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Performance Evaluation of a Three-Bed (Unequal Bed) Adsorption Chiller Employing an Advanced Mass Recovery Process

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Abstract: Performance evaluation of a three-bed (unequal bed) adsorption chiller employing an advanced mass recovery process has been numerically studied in this paper. 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. Silica gel/water is taken as adsorbent/adsorbate pair for the present chiller. 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, the configuration of Hex1 and Hex2 are identical, but the configuration of Hex3 is taken as half of Hex1 or Hex2. 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: Mass Recovery, Adsorption Chiller, Silica Gel-Water, Cooling Capacity, Coefficient of Performance

Introduction

Adsorption chillers are usually driven by heat, so these chillers are attractive for reducing electric power demand peaks resulting from air-conditioning and refrigeration equipment loads. The variety of heat sources available for driving the adsorption refrigeration cycle makes this a technology that contributes to CO_2 reduction by utilizing non-fossil fuel, such as solar energy or waste heat from industrial process, as its driving source by Ng et al. [1].

Adsorption chillers possess a low Coefficient of Performance (COP), not exceeding approximately 0.6 by Sah et al. [2], compared to vapor compressor chillers whose COP might be as high as 6 by Yu et al. [3]. As a result, many methods of increasing the COP have been investigated. For example, Shabir et al. [4] 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. [5]. 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. [6]. Pan et al. [7] experimentally investigated the influence of the heating water temperature on the two-bed adsorption chiller's performance. Woo et al. [8] also examined the two-bed adsorption chiller's performance under different operating conditions, but their chiller possessed another water desalination function. Experimental study of a three-bed adsorption chiller with desalination function explained by Sztekler et al. [9] and reported that the COP increased from 0.20 to 0.58 when the heating water temperature increased from 57^0 to 85^{0}C.

The aim of the present study is to determine the numerical result of a three-bed (unequal-bed) adsorption chiller employing an advanced mass recovery process. 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 effect of mass recovery time on CC and COP are also discussed in the present study.

Working Principal of the Mass Recovery Chiller

The schematic diagram and time allocation of the three-bed (unequal bed) mass recovery chiller are shown in Figure 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 metalic tubes for hot, cooling and chilled water flows as shown in Figure 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. [10] and [11].

The operational strategy of the proposed chiller is

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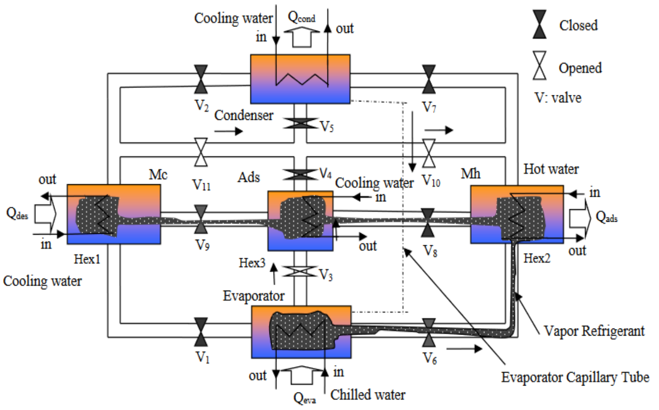
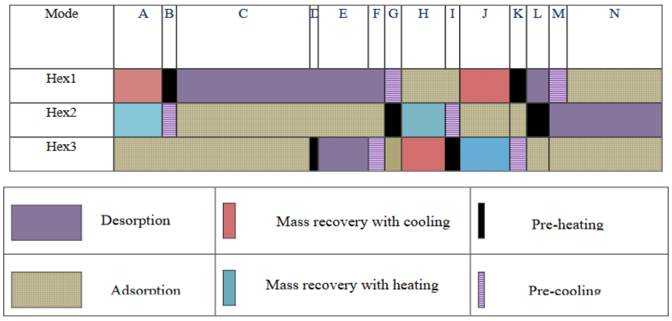
shown in Table 1. In proposed design, mass recovery process occurs in all bed. To complete a full cycle for the proposed system, the chiller needs 14 modes, namely A, B, C, D, E, F, G, H, I, J, K, L, M, and N as can be seen from Table 1.



1. Schematic of three bed chiller with mass recovery

Table 1. Operational Strategy of Three Bed Chiller with Mass Recovery



Mode	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Hex1	🟥	■	🟪	🟪	🟪	🟪	▤	▨	▨	🟥	■	🟪	▤	▨
Hex2	🟦	▤	▨	▨	▨	▨	■	🟦	▤	▨	▨	■	🟪	🟪
Hex3	▨	▨	▨	■	🟪	▤	▨	🟥	■	🟦	▤	▨	▨	▨

🟪	Desorption	🟥	Mass recovery with cooling	■	Pre-heating
▨	Adsorption	🟦	Mass recovery with heating	▤	Pre-cooling

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 sorption-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 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.

