Effect of Mass Recovery time on a Three-Bed Adsorption Chiller

Gulshan Khatun[1], Shakila Sultana[2], Md. Zafar Iqbal Khan[3], Khandker Farid Uddin Ahmed[4],
Nazma Parveen[5], and Muhammad Mahfuz Hasan[6]

Corresponding Author Email: gulshan@easternuni.edu.bd

Abstract— In this paper, the effect of mass recovery time on a three-bed adsorption chiller has been numerically studied. In the present numerical solution, the heat source temperature variation is taken from 50°C to 90°C along with coolant inlet temperature at 30°C and the chilled water inlet temperature at 14°C. The configuration of beds in the three-bed chiller with mass recovery were taken as uniform in size. The performances in terms of cooling capacity (CC) and coefficient of performance (COP) are compared with those of conventional three-bed without mass recovery scheme. Results show that three-bed adsorption chiller with mass recovery scheme provides more CC values than those provided by the three-bed system without mass recovery scheme while it provides better COP values for 85°C heat sources temperature.

Keywords*:* Adsorption Chiller, Mass recovery, Silica gel-water, CC, COP, Chiller efficiency

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1. INTRODUCTION

Refrigeration has been developing dynamically since the nineteenth century due to its application in numerous fields, including production, transport and food storage, industry (the necessity of cooling various devices and machines), air conditioning of buildings, household refrigerators, etc. Adsorption chillers might be applied wherever the heat in the temperature range of 60^0–75^0C or a steam in the pressure range of 1-8 bars is available. Nevertheless, adsorption chillers possess a low Coefficient of Performance (COP), not exceeding approximately 0.6 by Sah et al. [1], compared to vapor compressor chillers whose COP might be as high as 6 Yu et al. [2]. As a result, many methods of increasing the COP have been investigated. For example, Shabir et al. [3] investigated the COP of the adsorption chiller with different adsorbent/refrigerant pairs. Performance Simulation of Two-Bed Adsorption Refrigeration Chiller with Mass Recovery described by Ghilen et al. [4].

In addition to the low COP of adsorption chillers, a cyclic operation resulting in an irregular cold production is their significant drawback described by Rouf et al. [5]. Two-bed and four-bed adsorption chillers have gained much attention in the scientific community in the last years. For example, Pan et al. [6] experimentally investigated the influence of the heating water temperature on the two-bed adsorption chiller's performance. Woo et al. [7] also examined the two-bed adsorption chiller's performance under different operating conditions, but their chiller possessed another water desalination function. Similar studies were conducted by Kim et al. [8], who investigated the water quality produced in the four-bed adsorption chiller.

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) and waste heat recovery efficiency.

2. WORKINGPRINCIPLEOF THE MASS RECOVERY CHILLER

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

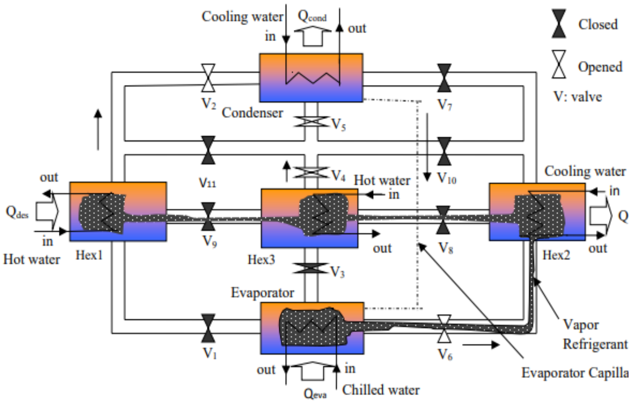
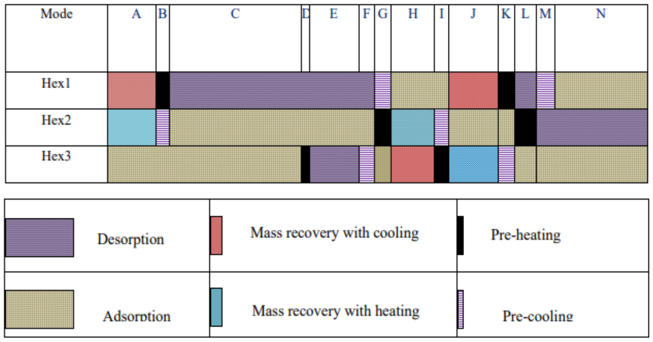


Fig. 1. Schematic of three bed chiller with mass recovery

TABLE 1

OPERATIONAL STRATEGY OF THE THREE BED CHILLER WITH MASS RECOVERY



Operational strategy of the three bed 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 14 modes, namely A, B, C, D, E, F, G, H, I, J, K, L, M, and N as can be seen from Table 1.

