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Performance Comparison Between Cycle1(Equal Bed) and Cycle2(Unequal Bed)

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Abstract – The performance comparison of CC, COP and waste heat recovery efficiency (*η)* of cycle1 (equal bed) and cycle2 (unequal bed) has been numerically discussed in this paper. In the present numerical solution, the heat source temperature variation are taken from 50°C to 70°C (for both cycle) and along with coolant inlet temperature at 30°C and the chilled water inlet temperature at 14°C. Silica gel-water is chosen as adsorbent-refrigerant pair. In the new strategy, mass recovery process occurs in all beds. In cycle1, the configuration of beds in the three bed chiller with mass recovery were taken as uniform in size but in cycle2, the configuration of Hex3 is taken as half of Hex1 or Hex2(where Hex1 and Hex2 are identical). A cycle simulation computer program is constructed to analyze the influence of operating conditions (hot and cooling water temperature) on COP (coefficient of performance), CC (cooling capacity). The performances in terms of cooling capacity (CC) and coefficient of performances (COP) are compared with those of conventional three-bed mass recovery scheme. Results show that the cooling capacity (CC), coefficient of performance (COP) and chiller efficiency (*η*) of the proposed cycle1 is much better than that of the proposed cycle2 in the range of heat source temperature from 50°C to 70°C.

Keywords – Mass Recovery, Silica gel-water, Cooling Capacity, Coefficient of Performance, Chiller Efficiency.

I. INTRODUCTION

Most of the advanced cycles in adsorption refrigeration/heat pump are proposed to achieve high Coefficient of Performance (COP) and/or Cooling Capacity (CC) values. Few cycles, however, are proposed to utilize relatively low temperature heat source. Saha et al. [1] proposed two-stage chiller where the driving heat source temperature was validated experimentally. Khan et al. [2] studied the performance investigation on mass recovery three-bed adsorption cycle. Later, Khan et al. [3] proposed and investigated numerically the advanced three-bed adsorption chiller employing mass recovery scheme. Saha et al. [4] studied waste heat driven dual-mode, multi-stage, multi-bed regenerative adsorption system. To improve the coefficient of performance, Shelton et al. [5] proposed a thermal wave regenerative adsorption heat pump system. Wang [6] showed that mass recovery process is very effective for the high evaporating pressure lift as well as for the low regenerating temperature. Alam et al. [7] analyzed four-bed mass recovery cycle with silica gel/water pair employing a new strategy to improve the cooling effect. Recently, Saha et al.[8] analyzed a dual-mode, multi-bed adsorption chiller to improve the heat recovery efficiency.The performance of the adsorption refrigeration cycle can be enhanced by applying a mass recovery cycle into the adsorption cycle. The advanced mass recovery cycle was also applied to a three-bed cycle. Recently, Khan et al. [9] studied experimentally on a three-bed adsorption chiller and reported that it provided better COP values for 65-750C heat source temperature.

Silica gel-water is widely used as an adsorbent-adsorbate pair in adsorption refrigeration system. Compared to other adsorbents, silica gel can be regenerated at a relatively low temperature that is below 1000C. It also has a large uptake capacity for adsorption of water up to 35%-40% of its dry mass, which has a high latent heat of evaporation. Because of the low regeneration temperature, a silica gel-water adsorption chiller can utilize industrial waste heat or renewable energy resources in Chu et al. [10] and Ng et al. [11].

II. WORKING PRINCIPLE OF THE MASS RECOVERY CHILLER

The schematic diagram and time allocation of the proposed three-bed mass recovery chiller are shown in Figure1 & Figure 2 and Table 1, respectively. The three-bed mass recovery chiller comprises with three sorption elements (adsorber/desorber heat exchangers), a condenser, an evaporator, and metalic tubes for hot, cooling and chilled water flows as shown in Figure 1 & Figure 2.

Operational strategy of the proposed chiller is shown in Table 1. In proposed design, mass recovery process occurs in all bed. To complete a full cycle for the proposed system, the chiller needs 20 modes, namely A, B, C, D, E, F, G, H, I, J, K, L, M, N,O, P, Q, R, S and T as can be seen from Table 1.

