

## **Performance Investigation on Advanced Adsorption Cycle**

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*Received October 19, 2012; accepted December 18, 2012*

### **ABSTRACT**

Adsorption chiller has lower environmental impact and large energy saving potential, because the system does not use the fossil fuel and electricity as driving source. Especially, the cycle with silica gel-water pair can use the heat at temperatures below 85°C as driving source. Waste heat of near environmental temperature can be utilized to drive the adsorption refrigeration cycle. In the adsorption chiller, it is important that which material is selected for adsorbent-adsorbate pair. Water, methanol or ammonia has been used as adsorbate, and silica-gel, zeolite or activated carbon has been combined with the adsorbate as adsorbent. The present study, silica gel-water pair has been selected as adsorbent-adsorbate pair. A cycle simulation computer program of the three-stage chiller using re-heat scheme is developed to improve the cooling effect comparing with conventional three-stage chiller. Simulation results show that the cooling capacity for the re-heat three-stage scheme is about 20% higher than that of the three-stage cycle with the same operation conditions.

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

**AMS Mathematics Subject Classification (2010):**

**Nomenclature**

A	area ( $\text{m}^2$ )	ads	adsorber, adsorption
C	specific heat ( $\text{Jkg}^{-1}\text{K}^{-1}$ )	cond	condenser
L	latent heat of vaporization ( $\text{Jkg}^{-1}$ )	chill	chilled water
$\dot{m}$	mass flow rate ( $\text{kgs}^{-1}$ )	cw	cooling water
$P_s$	saturated vapor pressure (Pa)	des	desorber, desorption
$q$	concentration (kg / kg)	eva	evaporator
$q^*$	concentration equilibrium (kg / kg)	Hex(SE)	heat exchanger
$Q_{st}$	isosteric heat of adsorption ( $\text{Jkg}^{-1}$ )	hw	hot water
T	temperature (K)	in	inlet
t	time (s)	out	outlet
U	heat transfer coefficient ( $\text{Wm}^{-2}\text{K}^{-1}$ )	s	silica gel
W	weight (kg)	se	sorption element
		w	water
		wv	water vapor

**1. Introduction**

In recent years adsorption refrigeration technology has been attracting considerable attentions because it can save energy and is environmentally benign. Adsorption cycles can be driven by low-grade waste heat or solar energy below  $100^\circ\text{C}$ . Being low-temperature waste heat driven, the coefficient of performance (COP) of the thermally driven adsorption systems is low, which is classified by Ng [1]. Therefore, there is a need to explore various thermal utilization schemes. They do not use ozone-depleting chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs) and do not need electricity or fossil fuels as driving sources.

A silica gel–water adsorption chiller driven by the waste heat source has been successfully commercialized in Japan, as reported by Saha et al. [2]. Khan et al. [3] developed mass recovery three bed silica gel–water adsorption chiller having higher performance. Saha et al. [4] also developed a three-stage adsorption chiller which utilized about  $50^\circ\text{C}$  waste heat as the driving source and  $30^\circ\text{C}$  cooling water as the cooling source. K.C. Alam et al. [5] developed a two-stage adsorption refrigeration chiller prototype driven by heat source temperature from  $53$  to  $61^\circ\text{C}$  with the evaporator and condenser temperatures at  $7$  and  $30^\circ\text{C}$ , respectively. Recently Saha et al. [6] introduced a novel electro-adsorption chiller (EAC) amalgamating two individually low Coefficient-of-Performance (COP) cycles into

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a combined cycle, which has the potential to increase the COP by several fold, and validated with results from an experimental prototype.

In this study, silica gel–water has been selected as the adsorbent/refrigerant pair because of the low regeneration temperature of silica gel and the high latent heat of vaporization of water. Additionally, this working pair is non-toxic. The present research investigates with the utilization of unexploited, near ambient temperature waste heat between 50 and 70°C as the driving heat source with a cooling source at 30°C. The influences of heat transfer fluid temperature on cooling capacity, COP and chilled water outlet temperature are determined by a cycle simulation computer program. Performances are also compared with that of the conventional three-stage chiller. In the present treatment, the performances of the proposed chiller which operational strategy is shown in Table 1 are compared with those of the three-stage chiller which operational strategy is shown in (Table 2).