In mode A, 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 B (pre-heating or pre-cooling). Hex3 works as adsorber in this mode. In mode B, Hex1 is heated up by hot water, and Hex2 is cooled down by cooling water. When the pressure of Hex1 and Hex2 are nearly equal to the pressure of condenser and evaporator, respectively then Hex1 and Hex2 are connected to condenser and evaporator, respectively. This connection will continue to modes C, D, E, and F for both Hex1 and Hex2. In mode C, D, E, and F, Hex1 works as desorber and Hex2 works as adsorber. 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} . The desorption-condensation process takes place at condenser pressure (P_{cond}). The desorber (Hex1) is heated up to temperature (T_{des}) by 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 condensation heat, Q_{cond}. In modes A, B, and C, Hex3 is connected to the evaporator. Mode D is the warming process for Hex3 (pre-heating process), after mode D, Hex3 works as desorber connecting with condenser, called mode E. Mode F is the pre-cooling process for Hex3.

In mode G, Hex2 is heated up by hot water, and Hex1 is cooled down by cooling water. When the pressure of Hex2 and Hex1 are nearly equal to the pressure of condenser and evaporator, respectively then Hex2 and Hex1 are connected to condenser and evaporator, respectively. In modes G, Hex3 is connected to the evaporator. In mode H, 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 I (pre-heating or pre-cooling). Hex1 works as adsorber in this mode. In mode I, Hex3 is heated up by hot water, and Hex2 is cooled down by cooling water. When the pressure of Hex3 and Hex2 are nearly equal to the pressure of condenser and evaporator, respectively then Hex3 and Hex2 are connected to condenser and evaporator, respectively. In modes I, Hex1 is connected to the evaporator.

The mode J is same as mode A. In these modes, 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. 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 K (pre-heating or pre-cooling). The mode K is same as mode B. In mode K, Hex1 is heated up by hot water, and Hex3 is cooled down by cooling water. When the pressure of Hex1 and Hex3 are nearly equal to the pressure of condenser and evaporator, respectively then Hex1 and Hex2 are connected to condenser and evaporator, respectively. Hex2 works as adsorber in this mode. In mode L, Hex1 work as desorber and Hex3 works as adsorber. Mode L is the warming process for Hex2 (pre-heating process), after mode L, Hex2 works as desorber connecting with condenser, called mode M. Mode M is the pre-cooling process for Hex1. Hex3 works as adsorber in mode M. In mode N, Hex1 and Hex3 works as adsorber and Hex2 work as desorber. Mode N 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 14 modes.

3. MATHEMATICAL FORMULATION

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

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

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

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:

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

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

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

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

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

The mass balance for the refrigerant can be expressed as:

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

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

4. 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:

Cooling Capacity (CC) =

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

Coefficient of Performance (COP) =

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

5. 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 [ºC]	Flow rate (kg/s)
Hot water	50 ~ 90	0.2
Cooling water	30	0.54[=0.2(ads)+0.34(cond)]
Chilled water	14	0.15
Cycle Time	3600s=(1700 ads/ des+40 mr+30ph+30pc) s×2	

TABLE 4

Both of the cycles were tested at the same conditions based on the input parameters-

Cycle time = 3600s, Mass recovery = 40s, T_{hotin} =85^{0}C, $T_{chilledin}$=14°C

	CC[kW]	COP[-]	Chiller Efficiency η
With Mass Recovery (WMR)	3.7904	0.6685	.0824
Without Mass Recovery(WOMR)	2.5082	0.6009	.0545

5.1 COMPARISON OF THE RESULTS

The results demonstrate that the mass recovery process enhances the refrigeration performance of the system. Figures 2-4 show the comparison of the numerical results between the three bed adsorption chiller with and without mass recovery process. Both of the mass recovery process were tested at the same conditions based on the input parameters presented in Table 4. From Fig.3, it is clearly found that COP of the cycle with mass recovery is higher than that of the cycle without mass recovery if the heat source temperature is 85^0 C. The coefficients of performance (COPs) of cycles with mass recovery (40s) and without mass recovery are 0.6685 and 0.6009, respectively; mass recovery increases the COP by 11.25%. It is also indicated that there is an optimal mass recovery time for the refrigeration cycle, which is 40s in this study. It should be noted that the cooling capacity (CC) of the three bed adsorption chiller with mass recovery is much better than that of the cycle without mass recovery (see Fig.2) in the range of heat source temperature from 50^{0}C to 90^0 C.

