

NUMERICAL STUDY OF A TWO-STAGE ADSORPTION CHILLER EMPLOYING RE-HEAT SCHEME WITH DIFFERENT MASS RATIOS

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ABSTRACT

This paper deals with the performance investigation of a silica gel/ water-based two-stage adsorption chiller employing re-heat scheme with different mass ratios and compared with that of the two-stage conventional chiller with re-heat scheme using equal mass allocation (upper bed : lower bed = 1:1). The performance of a two-stage adsorption chiller using re-heat scheme with different mass allocation between upper and lower beds have been investigated numerically. Results show that cooling capacity can be improved with the optimum allocation of adsorbent mass to the upper beds than that of lower beds. The improvement in Co-efficient of Performance (COP) values, however, is less significant. It is also seen that the improvement in cooling capacity is more significant for the relatively higher heat source temperature. It is shown that the cooling capacity can be improved up to 8% if the heat source temperature is 80°C.

Keyword: Adsorption Cycle, Two-Stage Chiller, Re-Heat, Silica Gel, Water

1. INTRODUCTION

With the increasing awareness of global warming and ozone depletion problems, adsorption refrigeration and heat pump systems have received much attention by researchers in many parts of the world; in particular, the low-temperature waste heat sources for cooling energy production. 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 absorption systems in their ability to be driven by relatively low-temperature heat source, which cannot effectively regenerate the absorption systems [1]. In the last three decades, extensive investigations on the performances of adsorption refrigeration/heat pump systems have been conducted considering various adsorbent/ refrigerant pairs, such as zeolite/ water [2], activated carbon/ammonia [3], activated carbon/methanol [4] and silica gel/water [5]. It is well known that the performance of adsorption cooling/heating system is lower than that of other heat driven heating/cooling systems specially, absorption system provided that the available heat source temperature is at 75°C or higher. Many authors proposed and/or investigated the adsorption cooling and heating system to improve the performance. To improve the coefficient of performance, Akahira et al. [6]

investigated two-bed mass recovery cycle with novel strategy, which shows that mass recovery cycle with heating/cooling improves the cooling power. To utilize low-temperature waste heat source between 40°C and 60°C, Saha et al. [7] proposed and examined experimentally a three-stage adsorption chiller with silica gel/ water pair. Saha et al. [8] introduced a two-stage adsorption chiller and the required driving heat source temperature is validated experimentally. Alam et al. [9] proposed and analyzed a re-heat two-stage adsorption chiller, which can be operated with driving heat source temperatures between 50°C and 90°C along with a coolant at 30°C. The COP of the re-heat two-stage chiller is higher than that of two-stage chiller without re-heat. Moreover, the re-heat two-stage chiller produces effective cooling even though heat source temperatures are varied between 50°C and 90°C. Recently, Khan et al. [10] studied on a re-heat two-stage adsorption chiller with silica gel/ water as adsorbent/ adsorbate pair. In the present study, the chiller investigated the effect of mass allocation between upper and bottom beds on cooling capacity (CC), Co-efficient of Performance (COP), chilled water outlet and their improvement ratios.

2. WORKING PRINCIPLE OF THE TWO-STAGE CHILLER WITH RE-HEAT SCHEME

The schematic diagram and time allocation of the two-stage chiller are shown in Fig. 1 and Table 1, respectively. The design criteria of the two-stage adsorption chiller using re-heat is almost similar to that

