Proceedings of the International Conference on Heat Transfer and Fluid Flow
Prague, Czech Republic, August 11-12, 2014
Paper No. 180

CFD Simulation of Honeycomb Adsorption Bed for Automotive Cooling System

B. Shi, A. Elsayed, R.K. AL-Dadah, S. Mahmoud
School of Mechanical Engineering, University of Birmingham
Birmingham, United Kingdom, B15 2TT
+0044 1214143513, r.k.al-dadah@bham.ac.uk

Abstract **-** Heat powered adsorption cooling technology offers advantages in various applications where waste heat is available such as in automotive application. Various adsorption bed designs were reported in the literature but size, weight and cost were limiting factors for implementing such systems. Honeycomb structure has the advantages of low cost, low weight and good heat transfer proprieties which makes it suitable for adsorption bed designs in automotive air conditioning application. In this work, computational fluid dynamics (CFD) modelling was used to simulate the adsorption process for a honeycomb based adsorption bed packed with silica gel adsorbent material. The effects of honeycomb structure geometry in terms of cell height and size on the silica gel water uptake were investigated at various cooling water flow rates using COMSOL Multiphysics software. Results showed that as the honeycomb cell height increases the water uptake decreases. Also, as the honeycomb cell size decreases the water uptake increases to be maximum at cell size of 3.2mm and height of 5mm. Regarding the effect of cooling water flow rate, results showed that increasing the Reynolds number above 5000 has no significant impact on the water uptake.

Keywords**:** Adsorption bed, Automotive cooling system, CFD model, Honeycomb structure, COMSOL Multiphysics, Silica gel.

1. Introduction

Over the past two decades there has been increasing research on the development of adsorption cooling systems due to their ability to utilize low grade waste heat. Also they have environmental advantages compared to the traditional vapour compression refrigeration systems since they use no ozone depletion refrigerants.

But due to their large volume, high weight and lower efficiency, the application of adsorption chillers is still limited (Zhong et al., 2011a; Boer et al. 2009; Zhang, 2000; Lambert and Jones, 2006a, b; Tamainot-Telto et al., 2009; Vasta et al., 2012). Several adsorption pairs were investigated like silica gel-water, zeolite-water, activated carbon-ammonia, activated carbon-methanol and activated carbon-ethanol (Srivastava and Eames, 1998). Silica gel-water pair has shown some advantages especially in terms of thermal performance and environmental effects (Srivastava and Eames, 1998; Loh et al., 2009; Chua et al., 1999).

Adsorption cooling systems have been investigated for automotive application since they can be driven by utilising the waste heat from the engine coolant water or from the engine exhaust gas, therefore decreasing fuel consumption and exhaust gas emissions. Verde et al. (2010) constructed and tested an adsorption system for truck cabin by using zeolite-water pair which can achieve cooling power of 2 to 3kW and coefficient of performance (COP) of 0.6. Boer et al. (2009) developed a compact adsorption cooling system and carried out an on-board test which achieved enough cooling power to maintain comfortable temperature level in the cabin. Lambert and Jones (2006a, b) described an adsorption chiller driven by exhaust gas and concluded that adsorption cooling system can reduce the fuel consumption while increasing the whole mass. Tamainot-Telto et al. (2009) designed an automotive adsorption chiller using waste heat from engine coolant water with cooling capacity of 1.6kW and COP of 0.22. Vasta et al. (2012) developed and tested a mobile adsorption air conditioner for truck which has overall size of

170dm^3 and weight of 60kg, giving cooling power of 2kW to maintain truck cabin temperature at 24°C. Zhang (2000) designed and experimentally tested an automobile adsorption cooling system using zeolite-water pair using finned tubes bed which has COP of 0.38 and specific cooling power (SCP) of 25.7W/kg.

Investigations using numerical simulations proved to be useful and efficient techniques to design adsorption systems and investigate adsorption cycles. Zhang and Wang (1997) set up a lumped parameter model and concluded that improving overall heat and mass transfer coefficients increases the specific cooling power (SCP). Saha et al. (2003) developed a mathematical model to simulate a six bed silica gel adsorption cooling system and studied the effects of cooling water temperature and hot water temperature on the cooling capacity and COP. Chua et al. (1999) described a transient model for a commercial adsorption chiller and predicted switching and cycle times close to achieve maximum cooling capacity operation. Zhong et al. (2011b) proposed a model for simulating an adsorption air conditioning system using zeolite-water for heavy-duty truck application. Freni et al. (2012) developed a CFD model to study water dynamic sorption process in different layers of silica gel granules for adsorption chiller while estimated the SCP based on results.

