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Effects of contact resistance and metal additives in finned-tube adsorbent beds on the performance of silica gel/water adsorption chiller

A. Rezk, R.K. Al-Dadah*, S. Mahmoud, A. Elsayed

School of Mechanical Engineering, University of Birmingham, Birmingham Edgbaston, B15 2TT, United Kingdom

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ABSTRACT

Recently interest in adsorption cooling systems has increased due to their capability to utilise low grade heat sources and environmentally friendly refrigerants. Currently, most of the commercially available adsorption cooling systems utilise granular packed adsorbent beds. Enhancing the heat transfer process inside the adsorbent bed will improve the overall efficiency of the adsorption system. Using recently developed empirical lumped analytical simulation model for a 450 kW two-bed silica gel/water adsorption chiller, this paper theoretically investigates the effects of various adsorbent bed heat transfer enhancement techniques on the adsorption system cooling capacity. Firstly, coating the first adsorbent layer to the metal part and packing the rest of adsorbent granules to eliminate the thermal contact resistance between heat exchanger metal and granules while keeping the same level of permeability. Secondly, adding metal particles to the adsorbent in order to enhance the granules thermal conductivity. The effective thermal conductivity of adsorbent/metal mixtures were determined and validated by comparing it with published experimental data. Also, the combined effect of using both techniques simultaneously was investigated. All these investigations were carried out at various adsorption bed fin spacing. Results of the combined techniques showed that the enhancement in the cooling capacity and system coefficient of performance (COP) increased with increasing the fin spacing ratio to reach maximum of 25% and 10% respectively at fin spacing ratio of 2.

1. Introduction

Adsorption cooling systems are increasingly used for applications where cooling is required and low grade heat is available [1]. They are applied in combined cooling, heating and power (CCHP) systems employed in many industrial and commercial applications [2] and in sustainable building climatisation using solar energy as heat source [3,4]. Several adsorption pairs were evaluated and silica gel/water has shown significant advantages in terms of thermal performance and environmental impact [5]. Although water refrigerant is considered in chilling applications only, it has excellent thermo-physical properties of high latent heat of evaporation, high thermal conductivity, low viscosity, thermally stable in wide range of operating temperatures and the compatibility with wide range of materials. Silica gel as water vapour adsorbent has the advantages of high adsorption/desorption rate, low generation heat and low generation temperature.

Many commercially available adsorption cooling systems use granular packed adsorbent bed design. Such type of adsorbent bed has the advantage of high mass transfer performance due to the high permeability level [6], but it has the drawbacks of poor heat transfer performance where; high contact thermal resistance between adsorbent granules and heat exchanger metal surface [7], discontinuity of heat transfer through granules due to the voids in-between the granules [8] and poor thermal conductivity of the commonly used physical adsorbents. Therefore many methods were investigated to enhance the heat transfer performance of adsorbent material such as mixing adsorbent granules with metal additives to improve their thermal conductivity [9], coating the bed heat exchanger metal with all the adsorbent to eliminate the contact thermal resistance [7], covering adsorbent granules by polyaniline net [9], adsorbent deposition over metallic foam [6] and using consolidated bed techniques (compressed granules and clay [9], using expandable graphite [10], moulding granules and binder addition [11] and adsorbent granules and metal foam [12]). Most of these methods improve the heat transfer performance of adsorbent material but reduce its mass transfer performance [13].

Modelling is an effective tool for the design of adsorption cooling systems [14]. A recently constructed and validated empirical lumped analytical simulation model based on the fundamental

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* Corresponding author. Tel.: +44 (0) 121 4143513.
E-mail address: r.k.al-dadah@bham.ac.uk (R.K. Al-Dadah).

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heat and mass transfer equations was developed [5]. In such model the overall heat transfer conductance was calculated using empirical correlations taking into account the operating conditions and the geometry of heat exchangers. Thus, the model can be used to predict the effect of changing physical and operating conditions on chiller performance [15].