of a two-stage adsorption chiller without re-heat, which is developed by Alam et al. [9]. Operational strategy of the re-heat chiller is completely different from the operational strategy of a conventional two-stage without re-heat chiller. In two-stage adsorption chiller, the evaporating pressure lift is divided into two consecutive pressure lifts to exploit low heat source temperature by introducing four adsorbent beds. In the two-stage adsorption chiller using re-heat, the evaporating pressure (temperature) lift, however, can be divided into different ways from the conventional two-stage chiller. To complete one full cycle in re-heat scheme, all adsorbent 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 two-stage adsorption chiller using re-heat comprises with four adsorbent beds, one condenser, one evaporator, and metallic tubes for hot, cooling and chilled water flows as shown in Fig.1. In a conventional two-stage chiller, lower two beds never interact with the condenser and upper two beds never interact with the evaporator. However, in the two-stage adsorption chiller using re-heat, all beds undergo through all processes and interact with the condenser and evaporator. The chiller can be operated in different strategies. However, only one strategy has been considered in the present study. The chiller has 10 modes, mode A, B, C, D, E, F, G, H, I, and J. Table 1. mode A, B, and C, eva-Hex-2 is in adsorption process and cond-Hex-1 is in desorption process. In the adsorption-evaporation process, refrigerant (water) in evaporator is evaporated at evaporation temperature, T_{eva} , and seized heat, Q_{eva} from the chilled water. The evaporated vapor is adsorbed by adsorbent (silica gel), at which cooling water removes the adsorption heat, Q_{ads} . The desorber (Hex-1) is heated up to the temperature (T_{des}) by heat 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 heat, Q_{cond} . In mode A, adsorber (Hex-4) is connected with desorber (Hex-3) through pipe with continuing cooling water in Hex-4 and hot water in Hex-3. It is noted that, at the beginning of mode A, Hex-4 was in the end position of evaporation-adsorption process and Hex-3 was in the end position of desorption-condensation process. Due to higher-pressure difference at Hex-3 and Hex-4 in mode A, the refrigerant mass circulation will be higher than that of conventional two stages. This will lead the chiller to provide better performance. In mode B, adsorber (Hex-4) is heated up by hot water, and the desorber (Hex-3) is cooled down by cooling. Mode B is warm up process for Hex-4 and Hex-3. When the pressure of adsorber (Hex-3) and desorber (Hex-4) are nearly equal to the pressure of evaporator and condenser respectively, then Hex-3 and Hex-4 are connected to evaporator and condenser respectively to flow the refrigerant. This mode is denoted as mode C. In mode C, Hex-4 works as desorber and Hex-3 works, as adsorber and this process will continue up to mode E. In mode D, Hex-2 (at the end position of adsorption-evaporation process) and Hex-1 (at the end position of desorption-condensation process) are

connected with each other continuing cooling water and hot water respectively. When the pressure (temperature) of both Hex-1 and Hex-2 nearly equal, then warm up process will start, called mode E. In mode E, Hex-2

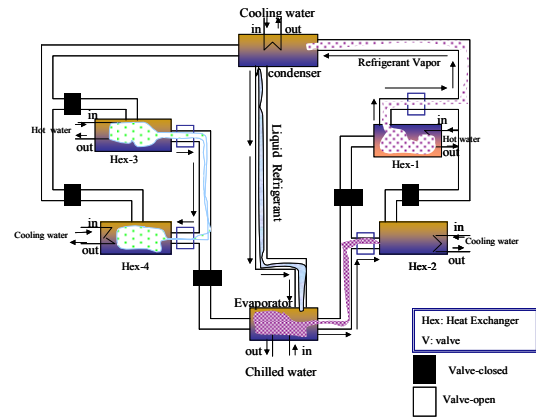


Fig 1. Schematic of a re-heat two-stage chiller

Table 1: Operational strategy of the two-stage chiller using re-heat scheme

Mode	A	B	C	D	E	F	G	H	I	J
Hex-1										
Hex-2										
Hex-3										
Hex-4										

	Adsorption		Mass recovery With heating		Pre-heating
	desorption		Mass recovery With cooling		Pre-cooling

is heated up by hot water, and cooling water-cools down the Hex-1. When the pressure of Hex-1 and Hex-2 are nearly equal to the pressure of evaporator and condenser respectively, then Hex-1 and Hex-2 are connected to evaporator and condenser respectively to flow the refrigerant. This connection will continue up to mode F, G, and H for Hex-1 and Hex-2. In mode F, Hex-3 (at the end position of adsorption-evaporation process) and Hex-4 (at the end position of desorption-condensation process) are connected with each other continuing cooling water and hot water respectively. When the pressure (temperature) of both Hex-3 and Hex-4 are nearly equal, then warm up process will start, called mode G. In mode G, Hex-3 is heated up by hot water, and cooling water-cools down the Hex-4. When the pressure of Hex-4 and Hex-3 are nearly equal to the pressure of evaporator and condenser respectively, then Hex-4 and Hex-3 are connected to evaporator and condenser respectively to flow the refrigerant. This connection will continue up to mode H, I, and J for Hex-3 and Hex-4. In mode I, Hex-1 (at the end position of adsorption-evaporation process) and Hex-2 (at the end position of desorption-condensation process) are connected with each other continuing cooling water and