### **2. Working Principle of Three-Stage Chiller Using Re-Heat Scheme**

The design criteria of three stage chiller using re-heat scheme is almost similar to that of a conventional three-stage chiller developed by Saha et al. [4]. Operational strategy of this chiller, however, is completely different from the operational strategy of a conventional three-stage chiller. In three-stage adsorption chiller, the evaporating pressure lift is divided into three consecutive pressure lifts to exploit low heat source temperature by introducing three pairs of adsorbent beds. In three-stage chiller using re-heat scheme, the evaporating pressure (temperature) lift, however, can be divided into different ways from the conventional three-stage chiller. To complete one full cycle, all beds pass through six consecutive steps: (i) desorption (ii) mass recovery process with heating (iii) pre-cooling (iv) adsorption (v) mass recovery process with cooling, and (vi) pre-heating.

The adsorbent is packed in the adsorber/desorber heat exchanger, which undergo alternate cooling and heating to allow refrigerant adsorption and desorption. In the

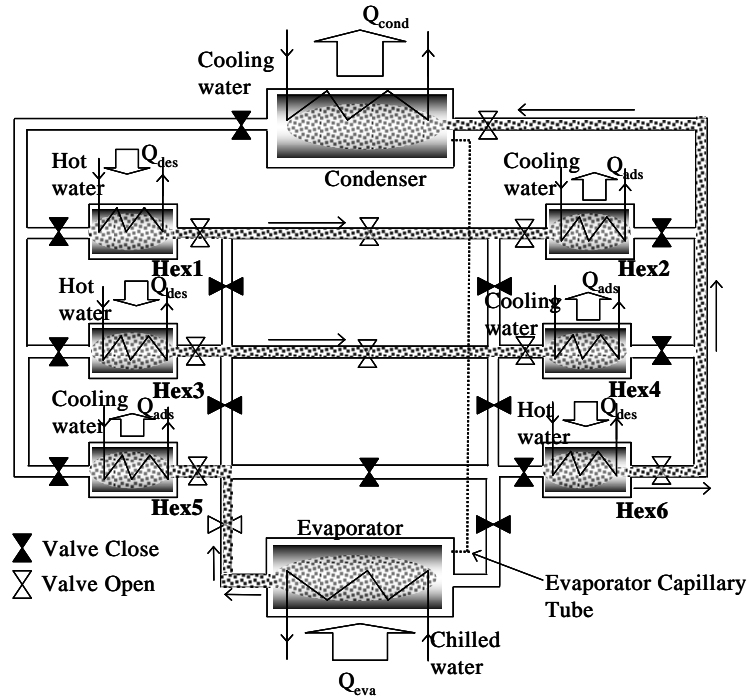


Fig. 1 Schematic of the three stage chiller using re-heat scheme

adsorption-evaporation process, refrigerant (water) in evaporator is evaporated at evaporation temperature,  $T_{eva}$ , and seized heat,  $Q_{eva}$  from chilled water. The evaporated vapor is adsorbed by the adsorbent (silica gel), at which cooling water removes the adsorption heat,  $Q_{ads}$ . The desorption-condensation process takes place at pressure ( $P_{cond}$ ). The desorber is heated up to temperature ( $T_{des}$ ) by the heat input  $Q_{des}$ , provided by the driving heat source. The resulting refrigerant is cooled down by temperature ( $T_{cond}$ ) in the condenser by the cooling water, which removes the condensation heat,  $Q_{cond}$ . The resulting condensate flows back to the evaporator via evaporator capillary tube to complete a cycle.

The three stage chiller using re-heat scheme comprises with three pairs of adsorbent beds, one condenser, one evaporator, and metallic tubes for hot water, cooling water and chilled water flows as shown in Fig. 1. In the conventional three stage chiller, lower four beds never interact with the condenser and upper four beds never interact with the evaporator, and the middle two beds never interact with evaporator or condenser. However, in the three-stage chiller using re-heat scheme,

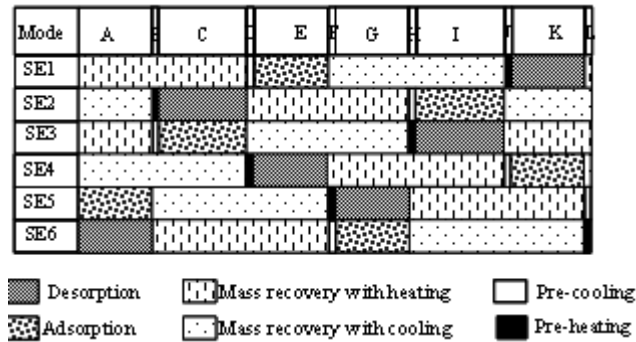
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all beds undergo through all processes and interact with the condenser and evaporator. Chiller operational strategy has been presented in Table 1 (the three-stage chiller using re-heat scheme) and Table 2 (the three-stage chiller). The values adapted in simulation are presented in Ref. [7].

