

Analysis of Thermal Conductance on a Two Stage Adsorption Chiller

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Abstract

Silica gel/water based adsorption cycles have a distinct advantage in their ability to be driven by heat of relatively low, near environment temperature so that waste heat below 100°C can be recovered, which is highly desirable. One interesting feature of refrigeration cycles driven by waste heat is that they do not use electricity or fossil fuels as driving sources and hence are energy savers. From this context, many researchers investigated the performance of advanced adsorption refrigeration cycle which can be operated by the heat source of near ambient temperature (60°C) with the cooling source temperature 30°C. However, performances of that system are very low. From this point of view, an analytic investigation on a two stage chiller using re-heat is performed to clarify the effect of overall thermal conductance of adsorber/desorber and evaporator as well as thermal capacitance ratio of the adsorbent and inert metal of an adsorber/desorber heat exchanger on chiller performance. Results show that cycle performance is strongly influenced by the adsorber/desorber overall thermal conductance values due to their severe sensible heating and cooling requirements resulting from batched cycle operation.

Keywords: *Adsorption chiller, Two-stage cycle, Re-heat scheme, Silica gel, Water*

Introduction

The use of waste heat at near environment temperature is an important contemporary problem. Heat driven sorption (absorption or adsorption) cycle is one of the promising candidates to utilize waste heat at near environment temperature. Though the absorption cycles are predominant in the area of heat driven refrigeration cycles, adsorption cycle has a distinct advantage over other thermally powered systems in their ability to be driven by relatively low heat source temperature so that waste heat below 100°C can be recovered, which is highly desirable.

In the last three decades, extensive investigations on the performances of adsorption refrigeration/heat pump system have been conducted considering various adsorbent/adsorbate pairs such as activated carbon/ammonia (Critoph and Vogel 1986), zeolite/

water (Karagiorgas and Meunier 1987), activated carbon/methanol (Critoph 1989) and silica gel/water (Chua et al. 1999). Utilizing silica gel/water pair, Saha et al. (2001) introduced a two stage chiller to utilize waste heat of temperature around 55°C along with a coolant of temperature 30°C. The driving heat source temperature of the two-stage cycle is validated experimentally. Recently, Alam et al. (2003) proposed and analyzed a re-heat two-stage adsorption chiller, which can be operated with driving heat source of temperature between 50 and 90°C along with a heat sink of temperature 30°C.

It is assumed that the performance of a re-heat two stage adsorption chiller is highly dependent on the heat transfer characteristics of adsorber/desorber heat exchangers. From this viewpoint, a silica gel/water, re-heat two-stage adsorption chiller is analyzed to determine the influence of sorption element overall thermal conductance and silica gel mass on the chiller cooling capacity and COP.

Working principle of re-heat two-stage chiller

The re-heat two-stage chiller comprises with four adsorbent beds, one condenser, one evaporator, and metallic tubes for heat transfer fluid (hot and cooling water) flows. The schematic of the re-heat two-stage chiller is shown in Fig. 1. In the two-stage adsorption chiller, the pressure lift between the evaporator and condenser is divided into two consecutive pressure lifts to exploit low temperature heat source by introducing four adsorbent beds. In the re-heat two-stage chiller the same pressure (that is equivalent to temperature) lift, however, can be divided into different ways as opposed to the basic two-stage chiller. If one bed is in the end position of adsorption-evaporation process and another bed is in the end position of desorption-condensation process; these two beds can be connected with each other by continuing cooling and heating. At the same time, remaining two beds are also connected, one with the condenser and the other with the evaporator to obtain continuous condensation and cooling effect, respectively. To complete one cycle, chiller needs 10 steps (cycle A to J). The states of the all four sorption