Honeycomb structures are widely used in various industrial applications such as thermal management, impact energy absorption and structure load support because of their low cost, light weight and favourable heat transfer proprieties (Lu, 1999; Liu et al., 2008). In this work, the adsorption process of silica gel packed in honeycomb structure bed was simulated using COMSOL Multiphysics software and the effect of various cell size parameters were investigated.

2. Adsorption Bed Description

The adsorption bed contains three rectangular aluminium tubes and two layers of aluminium honeycomb structure. The cooling water flows through tubes to cool down the adsorption bed after the desorption process. Honeycomb fins are glued on both upper and lower surfaces of the rectangular tubes. Silica gel granules are packed inside the honeycomb cells, with design parameters shown in Table. 1. Due to symmetry around longitudinal and lateral axes and to reduce the computational time, one quarter of the adsorption bed with full bed length was simulated. Fig. 1 shows section of the adsorption bed with honeycomb fins.

Table 1. Bed design parameters.

Parameter	Value
Bed length	275mm
Tube height	7.8mm
Tube width	38.3mm
Tube thickness	0.5mm
Fin height	11.1mm
Fin thickness	0.1mm
Fin cell size	6mm

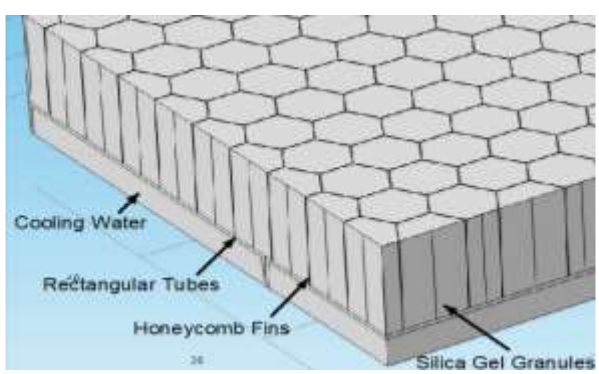


Fig. 1. Diagram for one quarter of adsorption bed.

3. CFD Model Set Up

The adsorption process inside the bed shown in fig. 1 is simulated using equations described in eqs. (1-13). Darcy equation, eq. (1), is used to describe the continuity of the adsorption process and eq. (2) is the energy equation.

$$\frac{\partial\left(\varepsilon_s \rho_w\right)}{\partial t} + \nabla\cdot\left(\rho_w \boldsymbol{u_w}\right) = -\frac{\partial\left(\rho_s w\right)}{\partial t} \tag{1}$$

$$\rho Cp \frac{\partial T_{bed}}{\partial t} + Cp_w \nabla\cdot\left(T_{bed}\rho_w \boldsymbol{u_w}\right) = \nabla\cdot\left(k_s \nabla T_{bed}\right) + \rho_s \Delta H_s \frac{\partial w}{\partial t} \tag{2}$$

$$\boldsymbol{u_w} = -\frac{\kappa}{\mu}\nabla P_w \tag{3}$$

$$\rho Cp = \left(\varepsilon_s \rho_w + \rho_s w\right)Cp_w + \rho_s Cp_s \tag{4}$$

$$\kappa = \frac{4\varepsilon_s^3 R_p^2}{150\left(1-\varepsilon_s\right)^2} \tag{5}$$

where ε_s is taken as 0.5 for porosity of adsorbent bed packed with silica gel granules [Shi et al., 2013]. $\boldsymbol{u_w}$ is the water vapour velocity which is determined by eq. (3) where ∇P_w is water vapour pressure gradient. ρCp is calculated by eq. (4). k_s is the thermal conductivity of the bed, which is 0.198 W/(m·K). κ is the permeability of silica gel and was determined by eq. (5).

