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Heat and mass transfer simulation of ethanol adsorption onto activated carbon packed heat exchanger

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Abstract: In this study, a 2D axisymmetric heat and mass transfer simulation of finned tube type adsorber bed employing activated carbon-ethanol working pair are performed. The model uses mass, momemtum, and energy conservation equations as well as adsorption equilibrium and adsorption rate equations. Moreover, almost identical experimental conditions are provided for the simulation to validate the simulation results. In the results section, temperature and pressure profiles are presented and validated by comparing with the experimental results. Specific cooling power and COP were evaluated and found 426.09 W/kg and 0.51 respectively. This CFD model will allow performance optimization of the system for different adsorber heat exchanger geometry and operating conditions.

Keywords: CFD simulation, Activated carbon, Ethanol, Finned tube type adsorber.

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[1], ethanol[2], ammonia[3], CO_2 [4], 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[5][6][7].

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 cooling capacity.

2. WORKING PRINCIPLE OF ADSORPTION COOLING SYSTEM

The schematic diagram of adsorption chiller is depicted in Fig.1. Components of the adsorption chiller are a condenser, an evaporator, an adsorber/desorber bed filled with the activated carbon powder (ACP) and an expansion valve. There are four processes to complete the cycle of adsorption cooling system. Firstly, the bed is disconnected from the system and heat is applied during the pre-heating process. The pressure in the bed increases so that it becomes higher than that in the condenser. Secondly desorption process starts with connecting the desorber bed to the condenser. Ethanol is desorbed from activated carbon because of additional heating of the bed and moves to condenser where it condensates. Pre-cooling is the third process where the bed is disconnected again and for decreasing temperature, cooling water is circulated in the heat exchanger. The pressure in the bed decreases and becomes lower than that in the evaporator. Evaporated ethanol is adsorbed in the activated carbon at this moment by connecting the adsorber bed to the evaporator. Combination of all these four processes is called the adsorption cycle. To remove the heat of adsorption, cooling water is supplied and maximum amount of adsorption is attained.

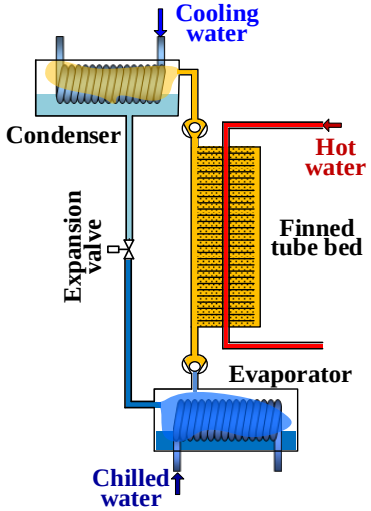

Fig.1. Schematic of adsorption cooling system in desorption process.

3. CFD MODEL

Experiment of finned tube adsorber with activated carbon-ethanol pair was conducted in our laboratory earlier [8]. 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.

3.1 Geometry

Fig. 2 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.

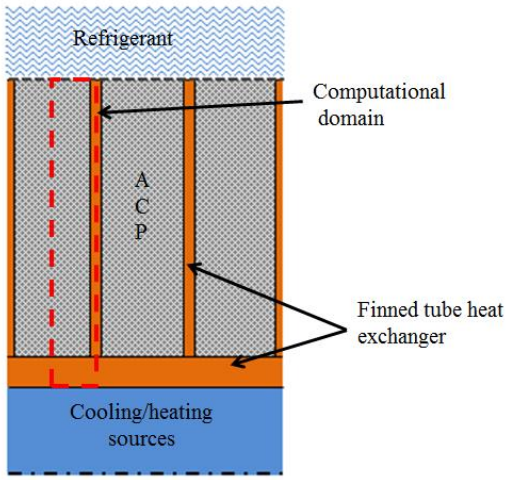

Fig. 2. The axisymmetric 2D geometry of finned tube adsorber.

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

3.2 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.

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.

Table 2. Properties of activated carbon powder

Parameter	Symbol	Value
Adsorbent's packing density (kg.m^{-3})	ρ_a	275
Adsorbent's skeletal density (kg.m^{-3})	ρ_s	2200
Adsorbent's particle density (kg.m^{-3})	ρ_p	464.14
Adsorbent's average particle diameter (μm)	D_p	70
Adsorbent's micropore volume (cm^3.g^{-1})	v_μ	1.7
Adsorbent's specific heat (kJ.kg^{-1}.K^{-1})	$C_{p,s}$	1
Adsorbent-adsorbate's thermal conductivity (W.m^{-1}.K^{-1})	k_s	0.066

3.3 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).

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

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

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.

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

Here, A = 0.2415 s^{-1} and Ea = 225 kJ/kg denote pre-exponential factor and activation energy respectively [9].

