.33 respectively. Finally, this CFD model is used for performance optimization of the system by varying heat exchanger fin specifications.

1. Introduction

Adsorption cooling system (ACS), a feasible alternative to vapor compression system, is gaining more attention nowadays as it employs natural and environment friendly refrigerants such as water, ethanol, ammonia, CO_2 etc. Moreover, it can be driven by waste heat or solar energy. Although this system has been commercialized, however, still it has some problems such as relatively low efficiency and bulkiness, which hinder this system from mass production. Several researchers are working continuously to improve the performance of ACS system. The performances of ACS already has been examined through lump-sum modeling using several adsorbent-adsorbate pairs such as silica gel-water, water-zeolite, ammonia-activated carbon, ethanol-activated carbon. Although performance prediction by lump-sum modeling is more practical rather than ideal cooling cycle simulation, however, the assumption, same temperature in the bed is not realistic. Consequently, heat and mass transfer of adsorber heat exchanger through CFD analysis is necessary to improve the system performance and optimize the heat exchanger design parameter. Some researchers have already started to analyze heat and mass transfer of adsorber bed heat exchanger through CFD simulation[1][2][3].

The objective of this study is to validate the CFD model of finned tube type adsorber with experimental results and investigate the performance of the system in terms of coefficient of performance (COP) and Specific cooling power (SCP). Moreover, this CFD model will be used for performance optimization of the system by varying heat exchanger fin specifications.

2. CFD Model

The experiment of finned tube adsorber with activated carbon-ethanol pair was conducted in our laboratory earlier [4]. For similar experimental conditions, the CFD simulation is carried out with Ansys fluent software v.18.1. Geometry and meshing were performed by Ansys Design Modeler and Ansys Meshing respectively.

2.1. Geometry

Figure 1 is showing the schematic geometry where the studied domain is decreased the half space between two fins; therefore, the simulation

was a 2D-axisymmetric simulation. Specifications of finned tube adsorber are furnished in table 1.

2.2. Materials & porous zone properties

Materials used in the simulations are as follows:

i. Activated carbon powder of type Maxsorb-III packed between the fins,
ii. Copper material for tube and fins,
iii. Ethanol as gas phase refrigerant.

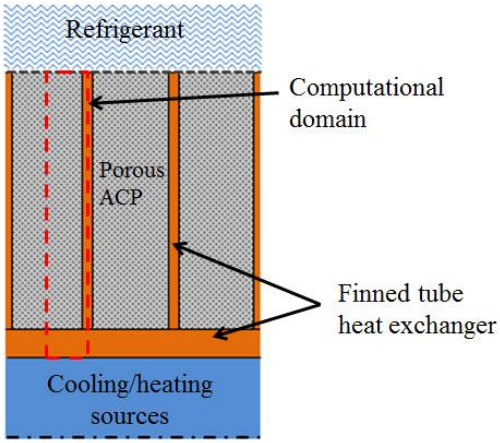

Figure 1. 2D axisymmetric geometry of finned tube adsorber

Table 1. Specification of finned tube adsorber

Parameter	Symbol	Value
Tube inner diameter (mm)	d_i	26
Tube outer diameter (mm)	d_o	29
Fin thickness (mm)	δ	0.53
Fin pitch (mm)	l	3.7
Fin height (mm)	h	10

Table 2 presents the properties of activated carbon powder. The porous zone properties of the activated carbon powder are characterized by equations (1-3).

$$\varepsilon_b = 1 - \frac{\rho_a}{\rho_s} - v_\mu \rho_a \quad (1)$$

$$\alpha = \frac{{D_P}^2}{150} \frac{\gamma^3}{(1-\gamma)^2} \quad (2)$$

$$C_2 = \frac{3.5}{D_P} \frac{(1-\gamma)}{\gamma^3} \quad (3)$$

Where ε_b, α and C_2 denote porosity, permeability and inertial resistance coefficient of porous zone respectively.

2.3 Adsorbent-adsorbate interactions

The adsorbent-adsorbate characteristics are the mass adsorbed/desorbed and heat released/adsorbed which is given by equations (4) and (5) to Fluent as user-defined functions (UDFs).

