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Numerical Study of a Three-Bed Adsorption Chiller Employing an Advanced Mass Recovery Process

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Abstract –The performance improvement of a three-bed (equal bed) adsorption chiller employing an advanced mass recovery process has been numerically studied in this paper. The mass recovery scheme is used to improve the cooling effect and a CFC-free-based sorption chiller driven by the low-grade waste heat or any renewable energy source can be developed for the next generation of refrigeration. Silica gel/water is taken as adsorbent/adsorbate pair for the present chiller. The three-bed adsorption chiller comprises with three adsorber/desorber heat exchanger, one evaporator and one condenser. In the present numerical solution, the heat source temperature variation is taken from 50^{0}C to 90^{0}C along with coolant inlet temperature at 30^{0}C and the chilled water inlet temperature at 14^{0}C. In the new strategy, if any one bed (3rd bed) is connect with the evaporator during pre-heating or pre-cooling time then it will give better performance than that of existing system. In this strategy, mass recovery process also occurs in all bed. A cycle simulation computer program is constructed to analyze the influence of operating conditions (hot and cooling water temperature) on COP (coefficient of performance), and CC (cooling capacity).

Keywords – Renewable Energy Sources, Silica Gel-Water, Mass Recovery, Cooling Capacity, Coefficient of Performance.

I. INTRODUCTION

Over the past few decades there have been considerable efforts to use adsorption (solid/vapor) for cooling and heat pump applications, but intensified efforts were initiated only since the imposition of international restrictions on the production and utilization of CFCs and HCFCs. The severity of the ozone layer destruction problem due to CFCs and HCFCs has been calling for rapid developments in environment friendly air conditioning technologies. With regard to energy use, global warming prevention has been requiring a thorough revision of energy utilization practices towards greater efficiency. From this perspective, interest in adsorption systems has been increased as they do not use ozone depleting substances as refrigerants nor do they need electricity or fossil fuels as driving sources.

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^{0}C 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.

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 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. The design criteria of the three-bed mass recovery chiller are almost similar to that of the three-bed chiller without mass recovery which is proposed and developed by Saha et al. [9] and [10]. The configuration of beds in the three bed chiller with mass recovery were taken as uniform in size.

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 14 modes, namely A, B, C, D, E, F, G, H, I, J, K, L, M and N as can be seen from Table1.

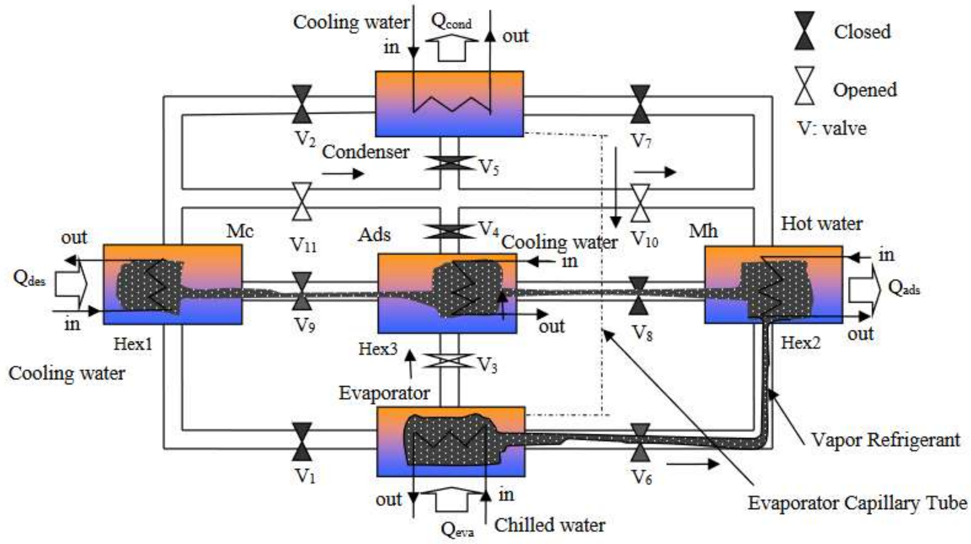
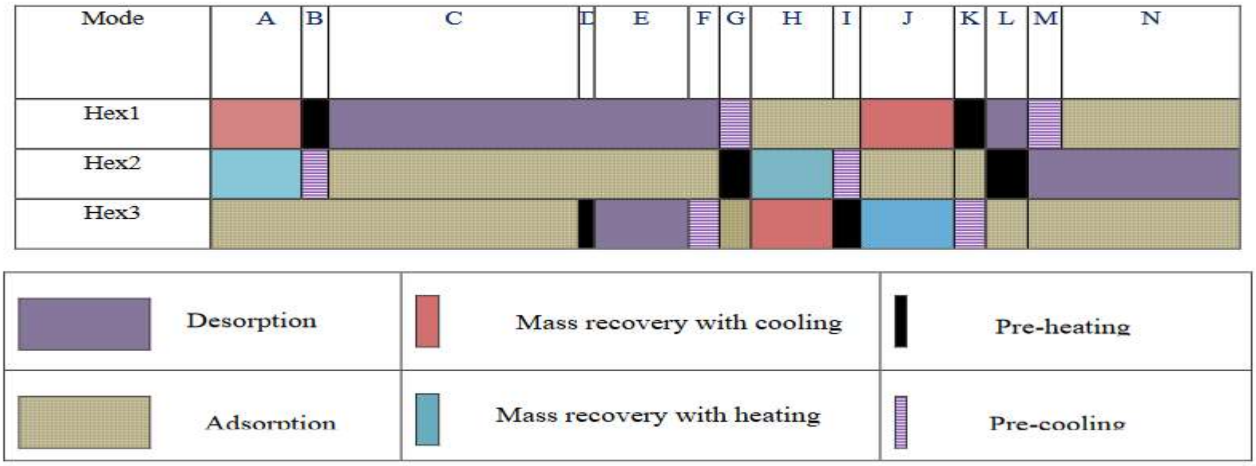