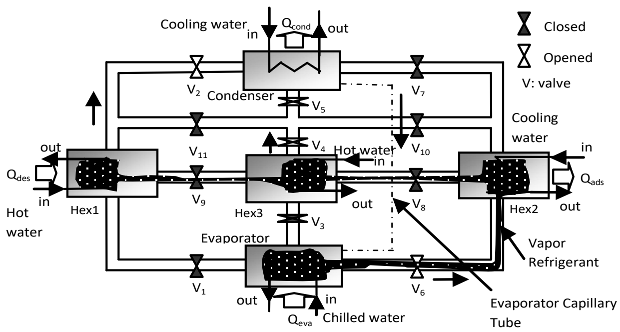


Figure 1. Schematic of three bed chiller with mass recovery (proposed cycle1).

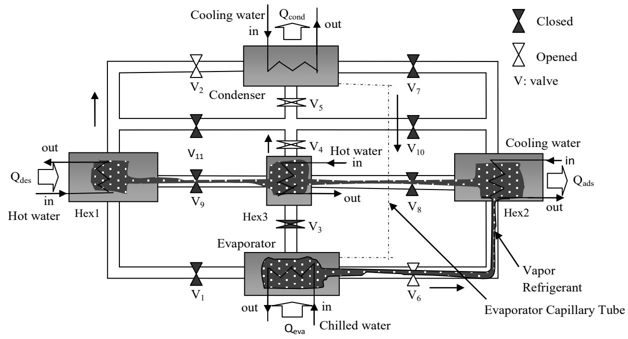
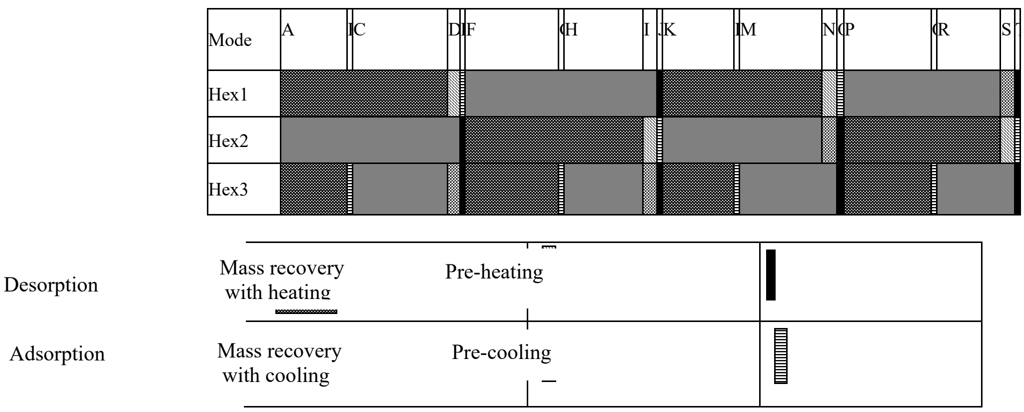


Figure 2. Schematic of three bed chiller with mass recovery (proposed cycle 2).

Table 1. Operational strategy of three bed chiller with mass recovery



In mode A, Hex1 and Hex3 work as desorber. The desorption-condensation process takes place at condenser pressure (P_{cond}).The desorber (Hex1, Hex3) is heated up to temperature (T_{des}) by heat input Q_{des}, provided by the driving heat sources. The resulting refrigerant is cooled down by temperature (T_{cond}) in the condenser by the cooling water, which removes condensation heat, Q_{cond}. Hex2 works as adsorber in mode A. In the 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 adsorbent (silica gel), at which cooling water removes the adsorption heat, Q_{ads}. Mode B is the pre-cooling process for Hex3. In pre-cooling process, Hex3 is isolated from evaporator, condensed or any other beds. Cooling water is supplied to the bed for short time (30s) in this period. Hex1 works as desorber and Hex2 works as adsorber in mode B also. Mode C is the adsorption process for Hex3, Hex2 and desorption process for Hex1. In mode D, Hex3 (at the end position of adsorption-evaporation process) and Hex1 (at the end position of desorption-condensation process) are connected with each other continuing cooling water and hot water, respectively that can be classified as two-bed mass recovery process. This time Hex3 is isolated from evaporated and Hex1 is isolated from condensed. Here mass recovery occurs only bed to bed. In this mode Hex2 works as adsorber. When the concentration levels of both beds Hex1 and Hex3 reach in nearly equilibrium levels, then warm up process will start, called mode E (pre-heating or pre-cooling).