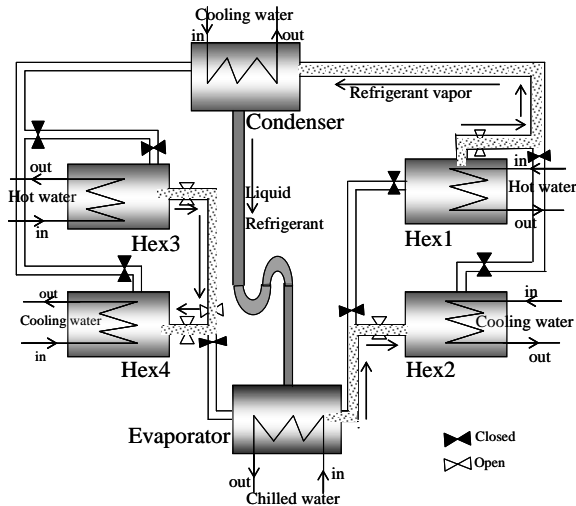


Fig. 1 Schematic of the re-heat two stage chiller

Table 1: Operational strategy of the chiller

Mode	A	B	C	D	E	F	G	H	I	J
Hex1	Desorption	Desorption	Desorption	Desorption	Desorption	Desorption	Desorption	Desorption	Desorption	Desorption
Hex2	Adsorption	Adsorption	Adsorption	Adsorption	Adsorption	Adsorption	Adsorption	Adsorption	Adsorption	Adsorption
Hex3	Pre-cooling	Pre-cooling	Pre-cooling	Pre-cooling	Pre-cooling	Pre-cooling	Pre-cooling	Pre-cooling	Pre-cooling	Pre-cooling
Hex4	Pre-heating	Pre-heating	Pre-heating	Pre-heating	Pre-heating	Pre-heating	Pre-heating	Pre-heating	Pre-heating	Pre-heating

Desorption
 Mass recovery with heating
 Pre-cooling
 Adsorption
 Mass recovery with cooling
 Pre-heating

elements in the re-heat two-stage chiller are shown in Table 1. The detail working principles of the re-heat two stage chiller can be found elsewhere (Alam et al. 2003).

Mathematical formalism

The heat transfer and energy balance equations for the adsorbent beds can be described as follows:

$$T_{out} = T + (T_{in} - T) \exp\left(-\frac{UA_{hex}}{\dot{m}_w C_w}\right) \quad (1)$$

$$\frac{d}{dt} \{(W_s C_s + W_s C_w q + W_{hex} C_{hex})T\} = W_s Q_{st} \frac{dq}{dt} - \delta \cdot W_s C_{wv} \{\gamma(T - T_{eva}) + (1 - \gamma)(T - T_{wv})\} \frac{dq}{dt} + \dot{m}_w C_w (T_{in} - T_{out}) \quad (2)$$

Where, δ is either 0 or 1 depending whether the adsorbent bed is working as a desorber or an adsorber and γ is either 1 or 0 depending on whether the adsorbent bed is connected with the evaporator or

another adsorbent bed.

The heat transfer and energy balance equations for the evaporator can be described as:

$$T_{chill,out} = T_{eva} + (T_{chill,in} - T_{eva}) \exp\left(-\frac{UA_{eva}}{\dot{m}_{chill} C_{chill}}\right) \quad (3)$$

$$\frac{d}{dt} \{(W_{eva,w} C_w + W_{eva,hex} C_{eva,hex})T_{eva}\} = -LW_s \frac{dq_{ads}}{dt} - W_s C_w (T_{con} - T_{eva}) \frac{dq_{des}}{dt} + \dot{m}_{chill} C_{chill} (T_{chill,in} - T_{chill,out}) \quad (4)$$

The heat transfer and energy balance equations for the condenser can be written as:

$$T_{cond,out} = T_{cond} + (T_{cw,in} - T_{cond}) \exp\left(-\frac{UA_{cond}}{\dot{m}_{cw} C_w}\right) \quad (5)$$

$$\frac{d}{dt} \{(W_{cw,w} C_w + W_{cond,hex} C_{cond,hex})T_{cond}\} = -LW_s \frac{dq_{des}}{dt} - W_s C_{wv} (T_{des} - T_{cond}) \frac{dq_{des}}{dt} + \dot{m}_{cw} C_w (T_{cw,in} - T_{cw,out}) \quad (6)$$

The mass balance for the refrigerant can be expressed as:

$$\frac{dW_{eva,w}}{dt} = -W_s \left(\frac{dq_{des-cond}}{dt} + \frac{dq_{eva-ads}}{dt} \right) \quad (7)$$

Where, the subscripts *des-cond* and *eva-ads* stand for the refrigerant vapor flow from desorber to condenser and evaporator to adsorber, respectively. The silica gel/water property model is similar to the model used by Alam et al. (2004). The adsorption equilibrium equation for silica gel/water pair is written as:

$$q^* = \{0.8 \times [P_s(T_w) / P_s(T_s)]\} / \{1 + 0.5 \times [P_s(T_w) / P_s(T_s)]\}$$