Figure1: Schematic of three bed chiller with mass recovery (proposed cycle).

Table1. Operational strategy of three bed chiller with mass recovery



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.

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:

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

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

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

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

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

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

Symbol	Value	Unit
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 ~ 90	0.2
Cooling water	30	0.54[=0.2(ads)+0.34(cond)]
Chilled water	14	0.13
Cycle Time	3600s=(1700 ads/ des+40 mr+30ph+30pc) s×2	

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

5.1 Effect of driving heat source temperature on CC and COP

Figures 2 and 3 show heat source temperature variation on CC and COP, respectively. It is seen that CC for three-bed mass recovery chiller increases with the increase of heat source temperature from 50^{0}C to 90^{0}C with a cooling water inlet temperature of 30^{0}C. This is because the amount of refrigerant circulated increases, due to increased refrigerant desorption with higher driving source temperature. Another reason is that, in the proposed cycle, Hex1 and Hex2 connect with Hex3 one by one during mass recovery, which accelerates cooling effect. The CC is improved due to the mass recovery process. The mass recovery process generates more desorption heat and that is transferred from the desorber through desorbed vapor. So, in the low heat source temperature (50^{0}C-90^{0}C), proposed chiller gives better performance. The optimum COP value is 0.6358for hot water inlet temperature at 85^{0}C along with the coolant and chilled water inlet temperature are at 30^{0}C and 14^{0}C, respectively. The delivered chilled water temperature is 8.1373^{0}C for this operation condition.