In mode E, Hex2 and Hex3 are heated up by hot water, and Hex1 is cooled down by cooling water.When the pressure of Hex2 and Hex3 are nearly equal to the pressure of condenser then Hex2 and Hex3 are connected to condenser. When the pressure of Hex1 is nearly equal to the pressure of evaporator then Hex1 is connected to evaporator. In mode F, Hex2 and Hex3 work as desorber and Hex1 works as adsorber. Mode G is the pre-cooling process for Hex3. In this mode, Hex2 works as desorber and Hex1 works as adsorber. Mode H is the adsorption-evaporation process for Hex1 and Hex3. Hex2 works as desorber in this mode. In mode I, Hex3 (at the end position of adsorption-evaporation process) and Hex2 (at the end position of desorption-condensation process) are connected with each other continuing cooling water and hot water, respectively that can be classified as two-bed mass recovery process. When the concentration levels of both beds Hex3 and Hex2 reach in nearly equilibrium levels, then warm up process will start, called mode J (pre-heating or pre-cooling).

Hex1 works as adsorber in this mode. Mode J is the pre-heating/pre-cooling process for all bed.In this period, Hex1 and Hex3 are heated up by hot water; Hex2 is cooled down by cooling water. Modes K, L and M are same as modes A, B and C respectively. In mode K, L and M Hex1 and Hex3 work as desorber and Hex2 works as adsorber. The mode N is same as mode D. In these modes, Hex2 (at the end position of adsorption-evaporation process) and Hex1 (at the end position of desorption-condensation process) are connected with each other continuing cooling water and hot water respectively. In this mode Hex3 works as adsorber. When the concentration levels of both beds Hex1 and Hex2 reach in nearly equilibrium levels, then warm up process will start, called mode O (pre-heating or pre-cooling). The mode O is same as mode E. Modes P, Q and R are same as modes F, G and H respectively. In mode P, Q and R, Hex2 and Hex3 work as desorber and Hex1 works as adsorber. The mode S is same as mode I. In mode S, Hex1 (at the end position of adsorption-evaporation process) and Hex2 (at the end position of desorption-condensation process) are connected with each other continuing cooling water and hot water, respectively that can be classified as two-bed mass recovery process. When the concentration levels of both beds Hex1 and Hex2 reach in nearly equilibrium levels, then warm up process will start, called mode T (pre-heating or pre-cooling). Hex3 works as adsorber in this mode. Mode T is the pre-heating/pre-cooling process for all bed. In this period, Hex1 and Hex3 are heated up by hot water; Hex2 is cooled down by cooling water. Mode T is the last process for all beds, after this mode, all beds will return to its initial position (Mode A). That's why to complete one cycle, it needs 20 modes.

III. MATHEMATICAL FORMULATION

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

$$T_{w,out} = T_{hex} + \left(T_{w,in} - T_{hex}\right)\exp\left(-\frac{U_{hex}A_{hex}}{\dot{m}_w C_{pw}}\right) \tag{1}$$

$$\frac{d}{dt}\left\{\left(W_s\left(C_{ps} + C_{pw}q\right) + W_{khex}C_{pcu} + W_{fhex}C_{pAl}\right)T_{hex}\right\} = W_s Q_{st}\frac{dq}{dt} - \delta W_s C_{pw}\left\{\gamma\left(T_{hex} - T_{eva}\right) + \left(1-\gamma\right)\left(T_{hex} - T_{wv}\right)\right\}\frac{dq}{dt} + \dot{m}_w C_{pw}\left(T_{w,in} - T_{w,out}\right) \tag{2}$$

where, δ is either 0 or 1 depending whether the adsorbent bed is working as desorber or adsorber and γ is either 1 or 0 depending on whether the bed is connected with evaporator or another bed.

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

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

$$\frac{d}{dt}\left\{\left(W_{eva,w}C_{pw} + W_{eva}C_{p,eva}\right)T_{eva}\right\} = -L\,W_s\frac{dq_{ads}}{dt} - W_sC_{pw}\left(T_{cond} - T_{eva}\right)\frac{dq_{des}}{dt} + \dot{m}_{chill}C_{p,chill}\left(T_{chill,in} - T_{chill,out}\right) \tag{4}$$