hot water respectively. When the pressure (temperature) of both Hex-1 and Hex-2 are nearly equal, then warm up process will start, called mode J. In mode J, Hex-1 is heated up by hot water, and cooling cools down the Hex-2. The mode J is the last process and after this mode, all return to mode A (Table-1). The values adapted in simulation are presented in Table. 2 and Table. 3

3. MATHEMATICAL FORMALISM

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

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

$$\begin{aligned} & \frac{d}{dt} \left\{ (w_s c_s + w_s c_w q + w_{hex} c_{hex}) T \right\} \\ & = w_s Q_{st} \frac{dq}{dt} - \delta w_s c_w \left\{ \gamma (T - T_{eva}) + (1 - \gamma) (T - T_w) \right\} \\ & \times \frac{dq}{dt} + \dot{m}_w c_w (T_{in} - T_{out}) \end{aligned} \quad (2)$$

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:

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

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

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

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

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

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

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

where $P_s(T_w)$ and $P_s(T_s)$ are the saturation vapor pressure at temperatures T_w (water vapor) and T_s (silica gel), respectively. The saturation vapor pressure and temperature are correlated by Antoine's equation, which can be written as:

$$P_s = 133.32 \times \exp\left(18.3 - \frac{3820}{T - 46.1}\right)$$

4. MEASUREMENT OF SYSTEM PERFORMANCE

The performance of a two-stage adsorption chiller using re-heat is mainly characterized by cooling capacity (CC), coefficient of performance (COP) and can be measured by the followings:

Cooling capacity =

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

Co-efficient of performance (COP) =

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

5. RESULTS AND DISCUSSION

In the present analysis, a cyclic simulation computer programme is developed to predict the performance of the innovative two-stage chiller using re-heat. The systems of differential equations (1) - (7) are solved by finite difference approximation with a time step 1 sec. The results taken in the study are from the cyclic steady state conditions. A real chiller starts its operation with unbalanced conditions, however, after a few cycles (typically 2-3 cycles) it reaches its cyclical steady state condition. Therefore, an iteration processes has been

employed in solution procedure to fix all the initial values for the cyclic steady state conditions. In the beginning of the solution process, the initial values are assumed and finally those are adjusted by the iteration process. When two beds are connected with evaporator or condenser, the vapor pressure is unknown that are calculated through the Antoine's equations as the vapor temperature is calculated from the energy balance equation of evaporator or condenser. It is however, difficult to calculate the saturated vapor pressure when two-beds are connected with each other, which are essential for the calculation of adsorption/ desorption rate inside the adsorbent beds. In the state, the pressure is assumed and the amounts of vapor adsorbed/ desorbed beds are calculated. Conceptually, the desorbed vapor is equal to the amount of adsorbed vapor by the other beds. If these amounts are not equal then vapor pressure are adjusted for next iteration. Once the satisfactory convergence criterion is achieved, then process goes for the next time step. The convergence criterion for all cases of present study will be taken as 10^{-3} . The effect of mass allocation between upper and lower beds on cooling capacity (CC), co-efficient of performance (COP), chilled water outlet and their improvement ratio is shown in Fig. (2) – (7). In Figs.2 and 3, numerical values of CC and improvement ratios are depicted against the driving heat source inlet temperature from 50°C to 90°C. The highest cooling capacity is obtained at 3:2 ratio of mass allocation of upper bed to bottom bed. It is seen that the CC and improvement ratio increases with the increase of heat source temperature from 60°C to 90°C in all cases. In Fig.3. It is seen that the improvement ratios are; 5.12%, 5.22%, 6.24% and 7.9%. But the CC and improvement ratio decreases with the increase of heat source temperature from 50°C to 90°C in all cases when the mass allocation is upper bed to bottom bed is 1:2. The decreases ratios are; 2%, 2.8%, 3.18%, 3.23% and 2.47%. In Figs.4 and 5, the effect of heat source temperature on COP, the COP increases with the increase of heat source temperature from 50°C to 90°C in all cases when the mass allocation is upper bed to bottom bed is 1:2 and when the mass allocation is upper bed to bottom bed is 3:2 then COP decreases at 50°C but increases from 60°C to 90°C in all cases. In Figs. 5, it is seen that the improvement ratios are; 37.05%, 26.81%, 20.86%, 15.67% and 11.38% when the mass allocation is upper bed to bottom bed is 1:2. When the mass allocation is upper bed to bottom bed is 3:2 COP decreases 0.59% at 50°C but increase from 60°C to 90°C in all cases 0.35%, 0.67%, 1.12% and 1.84%. Again, when the mass allocation is upper bed to bottom bed is 2:3 then COP increase at 50°C to 60°C but decreases from 61°C to 90°C in all cases. The increasing ratios at 50°C to 60°C are; 0.09%, 0.87% and the decreasing ratios are; 3.22%, 6.09%, 7.26%. In an adsorption chiller, the chilled water for air-condition 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 high. The chilled water outlet temperature, however, affects cooling demand of the demand side. Therefore the requirement