The uptake value of the refrigerant vapour by silica gel, w, can be determined using the linear driving force (LDF) kinetic model shown in eqs. (6-7).

$$dw/dt = K\left(w_{max} - w\right) \tag{6}$$

$$K = 15 D_{so} \exp\left(-\frac{E_a}{RT_{bed}}\right) / R_p^2 \tag{7}$$

where w_{max} is the maximum water vapour uptake of silica gel granules at the equilibrium condition. The modified Freundilich model is used to obtain this value as described in eqs. (8-10) and the values of its constants are given in Table. 2.

$$w_{max} = A\left[\frac{P(T_e)}{P(T_{bed})}\right]^B \tag{8}$$

$$A = A_0 + A_1 T_{bed} + A_2 T_{bed}^2 + A_3 T_{bed}^3 \tag{9}$$

$$B = B_0 + B_1 T_{bed} + B_2 T_{bed}^2 + B_3 T_{bed}^3 \tag{10}$$

Table 2. Constants for equilibrium uptake equation.

Constant	Value	Unit
A_0	-6.5314	$kg_{water}/kg_{silicagel}$
A_1	7.2452×10-2	$kg_{water}/(kg_{silicagel}\cdot)$
A_2	-2.3951×10-4	$kg_{water}/(kg_{silicagel}\cdot K^2)$
A_3	2.5493×10-7	$kg_{water}/(kg_{silicagel}\cdot K^3)$
B_0	-15.587	1
B_1	0.15915	K^{-1}
B_2	-5.0612×10-4	K^{-2}
B_3	5.3290×10-7	K^{-3}

The contact resistance between silica gel granules and aluminium tubes and honeycomb fins is described in eq. (11).

$$R_{cont} = 0.0013T_{bed}^2 - 0.1773T_{bed} + 8.6221 \tag{11}$$

As for the cooling water flow in the rectangular tubes, two conditions are considered in this work, which are laminar flow and turbulent flow, described by eq. (12) and eq. (13) respectively.

$$\rho_{wl}\frac{\partial \boldsymbol{u_{cw}}}{\partial t} + \rho_{wl}\left(\boldsymbol{u_{cw}}\cdot\nabla\right)\boldsymbol{u_{cw}} = \nabla\cdot\left[-p\boldsymbol{I} + \mu\left(\nabla\boldsymbol{u_{cw}} + \left(\nabla\boldsymbol{u_{cw}}\right)^T\right)\right] \tag{12}$$

$$\rho_{wl}\frac{\partial \boldsymbol{u_{cw}}}{\partial t} + \rho_{wl}\left(\boldsymbol{u_{cw}}\cdot\nabla\right)\boldsymbol{u_{cw}} = \nabla\cdot[-p\boldsymbol{I} + \left(\mu+\mu_T\right)\left(\nabla\boldsymbol{u_{cw}} + \left(\nabla\boldsymbol{u_{cw}}\right)^T\right) - \frac{2}{3}\rho_{wl}k_{tur}\boldsymbol{I}] \tag{13}$$

where $\boldsymbol{u_{cw}}$, ρ_{wl}, μ are flow velocity, density and dynamic viscosity of cooling water respectively, $\boldsymbol{I}$ is the unit matrix and k_{tur} is the turbulent kinetic energy.

All above equations are solved by COMSOL Multiphysics software. Fig. 2 shows the model in COMSOL with full length.