Table 2. Properties of activated carbon powder

Parameter	Symbol	Value
Packing density (kg.m^{-3})	ρ_a	275
Skeletal density (kg.m^{-3})	ρ_s	2200
Particle density (kg.m^{-3})	ρ_p	464.14
Average particle diameter (μm)	D_p	70
Micropore volume (cm^3.g^{-1})	v_μ	1.7
specific heat (kJ.kg^{-1}.K^{-1})	$C_{p,s}$	1
Thermal conductivity (W.m^{-1}.K^{-1})	k_s	0.066

$$S_m = -(1-\gamma)\rho_p \frac{dq}{dt} \quad (4)$$

$$S_h = -(1-\gamma)\rho_p Q_{st} \frac{dq}{dt} \quad (5)$$

Here, $\frac{dq}{dt}$ denotes adsorption rate which is calculated by using linear driving force (LDF) equation (6).

$$\frac{dq}{dt} = k\ (q^* - q) \quad (6)$$

Where k and $q*$ are diffusion time constant and equilibrium uptake and these are modeled by Arrhenius and Dubinin-Astakhov (D-A) equations ((7) and (8)) respectively.

$$k = A\ \exp\left(-\frac{E_a}{RT}\right) \quad (7)$$

Here, A = 0.2415 s^{-1} and E_a = 225 kJ/kg which denote pre-exponential factor and activation energy respectively [5].

$$q^* = q_s\ \exp\left(-\left(\frac{RT}{E} ln\left(\frac{P_s}{P}\right)\right)^n\right) \quad (8)$$

Where, q_s = 1.2 kg.kg^{-1}, E = 139.5 kJ.kg^{-1} and n = 1.8 [5].

2.4 Boundary conditions

Heating/Cooling surface: The supply water temperature is 20 ˚C during pre-cooling and adsorption processes and 80 ˚C during preheating and desorption processes. These conditions are given as convection boundary condition, and convection heat transfer coefficient is calculated for the water flow of 3 l/min by using Gnielinski correlation.

Inlet/Outlet condition: Adsorber is connected to the evaporator having the pressure of 3.85 kPa which is the inlet condition. Besides, the

refrigerant outlet condition during desorption process is at condenser pressure of 10.35 kPa.

2.5 Performance investigation

Performance indicating parameters of the adsorption cooling system, specific cooling power and coefficient of performance (COP), are calculated by using equations (9-10).

$$Q_{chill} = \frac{h_{fg} \cdot \int_{ads\_start}^{ads\_end} m_{ads}\ dt}{t_{cycle}} \quad (9)$$

$$COP = \frac{Q_{chill}}{Q_{des}} \quad (10)$$

3. Results and discussion

Figure 2 shows the pressure profile in the adsorber/desorber bed where adsorption takes place at 3.85 kPa pressure and desorption pressure is 10.35 kPa. There is a sharp change of pressure during the pre-cooling and preheating process, and constant during adsorption and desorption.

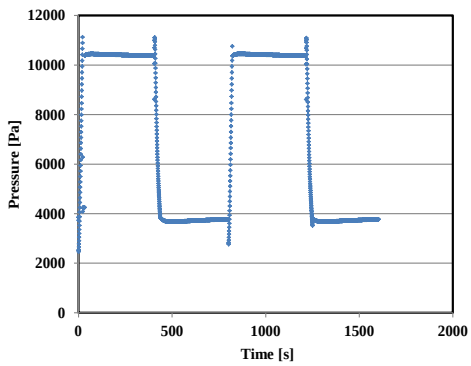

Figure 2. Simulated pressure profile in the adsorber/desorber bed.

Experimental temperature change vs. simulated temperature profiles at 1 and 5 mm adsorbent thickness from the outer surface of the copper tube is displayed in figure 3. Good agreement is found between experimental and simulated temperature results. In figure 5, temperature distributions inside the adsorber bed at the end of adsorption, pre-heating, desorption and pre-cooling processes is shown. As convection and conduction heat transfer at the center of the bed is not good, therefore, after pre-heating and desorption process, temperature distribution inside the bed is not same. Simulated equilibrium uptake and instantaneous uptake of the bed is shown in figure 4. The difference between maximum and minimum values of equilibrium uptake is 0.494 kg/kg whereas the change in case of instant uptake is 0.32 kg/kg. Therefore, ethanol adsorption onto activated carbon is only 66% of its capacity within the 400s adsorption time. The calculated specific cooling power of the system is found 210.63 W/kg and COP is 0.33 which are calculated by using the equation (9) and (10) respectively.

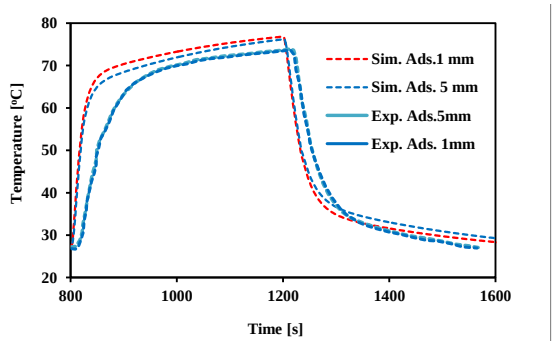

Figure 3. Simulated vs. experimental temperatures profile at 1 and 5mm adsorbent thickness.