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

$$T_{cond,out} = T_{cond} + \left(T_{cw,in} - T_{cond}\right)\exp\left(-\frac{U_{cond}A_{cond}}{\dot{m}_{cw}C_{pw}}\right) \tag{5}$$

$$\frac{d}{dt}\left\{\left(W_{cw,w}C_{pw} + W_{cond,hex}C_{p,cond}\right)T_{cond}\right\} = -L\,W_s\frac{dq_{des}}{dt} - W_sC_{p,w}\left(T_{des} - T_{cond}\right)\frac{dq_{des}}{dt} + \dot{m}_{cw}C_{pw}\left(T_{cw,in} - T_{cw,out}\right) \tag{6}$$

The mass balance for the refrigerant can be expressed as:

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

where, the subscripts *des-cond* and *eva-ads* stand for the vapor flow from desorber to condenser and evaporator to adsorber, respectively.

IV. MEASUREMENT OF THE SYSTEM PERFORMANCE

The performance of a three-bed adsorption chiller with mass recovery is mainly characterized by cooling capacity (CC) and coefficient of performance (COP) and can be measured by the following equations:

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

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

V. RESULTS AND DISCUSSION

In the present analysis, a cycle simulation computer program is developed to predict the performance of the three-bed chiller with mass recovery. The systems of differential equations (1)-(7) are solved by finite difference approximation with a time step 1 sec. 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 for all parameters of the present study will be taken as 10^{-3}.

The base line parameters and standard operating conditions for the chiller operation are listed in Table 2 and Table 3, respectively.

Table 2. Baseline parameters

Symbol	**Value**	**Unit**
A_{hex}	1.45	m^2
A_{eva}	0.665	m^2
A_{con}	0.998	m^2
C_{ps}	924	J/kg.K
C_{pw}	4.18E+3	J/kg.K
$C_{p,chill}$	4.20E+3	J/kg.K
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.K
R_p	0.35E-3	m
U_{ads}	1380	$W/m^2 \cdot K$
U_{des}	1540	$W/m^2 \cdot K$
U_{eva}	3550	$W/m^2 \cdot K$
U_{cond}	4070	$W/m^2 \cdot K$
W_s	14	kg
W_{cw}	5	kg
$C_{p,cu}$	386	J/kg.K
$C_{p,Al}$	905	J/kg.K
W_{khex}	12.67	kg
W_{fhex}	5.33	kg
$W_{eva,w}$	25	Kg

Table 3. Standard operating condition

	Temperature[^{0}C	**Flow rate (Kg/s)**
Hot water	50 ~ 70	0.4
Cooling water	30	0.74[=0.4(ads)+0.34(cond)]
Chilled water	14	0.11
Cycle Time	2100s=(950 ads/ des+40 mr+30ph+30pc) s×2	

ads/des = adsorption/desorption, mr = mass recovery, ph/pc = pre-heating/pre-cooling.

Table 4. Comparison of the result between two cycles

Cycle time = 2100s, Mass recovery = 40s

	Proposed Cycle1			Proposed Cycle2		
Heat Source Temperature	**CC [kW]**	**COP [-]**	**η**	**CC [kW]**	**COP [-]**	**η**
50	1.6332	0.4524	.0488	1.0652	0.4128	.0319
55	2.4351	0.5289	.0583	1.6190	0.4853	.0387
60	3.1288	0.5615	.0624	2.0845	0.5130	.0416
65	3.7298	0.5703	.0637	2.4967	0.5248	.0427
70	4.2444	0.5674	.0635	2.8432	0.5247	.0425

Figures 3-5 show the comparison of the numerical results between the proposed cycle1 and the proposed cycle 2. Both of the cycles were tested at the same conditions based on the input parameters presented in Table 4. From the figure 4, it is clearly found that COP of the proposed cycle1 is higher than that of the proposed cycle2 if heat source temperature is 65^{0}C. It should be noted that the cooling capacity (CC) of the proposed cycle1 is much better than that of the proposed cycle 2 (see Figure 3) in the range of heat source temperature from 50 to 70^{0}C. The waste heat recovery efficiency,η ,of the proposed cycle1 is much better than that of the proposed cycle 2(see Figure 5) in the range of heat source temperature from 50 to 70^{0}C.