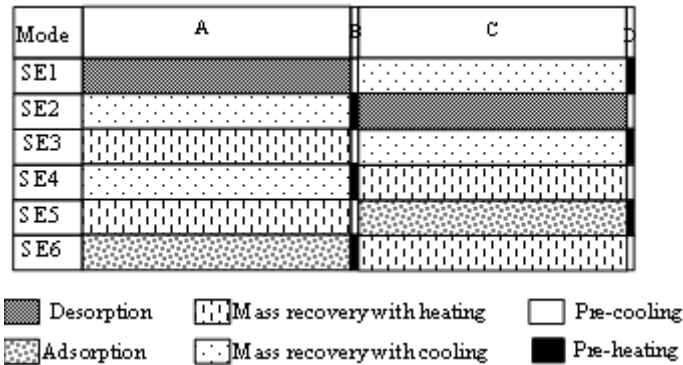
### 3. Mathematical Formalism

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

**Table 1:** Operational strategy of re-heat three stage chiller



**Table 2:** Operational strategy of three stage chiller



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

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

where,  $\delta$  is either 0 or 1 depending whether the adsorbent bed is working as a desorber or an adsorber and  $\gamma$  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:

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

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

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

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

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

The mass balance for the refrigerant can be expressed as:

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

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 Khan et al. [7]. The

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adsorption equilibrium equation for silica gel/water pair is taken as:

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

**Table 3:** Standard operating condition

	Temperature (°C)	Flow rate (kg/s)
Hot water	60	0.4
Cooling water	30	0.4(ads)+0.34(co nd)
Chilled water	14	0.11
Cycle time	810ads/des, 600mr, 30ph/pc	

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

### 4. System Performance Measurement

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

$$\text{Cooling Capacity} = \dot{m}_{\text{chill}} C_w \int_0^{t_{\text{cycle}}} (T_{\text{chill,in}} - T_{\text{chill,out}}) dt / t_{\text{cycle}}$$

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

### 5. Results and Discussion

In the present study, the system of differential equations is solved by finite difference approximation with time step of one second. The base line parameters are taken same as Ref. [7] and standard operating conditions for the chiller operation are listed in Table 3. In all Figures, RH3S and 3S mean the three stage chiller using re-heat scheme and the conventional three stage chiller, respectively.

In Fig. 2 and 3, numerical values of cooling capacity and COP are depicted against the driving heat source temperature from 50 to 70°C with cycle time 4400s only for comparison. In Fig. 2, it is seen that the cooling capacity increases with the increase of heat source temperature from 50 to 70°C. One interesting observation

is that the cooling capacity for the three-stage adsorption chiller using re-heat scheme is higher than that of the conventional three-stage adsorption chiller when heat source temperature is higher than 52°C. This causes as the long cycle time is

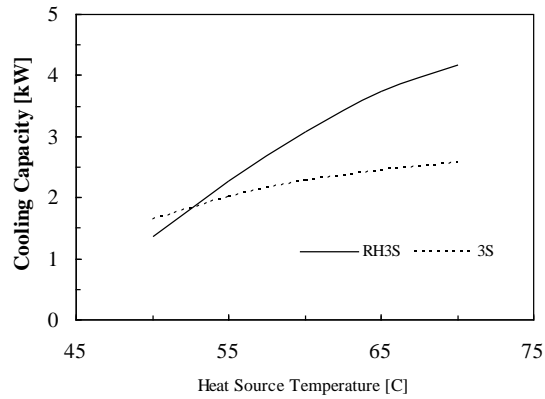


Fig. 2 The effect of heat source temperature on cooling capacity.