System performance measurement

The cooling capacity and COP of the re-heat two-stage adsorption chiller can be described as:

Cooling Capacity =

$$\frac{\dot{m}_{chill} C_w \int_0^{t_{cycle}} (T_{chill,in} - T_{chill,out}) dt}{t_{cycle}}$$

$$COP = \frac{\dot{m}_{chill} C_w \int_0^{t_{cycle}} (T_{chill,in} - T_{chill,out}) dt}{\dot{m}_{hot} C_w \int_0^{t_{cycle}} (T_{hot,in} - T_{hot,out}) dt}$$

Results and discussion

In the present analysis, the system of differential equations (1)–(7) are solved by finite difference approximation with time step of one second. In the numerical solution of the differential equations, successive substitutions of the newly calculated values were used, with the iterative loop repeating the calculations until the convergence test is satisfied. The convergence factor is taken as 0.001 for all parameters. The base line parameters and standard operating conditions for the chiller operation are listed in Table 2 and Table 3, respectively.

Figure 2(a) shows the simulated P-T-X diagram for the standard operating conditions, where heat source temperature is 80°C. In Fig. 2(a) the various parts of a complete cycle are designated by numbers, adsorption (1→2), mass recovery process with cooling (2→3), pre-heating (3→4), desorption (4→5), mass recovery process with heating (5→6) and pre-cooling (6→1). It is observed from Fig. 2(a) that the adsorbent (silica gel) temperature at the end of adsorption is about 4°C higher than the cooling water inlet temperature, and at the end of desorption, it is about 5°C lower than the hot water inlet temperature.

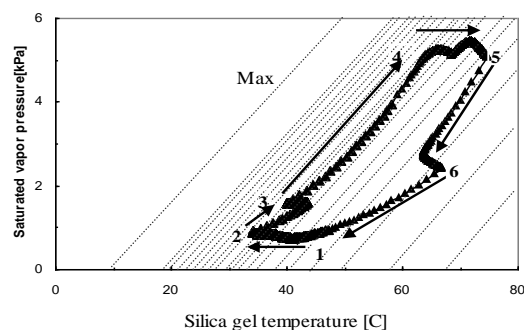


Fig. 2(a) P-T-X diagram of re-heat two stage chiller

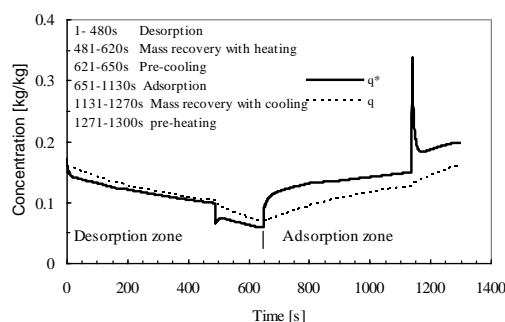


Fig. 2(b) Concentration as a function of time

Table 2: Baseline Parameters

Symbol	Value	Unit
C_s	924	J / kg. K
C_w	4.18E+3	J / kg. K
C_{chill}	4.20E+3	J / kg. K
C_{wv}	4.19E+3	J / kg. K
L	2.50E+6	J / kg
$U A_{ads}$	2497.6	W / K
$U A_{des}$	2532.5	W / K
$U A_{cond}$	2404.3	W / K
$U A_{eva}$	989.9	W / K
Q_{st}	2.80E+6	J / kg
W_s	16	kg
W_{cw}	5	kg
$W_{eva,w}$	25	kg

Table 3: Standard operating condition

	Temperature (°C)	Flow rate (kg/s)
Hot water	80(short cycle) 60 (long cycle)	0.5
Cooling water	30	0.5(ads)+0.3(cond)
Chilled water	14	0.3
Short cycle	1300s= 480ads/des+140mr+30ph/pc)s×2	
Long cycle	3400s=(870ads/des+800mr+30ph/pc)s×2	

Ads/des = adsorption/desorption, mr = mass recovery, ph/pc = pre-heat/pre-cool

This occurs because the sorption elements must periodically switch between adsorption and desorption operations within a relatively short time interval (650s for the designated short cycle and 1700s for the designated long cycle). It is also seen that mass recovery process for the present design increases the difference between maximum and minimum concentration levels that improves the cooling capacity of the system, which will be discussed in the following subsection. Figure 2(b) shows how the concentration of the sorption element varies with the cycle time. The equilibrium concentration (q^*) varies between 34 to 6% and the difference between maximum and minimum equilibrium concentration for the mass recovery process is highest. However, real concentration varies steadily over the whole cycle time. This happens because saturation pressure in the adsorbent bed changes suddenly with big difference during mass recovery process. However, real concentration is not only depends on saturation pressure but also on time. Therefore, real concentration changes steadily.

