Energy 78 (2014) 304–312

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Dynamic behaviors of adsorption chiller: Effects of the silica gel grain size and layers

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ARTICLE INFO

Article history:
Received 25 June 2014
Received in revised form
3 October 2014
Accepted 4 October 2014
Available online 6 November 2014

Keywords:
Adsorption
Adsorbent layers
Cooling
Grain size
Waste heat recovery

ABSTRACT

This article presents the dynamic behaviour of a single effect two bed adsorption chiller employing adsorbent beds with various layers of loose grain configurations and silica gel particle sizes, which is based on the experimentally confirmed adsorption isotherms and kinetics data. Compared with the experimental data of conventional adsorption chiller based on RD silica gel-water pair, we found that the silica gel configuration in terms of layers and sizes provides an interesting result, that is, the "grain size sensitive" regime is realized for large adsorbent grains with more layers. From numerical simulation, it is found that the specific cooling power and the coefficient of performance are reduced and the peak chilled water temperatures are increased with increasing the grain size and grain layers. We also demonstrate here that the sizes and layers of adsorbents should be considered for the design of adsorption heat exchanger for adsorption cooling applications.

1. Introduction

The advancement of adsorption chiller is based on the thermal compression of natural working refrigerants such as water and depends on the nature of porous adsorbents in terms of water vapour uptakes and offtakes and the appropriate kinetics rates. The widespread acceptance of the adsorption chiller is hindered by its relatively poor performances and bulky size due to limited properties of solid adsorbents even though it is amenable to regenerative use of adsorption heat, incorporates no mechanical moving parts and generates no noise or vibration. The performances of adsorption chiller depend mainly on the nature of adsorption isotherms, kinetics and the isosteric heat of adsorption of adsorbent-adsorbate pairs. Up to now, numerous investigations are reported on various adsorption system configurations, experimental investigations and mathematical modelling of adsorption cycles [1–10], and the isotherms and kinetics of various adsorbent-adsorbate pairs such as silica gel-water, zeolite-water, silica gel-methanol, activated carbon-methanol, activated charcoal-NH_3, zeolite-CO_2, MOFs-water etc. [11–22], from which it is understood that (i) the Freundlich, Tóth and Dubinin–Astakhov equations are mainly used for describing the amount of adsorbate uptakes for various pressures and temperatures, (ii) the enthalpy of adsorption derived from the isosteric chart of adsorbent-adsorbate pair in the Clausius–Clapeyron coordinates is used to calculate the theoretical maximum COP (coefficient of performance) and (iii) adsorption kinetics approximated by the LDF (linear driving force) model are used to calculated the dynamic behaviour of adsorption chiller [23–25]. All these information are needed to model and simulate an adsorption chiller. Silica gels and zeolites are mainly used as adsorbents for adsorption chiller purposes. However recently a new family of composite sorbents called SWSs (selective water sorbents) based on a porous host matrix (silica, alumina, etc.) and an inorganic salt ($CaCl_2$, LiBr, $MgCl_2$, $MgSO_4$, $Ca(NO_3)_2$, etc.) impregnated inside pores [26–29] has been presented for sorption cooling and heat pumping [2,26]. Among the different SWSs, the SWS-1L ("$CaCl_2$ confined to KSK silica gel") shows very high water sorption capacity (up to 0.7 g of water per 1 g of dry adsorbent) [26].

It is found experimentally that very simple monolayer configuration of loose adsorbent grains results in a quite fast adsorption

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http://dx.doi.org/10.1016/j.energy.2014.10.015
0360-5442/

dynamics and large specific cooling power [30,31]. Experimental desorption rate is also found to be faster than appropriate adsorption rate by a factor of 2.2–3.5. The size (d_p) of silica gel grains was found to be a powerful tool to manage the dynamics of isobaric water ad-/desorption [31]. For large grains (>0.5 mm), the characteristic time for adsorption and desorption was strongly dependent on the adsorbent grain size and is found to be proportional to d_p^2 that is in accordance with the LDF model. For smaller silica grains, the maximum specific cooling power can exceed 5 kW/kg, which is very attractive for designing compact adsorption chiller as a monolayer configuration of loose silica gel grains provides quite fast adsorption dynamics. However, it is expected that employing the present configuration of adsorption chiller as displayed in Table 1, the COP (coefficient of performance) is not optimal as the mass of adsorbent housed in the monolayer is small as compared with the inert masses of adsorption bed unit. Because of this, the design with more than one layer is more realistic. So, the investigation of adsorption dynamics in a thin bed containing a small number n of loose grain layers ($1 < n < 10$) is of high practical interest [31–33].

Experimental tests confirmed the promising properties of loose grains configurations of silica gel [31,32]. It can be shown that the use of various loose grains silica gel designs in the sorption bed allows significant effects on COP and cooling capacity of adsorption chiller even though the gross COP is affected by heat losses, the heat capacity of the inert masses and the heat exchangers efficiency which are not optimised in the unit tested. The authors mentioned that both the COP and cooling power are expected to be further improved in the multi-bed system with internal heat recovery and well-designed heat-exchanger with optimised silica gel grains configuration including particle sizes and layers. The aim of this study is to analyse the performances of adsorption chiller employing the dynamic behaviours of various silica gel grains arrangements with respect to the silica gel sizes and layers in more optimized configuration similar to that used in commercial adsorption chillers. Building from the previous works, this article presents both the steady-state and dynamic behaviours of various configurations of silica gel in a two-bed solid sorption cooling system using a transient distributed model. These results are compared with those of commercial adsorption cooler based on silica gel Fuji RD such that a device with various adsorbent sizes and layers for new generation of cooling can be enlightened commercially. Both the heat and mass transfer resistances of the adsorption heat exchanger as well as the temporal energetic behaviour in the evaporator and condenser are also taken into account in a distributed manner in the present model. In this paper, we also compare the present simulation results with the experimental data.