This paper evaluates some of the methodologies used to enhance the heat transfer performance of the adsorbent in terms of improving the bed thermal performance and the overall cooling capacity of the adsorption system. Firstly, coating the first adsorbent layer to the metal surface and packing the rest of adsorbent granules to eliminate the thermal contact resistance between heat exchanger metal and granules while keeping the same level of permeability. Secondly, adding various metal additives to the adsorbent in order to enhance its thermal conductivity. Finally, the combined effect of using both techniques simultaneously was investigated. All these investigations were carried out using fixed bed dimensions but at various fin spacing.

2. System description

Fig. 1 shows schematic diagram of the simulated two-bed adsorption chiller. Each adsorbent bed is connected to the evaporator or condenser by flap valves operated by the effect of pressure difference between heat exchangers during adsorbing or desorbing respectively. On the other hand, the flow of cooling and heating water to the adsorber and desorber respectively, flow of the chilled water through the evaporator and flow of cooling water to the condenser are controlled by 12 pneumatic valves.

Physically, the adsorbent bed heat exchanger is constructed from plain copper tubes with aluminium rectangular fins and the silica gel granules are packed to fill the gaps between fins, shown in Fig. 2. The adsorbent bed is covered by a metal mesh to prevent the falling of silica gel granules. These adsorbent beds are installed in two-bed silica gel/water adsorption chiller incorporating mass and heat recovery schemes. The operation modes and secondary flow valving control method were presented in details in [15].

3. Simulation model

The simulation model of the adsorption system was constructed from four sub-models describing the heat and mass transfer performance of evaporator, condenser, adsorber and desorber. The four sub-models were linked together taking into account the various operating modes. Eqs. (1)–(3) present the energy balance equations for adsorbent bed, evaporator and condenser respectively, where the adsorbent, adsorbate and heat exchanger metal are assumed to be individually momentarily at the same temperature. Eq. (4) presents the refrigerant mass balance in the evaporator taking into account no flow condition in case of heat and mass recovery.

$$\begin{aligned}&\Big(\zeta M_{\mathrm{bed-w}} C_{\mathrm{w}}(T_{\mathrm{bed}}) + M_{\mathrm{sg}} w_{\mathrm{sg}} \mathrm{Cp}_{\mathrm{ref}}(T_{\mathrm{bed}}) + M_{\mathrm{sg}} C_{\mathrm{sg}} \\ &\quad + M_{\mathrm{bed-met}} C_{\mathrm{bed-met}}\Big) \mathrm{d}T_{\mathrm{bed}}/\mathrm{d}t \\ &\quad = (1-\zeta) \sum_{n=1}^{n=N_{\mathrm{bed}}} dUA_{\mathrm{bed}-n} \times \mathrm{LMTD}_{\mathrm{bed}} + (\phi \bullet \partial)\big[\gamma\{h_{\mathrm{g}}(T_{\mathrm{Hex}}) \\ &\qquad - h_{\mathrm{g}}(P_{\mathrm{Hex}}, T_{\mathrm{bed}})\} + (1-\gamma)\{h_{\mathrm{g}}(P_{\mathrm{Hex}}, T_{\mathrm{Hex}}) - h_{\mathrm{g}}(P_{\mathrm{bed}}, T_{\mathrm{bed}}) \\ &\qquad \times\}\big] M_{\mathrm{sg}} \mathrm{d}w_{\mathrm{sg}}/\mathrm{d}t + \phi M_{\mathrm{sg}} \Delta H_{\mathrm{sg}} \mathrm{d}w_{\mathrm{sg}}/\mathrm{d}t\end{aligned} \tag{1}$$