of chilled outlet temperature is very important.

Table 2: Baseline Parameters

Values Adopted in Simulation		
Symbol	Value	Unit
A_{bed}	1.45	m^2
A_{eva}	0.665	m^2
A_{con}	0.998	m^2
C_s	924	J/kgK
C_w	4.18E+3	J/kgK
C_{chill}	4.20E+3	J/kgK
D_{so}	2.54E-4	m^2/s
E_a	2.33E+3	J/kg
L	2.50E+6	J/kg
Q_{st}	2.80E+6	J/kg
R	4.62E+2	J/kg
R_p	0.35E-3	M
UA_{ads}	2497.6	Wk^{-1}
UA_{des}	2532.5	Wk^{-1}
UA_e	989.9	Wk^{-1}
UA_{cond}	2404.3	Wk^{-1}
W_s	16	Kg
W_{cw}	5	Kg
W_{eva-w}	25	Kg

Table 3: Standard operating condition

	Temp.(°C)	Flow rate (kg/s)
Hot water	80	0.5
Cooling water	30	0.3 (ads) + 0.3 cond)
Chilled water	14	0.3
Cycle time	1300s = (480 ads/des + 140 mr + 30 ph/pc)s×2	

Ads/des = adsorption/desorption,
mr = mass recovery, ph/pc = pre heating/cooling

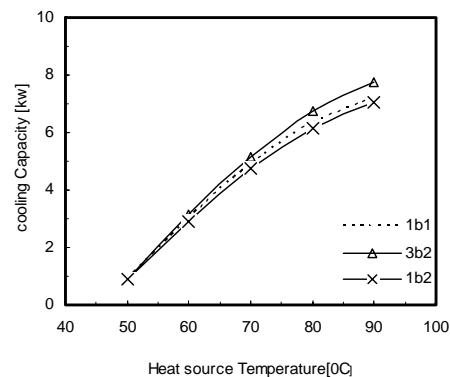


Fig.2. Effect of Heat source Temperature [°C] on cooling capacity

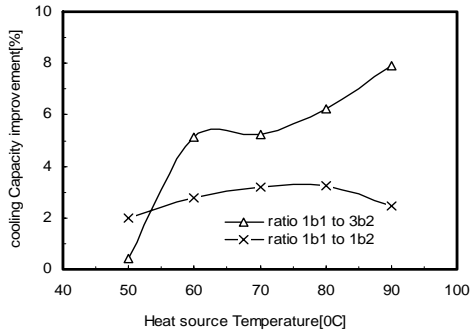


Fig.3. Effect of Heat source Temperature [OC] on cooling capacity improvement

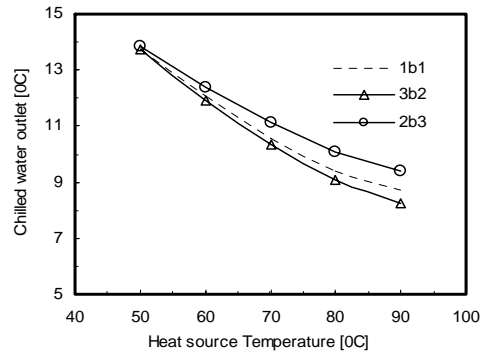


Fig.6. Effect of Heat source Temperature [OC] on chilled water outlet Temperature.