Table 1
The characteristic sorption times during adsorption/desorption periods for the two boundary conditions (50 = >30 °C and 58 = >80 °C) with various silica gel grain sizes and layers.

Grain size, mm	Adsorption/Desorption (°C)	Layers	τ	$\tau^{0.5}$
0.2–0.25	50 = >30	1	13.3	8.00
		2	17.0	11.0
		4	26.0	22.7
		8	38.0	45.1
	58 = >80	1	6.20	4.20
		2	6.20	4.40
		4	12.0	9.10
		8	21.0	20.5
0.4–0.5	50 = >30	1	18.0	11.5
		2	30.0	20.1
		4	86.0	58.7
	58 = >80	1	6.70	4.70
		2	13.5	9.10
		4	42.1	29.1
0.8–0.9	50 = >30	1	47.3	31.2
		2	100	65.1
		4	200	145
	58 = >80	1	16.5	11.1
		2	45.0	13.3
		4	115	79.0
1.6–1.8	50 = >30	1	182	112
		2	316	225
		4	588	380
	58 = >80	1	64.0	42.8
		2	169	116
		4	310	216

2. Mathematical modelling of adsorption chiller

It is well known that the adsorption chiller utilizes the adsorbent-adsorbate characteristics to produce the useful cooling effects at the evaporator by the union of “adsorption-triggered-evaporation” and “desorption-activated-condensation” and these are described elsewhere [14–16]. Fig. 1 shows the schematic layout of the adsorption chiller that comprises the evaporator, the condenser and the reactors or adsorbent beds. For continuous cooling operation, firstly a low-pressure refrigerant (hence water) is evaporated at the evaporator due to external cooling load (or chilled water) and is adsorbed into the solid adsorbent located in the adsorber, and these phenomena as shown in Fig. 2(a) with respect to control volume approach are represented mathematically in the following way.

At the evaporator, the chilled water is supplied through the heat exchanging tubes in the evaporator. The energy balance equation on the chilled water control volume is written as

$$\rho_f^{\text{chill}} c_{p,f}^{\text{chill}} \frac{\partial T^{\text{chill}}}{\partial t} = -u_f^{\text{chill}} \rho_f^{\text{chill}} c_{p,f}^{\text{chill}} \frac{\partial T^{\text{chill}}}{\partial z} + \lambda_f^{\text{chill}} \frac{\partial^2 T^{\text{chill}}}{\partial z^2} - \frac{4h_i}{d_{m,i}} \left(T^{\text{chill}} - T^{\text{evap}}\right) \quad (1)$$

The boundary conditions of the chilled water tube are $T^{\text{chill}}(z=0,t) = T^{\text{chill,in}}$ and $\partial T^{\text{chill}}/\partial z(z=L^{\text{tube}},t) = 0$. The heat of chilled water, which activates the enthalpy of evaporation, is absorbed at the refrigerant of the evaporator through the heat exchanger metal tubes. So the energy balance of the metal tube should be taken into account, and the energy balance equation is written as:

$$\rho_m c_{p,m} \frac{\partial T_m^{\text{evap}}}{\partial t} \frac{\left(d_{m,o}^2 - d_{m,i}^2\right)}{4} = \lambda_m \frac{\partial^2 T_m^{\text{evap}}}{\partial z^2} \frac{\left(d_{m,o}^2 - d_{m,i}^2\right)}{4} + d_{m,i} h_i \left(T^{\text{chill}} - T_m^{\text{evap}}\right) - d_{m,o} h_o \left(T_m^{\text{evap}} - T^{\text{evap}}\right) \quad (2)$$

Pool boiling is affected on the water refrigerant outside the heat exchanging tube in the evaporator by the vapour uptake at the adsorber. In that case, the mass and energy balance equations become

$$\frac{\mathrm{d}m^{\text{evap}}}{\mathrm{d}t} = \dot{m}_{\text{vap}}^{\text{cond}} - \dot{m}_{\text{vap}}^{\text{evap}}, \text{ and} \quad (3)$$

$$\rho \forall^{\text{evap}} c_p^{\text{evap}} \frac{\partial T^{evap}}{\partial t} = \frac{\mathrm{d}m^{\text{cond}}}{\mathrm{d}t} h_f \left(T^{\text{cond}}\right) - \dot{m}_{\text{vap}}^{\text{evap}} h_{\text{fg}}(T^{\text{evap}}) - (\pi d_{m,o} L) h_o \left(T_m^{\text{evap}} - T^{\text{evap}}\right), \quad (4)$$

where $(\rho \forall^{\text{evap}} c_p^{\text{evap}})$ is the sum of all mass capacities of the evaporator and the first term of the right hand side of Equation (4) indicates the amount of condensate (refrigerant) that is refluxed back