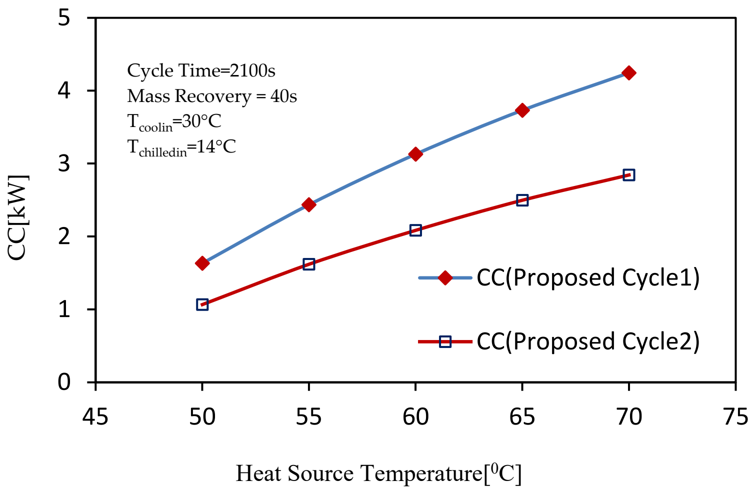


Figure 3. Performance comparison of CC between the proposed cycle1 and cycle2.

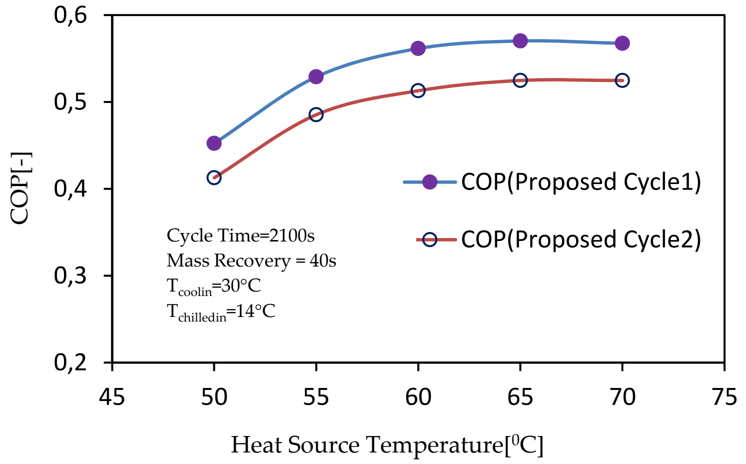


Figure 4. Performance comparison of COP between the proposed cycle1 and cycle2.

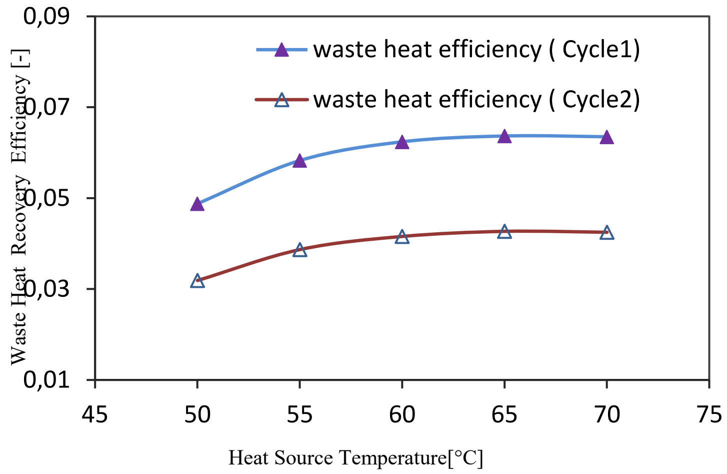


Figure 5. Performance comparison of waste heat recovery efficiency between the proposed cycle1 and cycle2.

VI. CONCLUSIONS

The comparison of the numerical results between the proposed cycle1 and the proposed cycle 2 are discussed in this paper. Both of the cycles were tested at the same conditions based on the input parameters. The following possible outcomes can be drawn from the present analysis:

(i) The main feature of the proposed chiller is the ability to be driven by relatively low temperature heat source. The chiller can utilize the fluctuated heat source temperature between 50^0C to 70^0C to produce effective cooling along with a coolant inlet at 30^0C.

(ii) The cooling capacity (CC) and coefficient of performance (COP) of the proposed cycle1 is much better than that of the proposed cycle2 in the range of heat source temperature from 50^0C to 70^0C. The optimum COP value is obtained for hot water inlet temperature at 65^0C.

(iii) The waste heat recovery efficiency,η ,of the proposed cycle1 is much better than that of the proposed cycle2 in the range of heat source temperature from 50^0C to 70^0C.

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