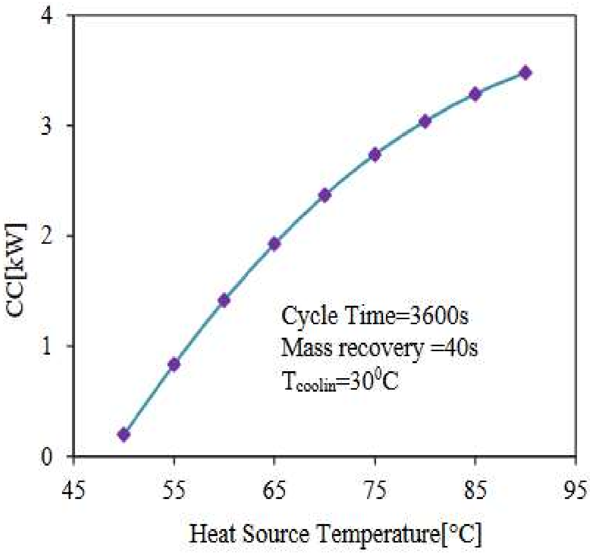


Figure 2: The effect of heat source temperature on CC

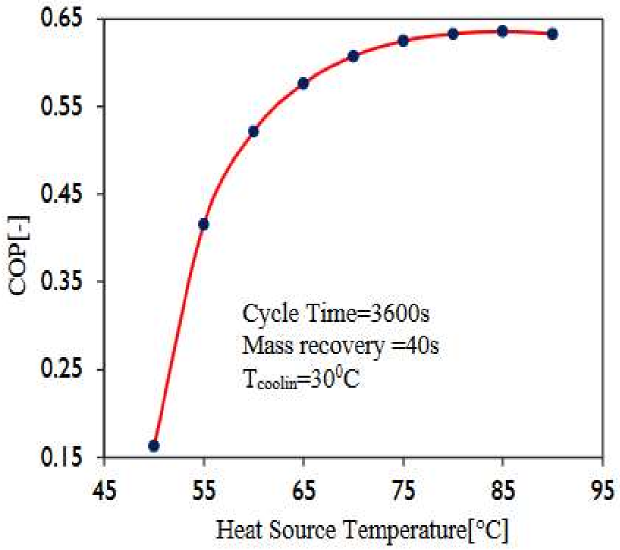


Figure 3: The effect of heat source temperature on COP

5.2 Effect of cooling source temperature on CC and COP

Figure 3 and 4 show the effect of cooling water inlet temperatures on CC and COP, respectively. In the present simulation, cooling water mass flow rate into adsorber is taken as 0.2 kg/s, while for the condenser the coolant mass flow rate is taken as 0.34 kg/s. The CC increases steadily as the cooling water inlet temperature is lowered from 40^{0}C to 28^{0}C. This is due to the fact that lower adsorption temperatures result in larger amounts of refrigerant being adsorbed and desorbed during each cycle. The simulated COP values also increases with lower cooling water inlet temperature. For the three bed chiller the COP value reaches 0.6402 with 85^{0}C driving source temperature in combination with a coolant inlet temperature of 28^{0}C.

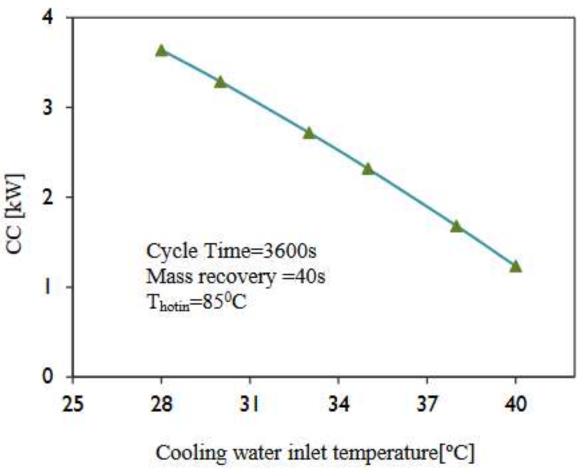


Figure 3: The effect of cooling water inlet temperature on CC

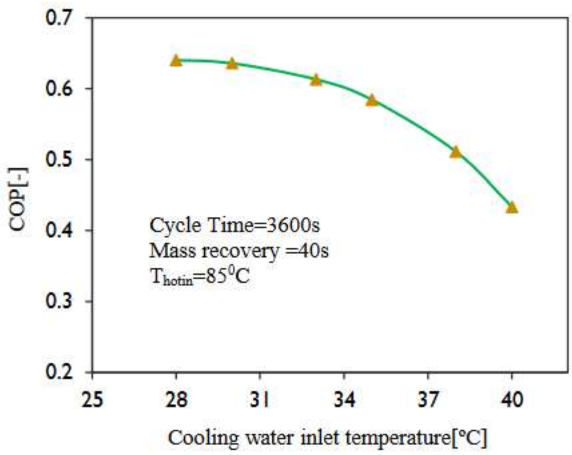


Figure 4: The effect of cooling water inlet temperature on COP

VI. CONCLUSIONS

There is an increasing need for energy efficiency and requirement for the system driven with low temperature heat source. For the utilization of the demand, multi-bed mass recovery cycle is presented and the effects of operating conditions are investigated. 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 90^0C to produce effective cooling along with a coolant inlet at 30^0C.

(ii) In the cycle simulation study, hot and cooling water temperatures are the most influential parameters. CC increases with the increase of hot water temperature and opposite tendency for cooling water temperature. Highest COP value (0.6358) is obtained for hot water inlet temperature at 85^0C.

(iii) The experimental studies show that the COP of the three-bed adsorption chiller is higher than that two-bed adsorption chiller [4] by about 15% for the heating water temperature of 85°C.

VII. ACKNOWLEDGEMENTS

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