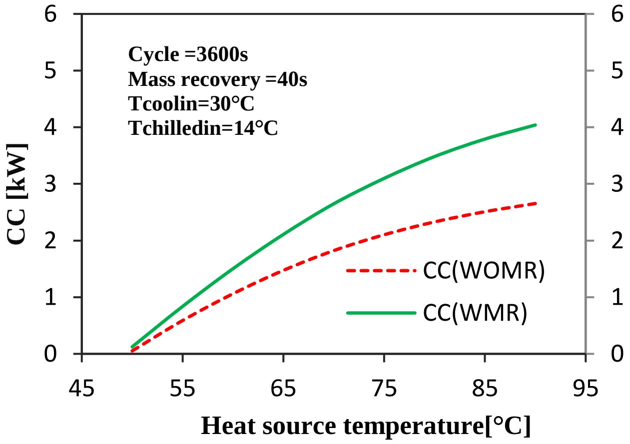


Fig.2. Performance comparison of CC between the three bed chiller with and without mass recovery

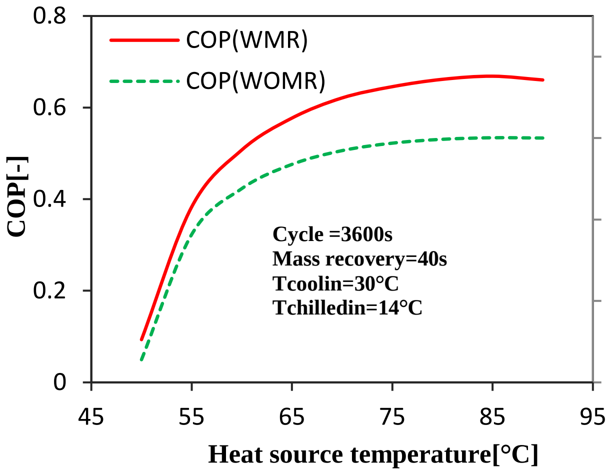


Fig.3. Performance comparison of COP between the three bed chiller with and without mass

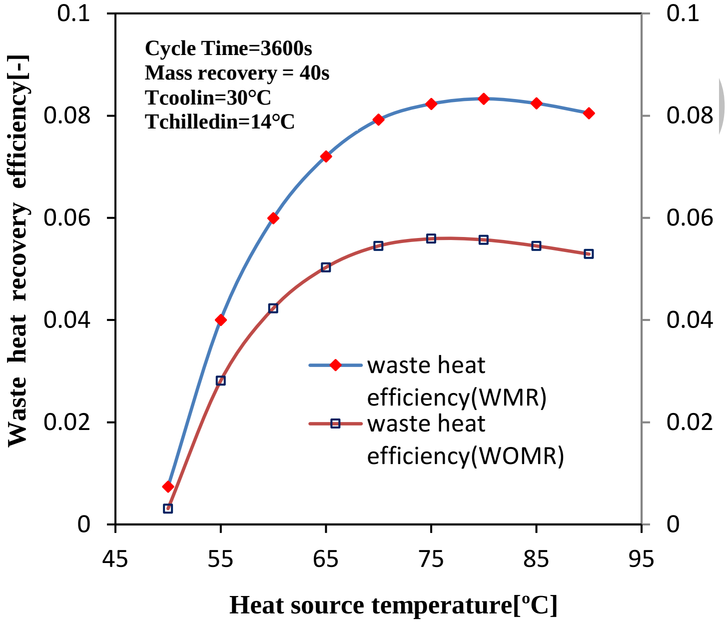


Fig.4. Performance comparison of waste heat recovery efficiency between the three bed chiller with and without mass recovery process

6. CONCLUSION

The comparison of the numerical results between two different mass recovery process are discussed in the present study. The following possible outcomes can be drawn from the present analysis:

(i) The CC and COP of three bed chiller with mass recovery (40s) can be improved up to 51.12% and 11.25% respectively than that the three bed chiller without mass recovery if the heat source temperature is considered to be 85°C.

(ii) It is also indicated that there is an optimal mass recovery time for the refrigeration cycle, which is 40s in this study.

(iii) The waste heat recovery efficiency of the cycle with mass recovery process is much better than that of the cycle without mass recovery process (see Fig.4) in the range of heat source temperature from 50^0C to 90^0C.

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