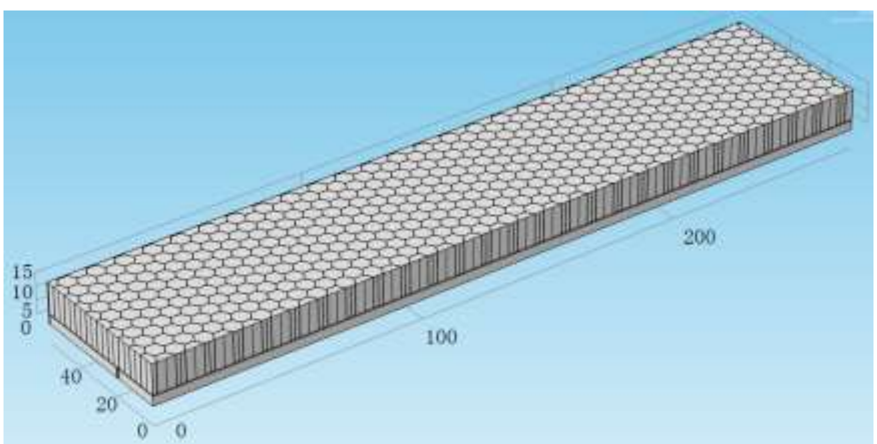
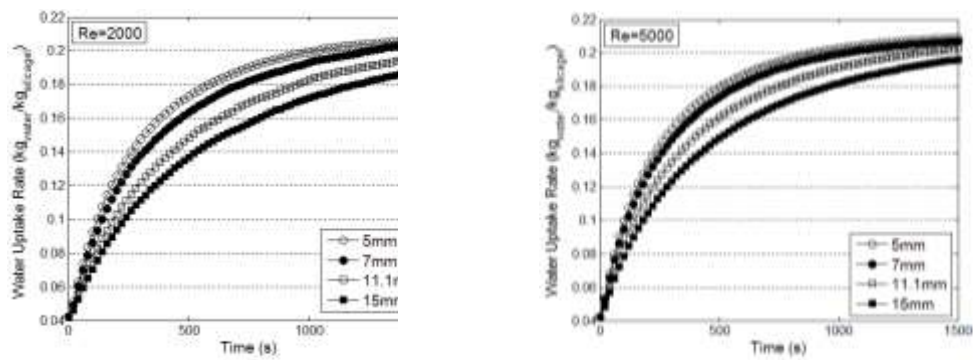


Fig. 2. COMSOL model of quarter of the adsorption bed.

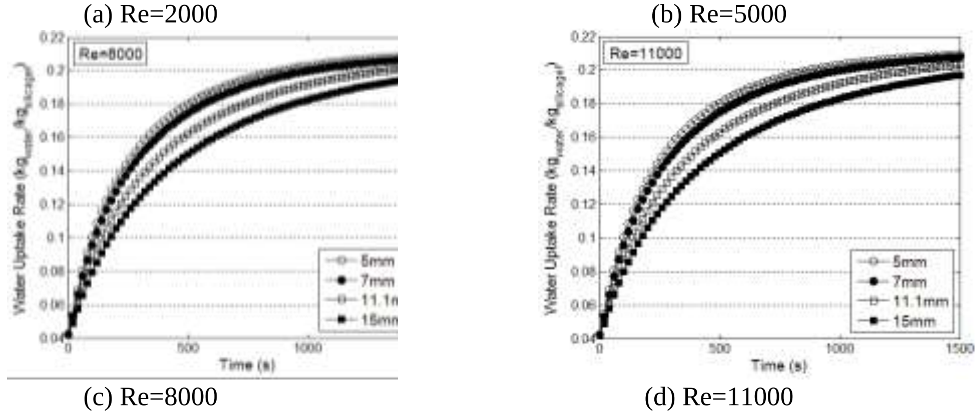
4. Results and Discussion

The simulation was carried out for the adsorption process of adsorption bed with honeycomb fins described in section 2 and 3 using CFD modelling technique. Operating conditions including inlet water temperature of 30℃, evaporator temperature of 15℃ and initial bed temperature of 60℃ which is obtained after desorption process, are used in this adsorption process simulation. The whole adsorption process runs for 1500s which is enough to predict the adsorption performance of adsorption bed packed with silica gel-water working pair. The cooling water flow rate of 0.139m/s, which can get a Reynolds number of 2000, is used for laminar flow while turbulent flow is obtained with cooling water flow rate of 0.348m/s and Reynolds number of 5000. The CFD model is used to investigate the effect of honeycomb cell height and fin cell size on the performance of the adsorption bed in the adsorption process at various cooling water flow Reynolds number.

Fig. 3 shows the effect of honeycomb cell height on the silica gel water uptake at various cooling water flow rates with Reynolds number changing from 2000 to 11000 for honeycomb cell size of 6mm. It is clear from this figure that as the honeycomb cell height increases the water uptake decreases. This could be attributed to the reduction in the water vapour diffusion to the silica gel granules as the silica gel adsorbent layer thickness increases. Fig. 4 shows the effect of honeycomb cell size on the silica gel water uptake at various cooling water flow rates with Reynolds number changing from 2000 to 11000. It is clear from this figure that as the honeycomb cell size decreases the water uptake increases. This could be attributed to the improvement in heat transfer from the cooling channels to the adsorbent material due to increasing surface contact. Fig. 5 shows the effect of cooling water flow rates using the best honeycomb geometry in terms of cell height (5mm) and cell size (3.2mm). It is clear from this figure that increasing the Reynolds number above 5000 has no significant impact on the water uptake.