UA in the Figures as the meaning of UA is mentioned in the paper. In Figs. 3(a)-(b) and 3(c)-(d), numerical values of cooling capacity and COP are depicted, respectively, against the sorption element overall thermal conductance which varies from 250 to 10000 W/K for both short cycle and long cycle times. Alam et al. (2003) demonstrated that short cycle time works effectively for relatively higher heat source temperature (above 65°C) and long cycle time works well for relatively lower heat source

temperature (below 65°C). Therefore, we select short cycle with heat source temperature at 80°C and long cycle with heat source temperature at 60°C. Overall thermal conductance values of evaporator and condenser are also kept at constant values (base line conditions as shown in Table 2). Four lines are depicted for different amount of adsorbent mass namely, 8, 16, 32 and 64 kg. From Figs. 3a and 3c, it is seen that the cooling capacity increases with the increase of silica gel mass from 8 to 32 kg. However, cooling capacity decreases when silica gel mass increases from 32 to 64 kg. One interesting observation is that the cooling capacity increases up to 36% (short cycle), 53% (long cycle) when silica gel mass increases from 8 to 16 kg and it increases only 15% (short cycle), 24% (long cycle) when silica gel mass increases from 16 to 32 kg. This causes because of the fixed external parameters (heat transfer fluid temperatures and flow rates). In the present treatment, 16 kg of silica gel is taken as standard and the associated external parameters are taken accordingly. Cooling capacity for 16 kg

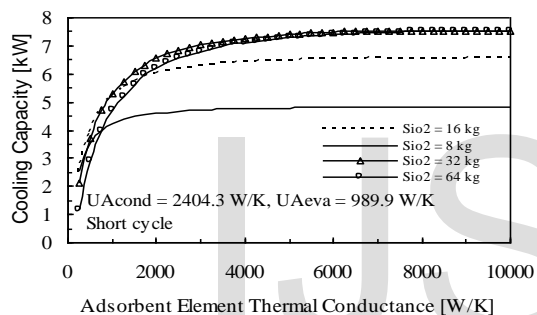


Fig.3(a) The effect of adsorbent element overall thermal conductance on cooling capacity.

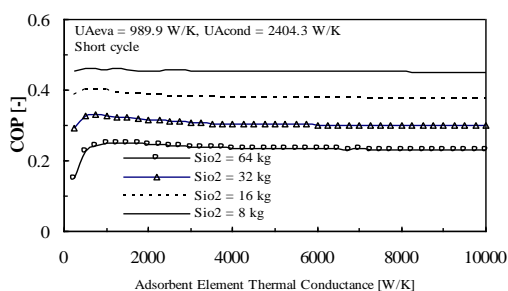


Fig.3(b) The effect of adsorbent element overall thermal conductance on COP.

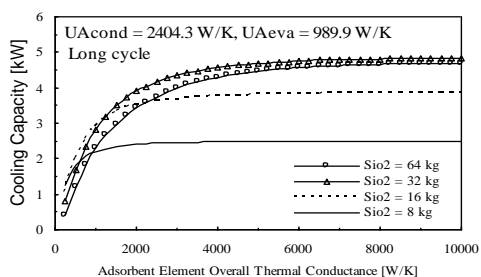


Fig.3(c) The effect of adsorbent element overall thermal conductance on cooling capacity.

silica gel is higher than that for other silica gel masses (for both short and long cycles), when sorption element overall thermal conductance varies from 250 to 1700 W/K (Figs. 3a and 3c). It is also seen that COP (Figs. 3b and 3d) increases with the decrease of silica gel mass, the reason is that low amount of silica gel requires relatively less heat input; however, the specific cooling production (kW/kg) for low amount of silica gel is relatively higher than that for relatively large amount of silica gel.