3.4 Boundary conditions

Heating/Cooling surface: Inner surface of the copper tube is acted as a heating surface during desorption and as a cooling surface during the adsorption process. 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 water flow of 3 l/min by using Gnielinski correlation.

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

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

3.5 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).

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

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

4. RESULTS AND DISCUSSION

Fig. 3 shows the simulated 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.

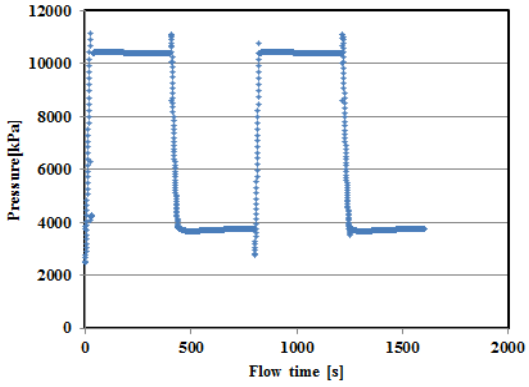

Fig.3. Simulated pressure profile in the adsorber/ desorber bed.

Experimental temperature change vs. simulated temperature profiles at 1 and 5 mm adsorbent thickness from the outer surface of the copper tube are displayed in fig. 4. Good agreement is found between experimental and simulated temperature results. In fig. 6, temperature distributions inside the adsorber bed at the end of adsorption, pre-heating, desorption and pre-cooling processes is showed. 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.

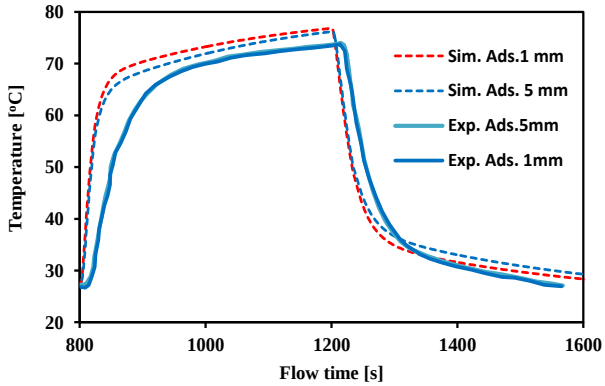

Fig. 4. Simulated vs. experimental temperatures profile at 1 and 5mm adsorbent thickness.

Simulated equilibrium uptake and instantaneous uptake of the bed is shown in fig. 5. 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 426.09 W/kg$_{ac}$ and COP is 0.51 which are calculated by using the equation (9) and (10) respectively.

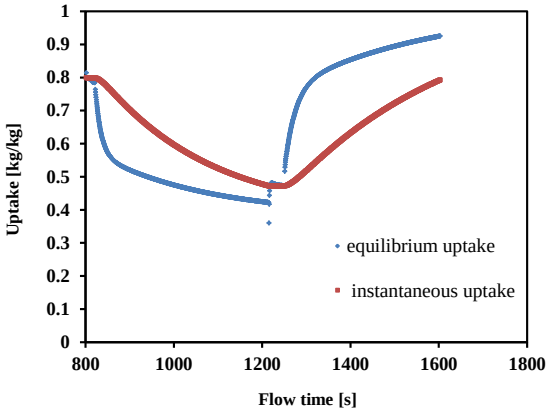

Fig. 5. Simulated instantaneous and equilibrium uptake.

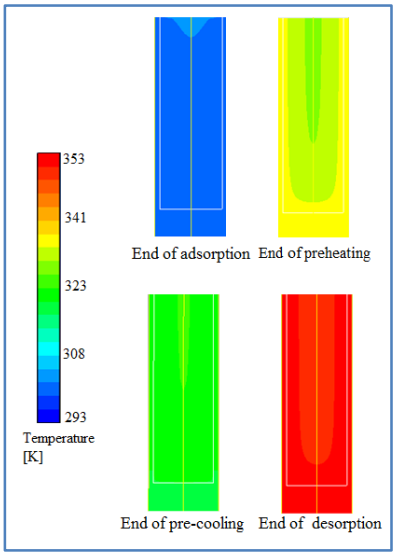

Fig. 6. Temperature change in the finned tube adsorber at the end of adsorption, pre-heating, desorption and pre-cooling process.

5. CONCLUSION

CFD simulations of finned tube adsorber employing activated carbon-ethanol were performed using similar experimental boundary conditions. Simulated temperature profile showed good agreement with experimental results. Moreover, Specific cooling power and COP were evaluated which were 426.09 W/kg and 0.51 respectively. Therefore, this CFD model will allow performance optimization of the system by optimizing the adsorber heat exchanger geometry and operating

conditions.

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