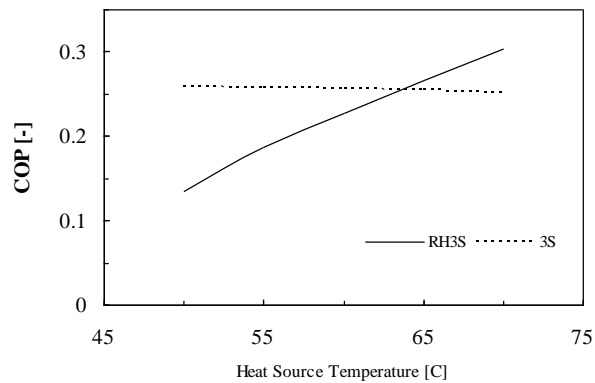


Fig. 3 The effect of heat source temperature on COP.



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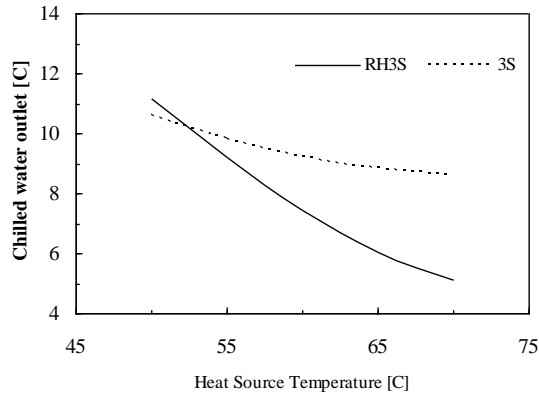


Fig. 4 The effect of heat source temperature on Chilled water outlet temperature.

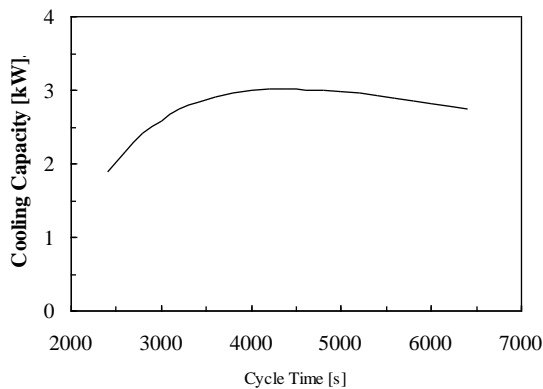


Fig. 5 The effect of cycle time on cooling capacity.

well suited for re-heat scheme. With the variation of heat source temperature in Fig. 3, COP for the three stage chiller is almost same but, for three-stage adsorption chiller using re-heat scheme is increased. COP of the proposed cycle exceeds that of the three-stage chiller when heat source temperature is higher than 64°C.

In an adsorption chiller, the chilled water for air-conditioning purposes is obtained from the outlet of the chilled water. Generally, less chilled water outlet temperature is expected, while the requirement of cooling capacity is relatively high. The chilled water outlet temperature, however, affects the cooling demand of the demand side. Therefore, the requirement of chilled water outlet temperature is very

important. Figure 4 shows the average chilled water outlet temperature with the variation of the driving heat source temperature. It can be seen that chilled water outlet temperature for three-stage adsorption chiller using re-heat scheme is lower than that of the conventional three-stage adsorption chiller when heat source temperature is higher than 52°C which causes more cooling effect (see Fig. 2). The outlet temperature of chilled water, however, can be controlled by adjusting the chilled water mass flow rate. In Fig. 4, the mass flow rate of chilled water is kept fixed at 0.11 kg/s.

Cooling capacity variations with adsorption/ desorption cycle time are depicted in Fig. 5. The sensible heating/cooling time is kept constant 30 s. The highest cooling capacity values are obtained for cycle time between 4000 and 4600 s. When cycle times are shorter than 3000 s, there is not enough time for adsorption or desorption, so cooling capacity decreases abruptly.

On the other hand, when cycle time are greater than 4800 s, cooling capacity decreases gradually as the adsorbent mass approaches to its equilibrium condition. For the proposed chiller, standard cycle time has been taken as 4400 s with 600 s for the mass recovery time.

## **6. Conclusions**

Cooling capacity of the three-stage adsorption chiller using re-heat scheme increases with the increase of heat source temperature from 50 to 70°C. Another noteworthy observation is that the cooling capacity of the proposed chiller using re-heat scheme is higher than that of the conventional three-stage adsorption chiller when heat source temperature is higher than 52°C. Chilled water outlet temperature of the proposed chiller is lower than that of the three-stage chiller when the heat source is higher than 52°C. The maximum performances are obtained for cycle time between 4000 and 4600 s.

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