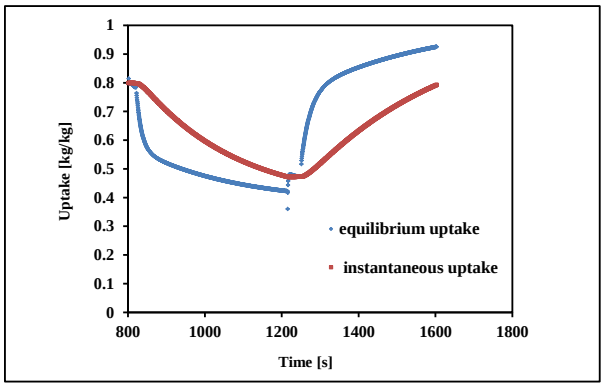

Figure 4. Simulated instantaneous and equilibrium uptake profile.

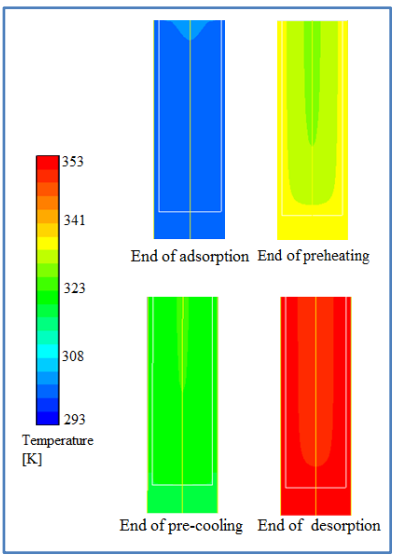

Figure 5. Temperature change in the finned tube adsorber at the end of adsorption, pre-heating, desorption and pre-cooling process.

4. Performance study for different fin specifications

4.1 Effect of fin height on performance

The effect of fin height at 5,10, 15 mm with constant fin pitch 3.7 mm have been checked to evaluate the system performance. From the figure 6, it is seen that with the increase of fin height SCP decreases, however, COP increases and after 10 mm fin height it decreases. As the mass diffusion into the adsorbent layer will be lowered with the larger fin height, therefore, it will result in the lower SCP. Besides, the larger fin height causes the decrease in the heat capacity ratio so that the COP can increase, however, due to a large decrease in the SCP at the fin height of 15 mm, the COP is deceased.

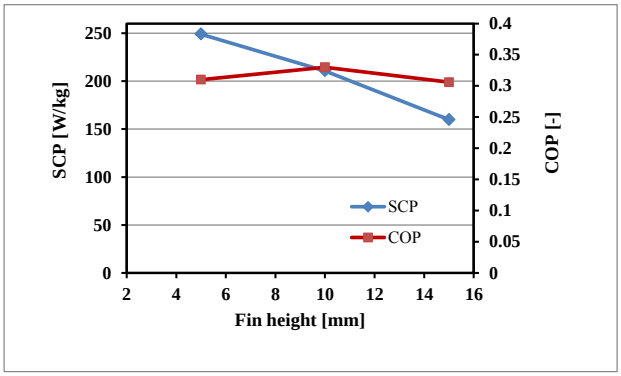

Figure 6. Effect of fin height variation on COP and SCP

4.2 Effect of fin pitch on performance

The effect of fin pitch of 2, 3.7, 5.5 mm with constant fin height 10 mm have been simulated. From the figure 7, it is evident that with the increase of fin height SCP decreases, however, COP increases. The increase of the fin pitch results in the decrease in heat capacity ratio. Therefore, the COP will be improved. Moreover, the heat transfer to the adsorbent will become worse, therefore, the SCP will decrease.

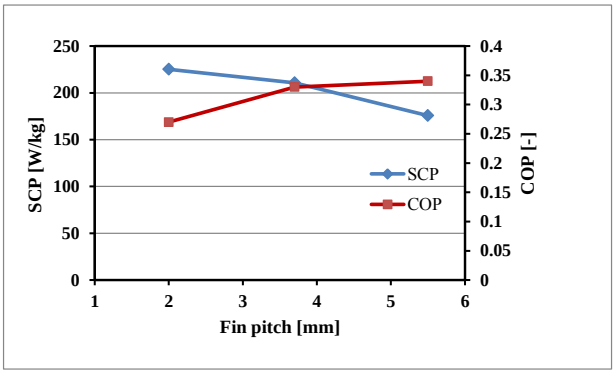

Figure 7. Effect of fin pitch variation on COP and SCP

5. Conclusion

The summary of this study are as follows-

I. CFD modeling of finned tube adsorber employing activated carbon-ethanol has been done and validated with experimental results.
II. Good agreement is found between experimental and simulation results.
III. Performance study for different fin specification has been done and results show that fin height less than 10mm and fin pitch around 4 mm is good regarding COP and SCP.
IV. This CFD model will allow performance optimization of the system by optimizing the operating conditions as well.

Acknowledgment

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