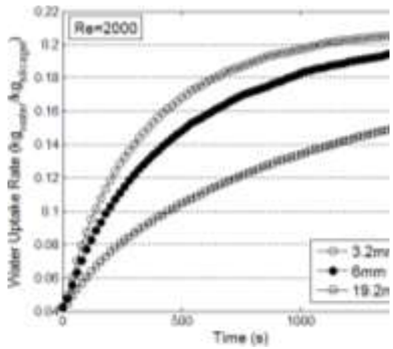


(a) Re=2000 (b) Re=5000

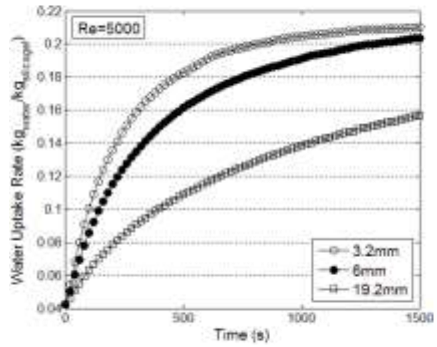


(c) Re=8000 (d) Re=11000

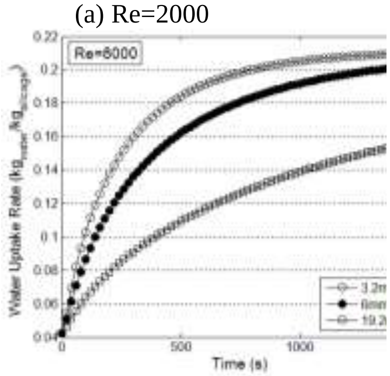
Fig. 3. Water uptake rate for different honeycomb cell height.



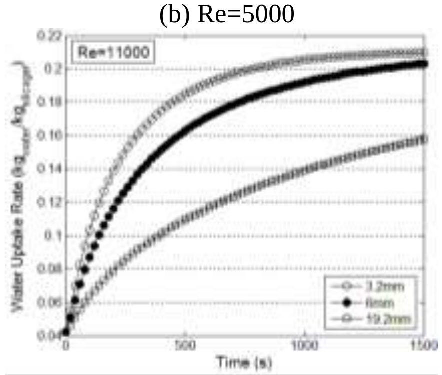
(a) Re=2000



(b) Re=5000



(c) Re=8000



(d) Re=11000

Fig. 4. Water uptake rate for different honeycomb cell size.

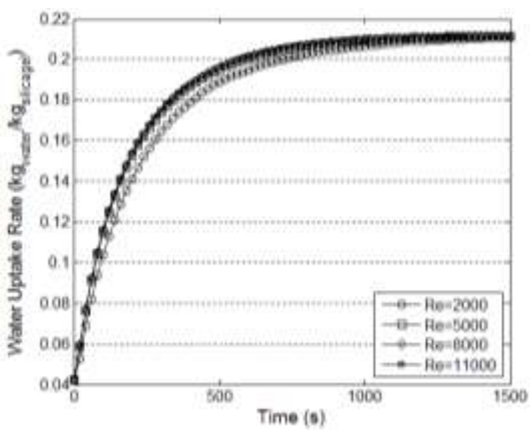


Fig. 5. Water uptake rate for different cooling water flow rates.

4. Conclusions

Honeycomb structures have the advantages of low cost, low weight and good heat transfer proprieties which make them suitable for various thermal applications. In this work, computational fluid dynamics (CFD) modelling technique was used to simulate the adsorption process for silica gel packed in a honeycomb adsorption bed with water as the refrigerant using COMSOL Multiphysics software. The effects of honeycomb structure geometry in terms of cell height and size on the silica gel water uptake were investigated at various cooling water flow rates. Results showed that as the honeycomb cell height increases the water uptake decreases due to the reduction in the water vapour diffusion through the silica gel granules. Also, as the honeycomb cell size decreases the water uptake increases due to the improvement in heat transfer from the cooling channels to the adsorbent material as the surface contact area increased. Regarding the effect of cooling water flow rate, results showed that increasing the Reynolds number above 5000 has no significant impact on the water uptake.