$$\begin{aligned}&\Big[\mathrm{Cp}_{\mathrm{ref,f}}(T_{\mathrm{evap}}) M_{\mathrm{ref,evap}} + C_{\mathrm{evap-met}} M_{\mathrm{evap-met}}\Big] \mathrm{d}T_{\mathrm{evap}}/\mathrm{d}t \\ &\quad = \mathrm{UA}_{\mathrm{evap}} \times \mathrm{LMTD}_{\mathrm{evap}} + \phi\Big[h_{\mathrm{ref,evap,in}} \\ &\qquad - h_{\mathrm{ref,evap,out}}\Big] M_{\mathrm{sg}} \mathrm{d}w_{\mathrm{sg}}/\mathrm{d}t + \mathrm{d}E_{\mathrm{pump}}/\mathrm{d}t\end{aligned} \tag{2}$$

$$\begin{aligned}&\Big[\mathrm{Cp}_{\mathrm{ref,l}}(T_{\mathrm{cond}}) M_{\mathrm{ref,cond}} + C_{\mathrm{cond-met}} M_{\mathrm{cond-met}}\Big] \mathrm{d}T_{\mathrm{cond}}/\mathrm{d}t \\ &\quad = \mathrm{UA}_{\mathrm{cond}} \times \mathrm{LMTD}_{\mathrm{cond}} + \phi\Big[\Big(h_{\mathrm{ref,cond,l}} - h_{\mathrm{ref,cond,g}}\Big) \\ &\qquad + \mathrm{Cp}_{\mathrm{ref}}(T_{\mathrm{cond}} - T_{\mathrm{bed}})\Big] M_{\mathrm{sg}} \mathrm{d}w_{\mathrm{sg}}/\mathrm{d}t\end{aligned} \tag{3}$$

$$\mathrm{d}M_{\mathrm{ref,f,evap}}/\mathrm{d}t = -\phi \cdot M_{\mathrm{sg}}(\mathrm{d}w_{\mathrm{des}}/\mathrm{d}t + \mathrm{d}w_{\mathrm{ads}}/\mathrm{d}t) \tag{4}$$

where M, C, Cp, T, LMTD, P, h, w, ΔH_{ads} and t are the mass, specific heat, specific heat at constant pressure, temperature, log mean temperature difference, pressure, specific enthalpy, uptake value, isosteric heat of adsorption, and time respectively. The subscripts bed, evap and cond refer to adsorbent bed (ads/des), evaporator and condenser condition respectively and w, sg, ref and met refer to water, silica gel, refrigerant and metal respectively. Subscripts g, f, refer to fluid vapour and liquid condition respectively and Hex

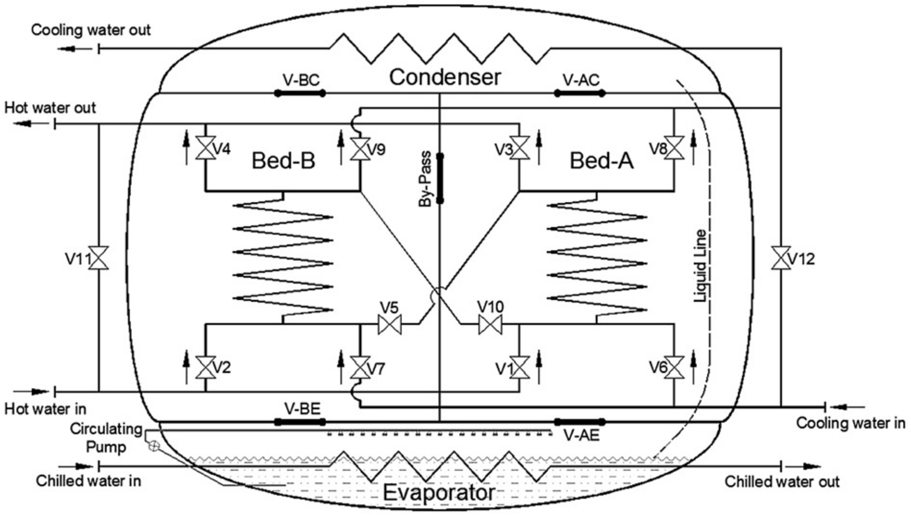

Fig. 1. Schematic diagram for simulated two-bed cycle adsorption heat pump.