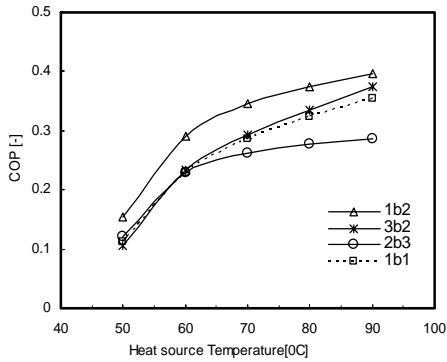


Fig.4. Effect of Heat source Temperature [OC] on cop

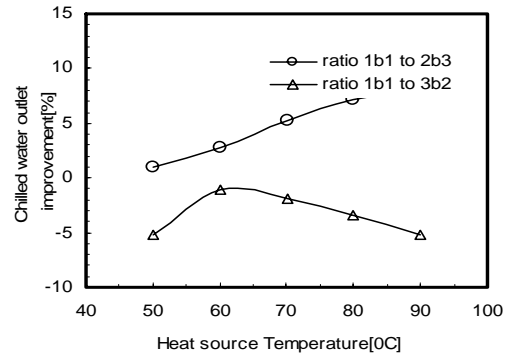


Fig.7. Effect of Heat source Temperature [OC] on chilled water outlet emperature.

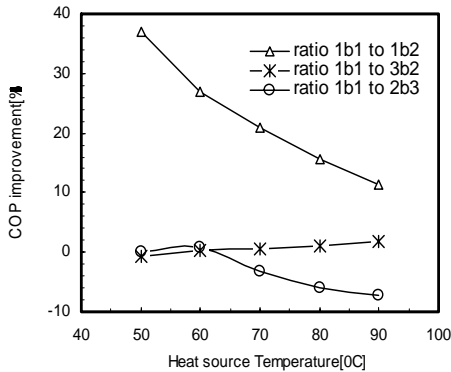


Fig.5. Effect of Heat source Temperature [OC] on cop improvement

From this context, the effect of heat source temperature as well as mass allocation ratios is presented in Figs.6 and 7. Therefore the requirement of chilled outlet temperature is very important. From this context, the effect of heat source temperature as well as mass allocation ratios is presented in Figs.6 and 7. It may be seen that the chiller with different level heat source temperature provides different level chilled water outlet temperature even the other operating conditions are the same. It can be also seen that the higher is the heat source temperature; the lower is the chilled water outlet temperature from the Fig.6, it is also observed that when the mass allocation is upper bed to bottom bed is 3:2 the chilled water outlet temperature is low. In Fig.7, it is seen that chilled water outlet temperature improvement ratios are; 0.97%, 2.74%, 5.26%, 7.2% and 7.82% when the mass allocation is upper bed to bottom bed is 2:3. But the chilled water outlet decreases ratios are; 5.19%, 1.02%, 1.92%, 3.35% and 5.194% when the mass allocation is upper bed to bottom bed is 3:2.

6. CONCLUSIONS

The performance of a two-stage adsorption chiller with different mass ratio of upper to bottom cycle was investigated numerically. It is found that the cooling capacity and COP of a two-stage adsorption chiller can be improved by allocating adsorbent mass between upper and bottom cycle. It can be found that the improvement ratio in cooling capacity, however, increases with the

increase of heat source temperature. It is also seen that the two-stage adsorption chiller with re-heat scheme for mass allocation 3:2 upper/bottom provides more cooling capacity than that of two-stage adsorption chiller with re-heat scheme for mass allocation 1:1 upper/bottom for the heat source temperature from 50°C to 90 °C. The COP is also improved significantly. Finally, it may be concluded that if a two-stage adsorption chiller with re-heat scheme is designed at 3:2 (upper/bottom) ratio, the chiller can perform better in terms of cooling capacity than that of conventional two-stage two-stage adsorption chiller with re-heat scheme for mass allocation 1:1 upper/bottom chiller even the heat source temperature is fluctuated between 50°C and 90 °C.

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