References

Zhong Y., Fang T., Wert. K.L. (2011). An adsorption air conditioning system to integrate with the recent development of emission control for heatvy-duty vehicles. Energy, 36, 4125-4135.

Boer R. de, Smeding S., Mola S. (2009). Silicagel-water adsorption cooling protorype system for mobile air conditioning. "Proc. of Heat Powered Cycles Conference," Berlin.

Zhang L.Z. (2000) Design and testing of an automobile waste heat adsorption cooling system. Applied Thermal Engineering, 20, 103-114.

Lambert M.A., Jones B.J. (2006). Automotive adsorption air conditioner powered by exhaust heat. Part 1: conceptual and embodiment design. Proc. of the Institution of Mechanical Engineers Part D: J. Automobile Engineering, 220, 995-72.

Lambert M.A., Jones B.J. (2006). Automotive adsorption air conditioner powered by exhaust heat. Part 2: detailed design and analysis. Proceedings of the Institution of Mechanical Engineers Part D: J. Automobile Engineering, 220, 973-89.

Tamainot-Telto Z., Metcalf S.J., Critoph R.E. (2009). Novel compact sorption generators for car air conditioning. International Journal of Refrigeration, 32, 727-733.

Vasta S., Freni A., Sapienza A., Costa F., Restuccia G. (2012). Development and lab-test of a mobile adsorption air-conditioner. International Journal of Refrigeration, 35, 701-708.

Srivastava N.C., Eames I.W. (1998). A review of adsorbents and adsorbates in solid-vapour adsorption heat pump systems. Applied Thermal Engineering, 18, 707-714.

Loh W.S., El-Sharkawy I.I., Ng K.C., Saha B.B. (2009). Adsorption cooling cycles for alternative adsorbent/adsorbate pairs working at partial vacuum and pressurized conditions. Applied Thermal Engineering, 29, 793-798.

Chua H.T., Ng K.C., Malek A., Kashiwagi T., Akisawa A., Saha B.B. (1999). Modeling the performance of two-bed, silicagel-water adsorption chillers. International Journal of Refrigeration, 22, 194-204.

Verde M., Cortés L., Corberán J.M., Sapienza A., Vasta S., Restuccia G. (2010) Modelling of an adsorption system driven by engine waste heat for truck cabin A/C. Performance estimation for a standard driving cycle. Applied Thermal Engineering, 30, 1511-1522.

Zhang L.Z. (2000). Design and testing of an automobile waste heat adsorption cooling system. Applied Thermal Engineering, 20, 103-114.

Zhang L.Z., Wang L. (1997). Performance estimation of an adsorption cooling system for automobile waste heat recovery. Applied Thermal Engineering, 17, 1127-1139.

Saha B.B., Koyama S., Kashiwagi T.K., Akisawa A., Ng K.C., Chua H.T. (2003). Waste heat driven dual-mode, multi-stage, multi-bed regenerative adsorption system. International Journal of Refrigeration, 26, 749-757.

Chua H.T., Ng K.C., Malek A., Kashiwagi T., Akisawa A., Saha B.B. (1999). Modeling the performance of two-bed, silica gel-water adsorption chillers. International Journal of Refrigeration, 22, 194-204.

Zhong Y., Fang T., Wert K.L. (2011). An adsorption air conditioning system to integrate with the recent development of emission control for heatvy-duty vehicles. Energy, 36, 4125-4135.

Freni A., Maggio G., Cipiti F., Aristiv Y. I. (2012). Simulation of water sorption dynamics in adsorption chillers: One, two and four layers of loose silica grains. Applied Thermal Engineering, 44, 69-77.

Lu T.J. (1999). Heat transfer efficiency of metal honeycombs. International Journal of Refrigeration, 42, 2031-2040.

Liu S., Zhang Y., Liu P. (2008). New analytical model for heat transfer efficiency of metallic honeycomb structures. International Journal of Refrigeration, 51, 6254-6258.

Shi B., AL-Dadah R.K., Mahmoud S., Elsayed A., Rezk A. (2013). Mathematical and CFD modelling for a rectangular finned tube adsorption bed for automotive cooling system. "Proc. of the 5th Heat Powered Cycles Conference 2009", Pretoria, 2013.