In Fig. 4, mass of silica gel varies from 4 to 100 kg. It is seen from Fig. 4 that cooling capacity increases substantially in the ranges of silica gel masses between 4 and 16 kg for UAads equals to 1000W/K, between 4 and 25 kg for UAads equals to 3000W/K and between 4 and 30 kg for UAads equals to both 5000W/K and 7000W/K. The reason is that, the overall thermal conductance of condenser and evaporator is relatively high for the silica gel mass, since overall thermal conductance of condenser and evaporator are kept at constant values in the whole region studied in the present paper. On the other hand, for adsorbent mass higher than 20 kg for UAads equal to 1000W/K and higher than 36 kg for UAads equal to 3000W/K, 5000W/K and 7000W/K, it is seen that cooling capacity decreases with the increase of silica gel mass. This tendency is attributed mainly to the fact that base line values are applied for the overall thermal conductance of heat exchangers become relatively low when the silica gel mass is increased as shown in Fig. 4. It is observed from Fig. 4 that for UAads equal to 3000W/K, if standard amount of silica gel is equal to 16 kg instead of 4 kg, cooling capacity gains 158%. On the other hand, for

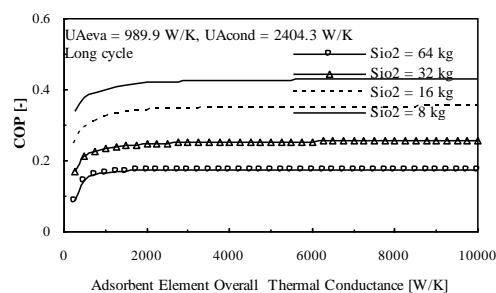


Fig.3(d) The effect of adsorbent element overall thermal conductance on COP.

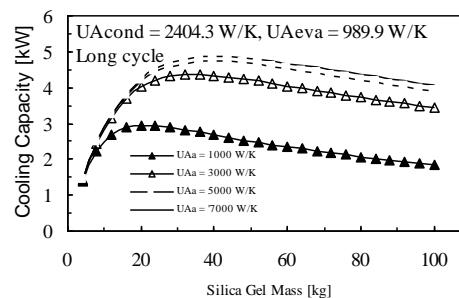


Fig. 4 The effect of adsorbent mass on cooling capacity.

same UAads equal to 3000W/K, if standard amount of silica gel is equal to 24 kg instead of 16 kg, cooling capacity gains only 14%. Therefore, it may be concluded here that 16 kg silica gel is suitable for the present base line conditions. It is also noted that standard amount of adsorbent (silica gel) will be changed if other parameters and operating conditions will be changed. From the above figures, it may be seen that sorption element overall thermal conductance value greater than 5000 W/K and silica gel mass higher than 40 kg are no longer beneficial.

Conclusions

The effect of sorption element overall thermal conductance and silica gel mass on the performance of a re-heat two stage chiller has been investigated numerically. From the present study, it may be concluded that the proposed strategy of mass recovery process improves mass circulation inside all four sorption elements, which results in cooling capacity improvement. For the present baseline conditions, the chiller presents best cooling capacity if sorption element overall thermal conductance (UA) value is less than 1700 W/K with silica gel mass of 16 kg. It is also observed that COP increases with the decrease of silica gel mass. In the present design and operating conditions, sorption element overall thermal conductance greater than 5000 W/K and silica gel mass higher than 40 kg is no longer effective.

Nomenclature

A	area (m ²)
C	specific heat (Jkg ⁻¹ K ⁻¹)
L	latent heat of vaporization (Jkg ⁻¹)
\dot{m}	mass flow rate (kg s ⁻¹)
P _s	saturated vapor pressure (Pa)
q	concentration (kg / kg)
q _*	concentration equilibrium (kg / kg)
Q _{st}	isosteric heat of adsorption (Jkg ⁻¹)
T	temperature (K)
t	time (s)
U	heat transfer coefficient (Wm ⁻² K ⁻¹)
W	weight (kg)

Subscripts

ads	adsorber, adsorption
cond	condenser
chill	chilled water
cw	cooling water
des	desorber, desorption
eva	evaporator
hex	heat exchanger
hw	hot water
in	inlet

out	outlet
s	silica gel
w	water
wv	water vapor

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