Mathematical Formulation

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

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

(1)

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

(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:

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

(3)

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

(4)

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

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

(5)

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

(6)

The mass balance for the refrigerant can be expressed as:

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

(7)

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

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) =

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

and the waste heat recovery efficiency (η) =

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

Results and Discussion

Since our main interest is to utilize the low grade waste heat as the driving source, the investigation was conducted for hot water between 50^0C and 90^0C. The effect of operating temperature (hot and cooling water) is calculated by the simulation runs. 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	16(for bed1 and bed2) and 8 (for bed3)	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	0.13
Cycle Time	3300s=(1550 ads/ des+40 mr+30ph+30pc) s×2	

Effect of Driving Heat Source Temperature on CC and COP

The experiments' results indicate the strong influence of the heating water temperature on the COP and CC. Figures 2 and 3 show heat source temperature variations 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 50^0C to 90^0C with a cooling water inlet temperature of 30^0C. 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 (70^0C-80^0C), proposed chiller gives better performance. The optimum COP value is 0.6307 for hot water inlet temperature at 80^0C along with the coolant and chilled water inlet temperature are at 30^0C and 14^0C, respectively. The delivered chilled water temperature is 9.9117^0C for this operation condition.

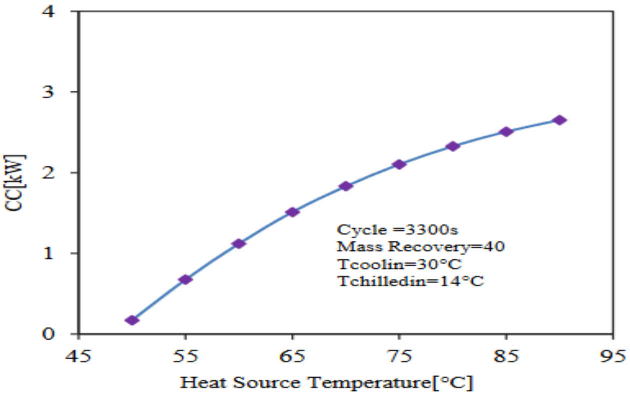


Figure 2. The effect of heat source temperature on CC

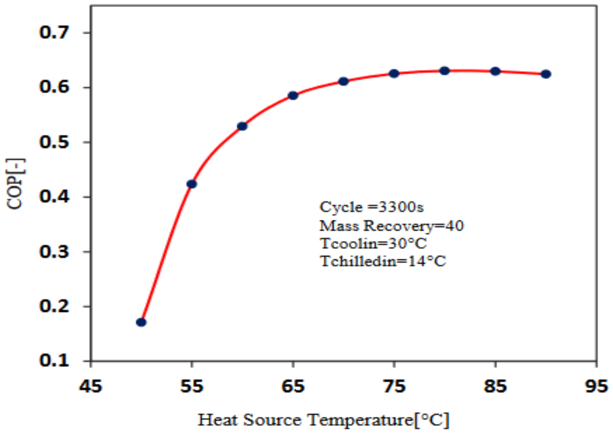


Figure 3. The effect of heat source temperature on COP

Effect of Cooling Source Temperature on CC and COP

Figure 4 and 5 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 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 0.6415 with

80^0C driving source temperature in combination with a coolant inlet temperature of 28^0C.

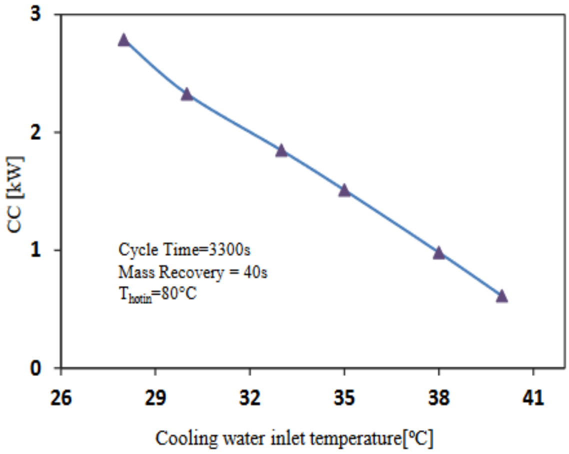


Figure 4. The effect of cooling water inlet temperature on CC

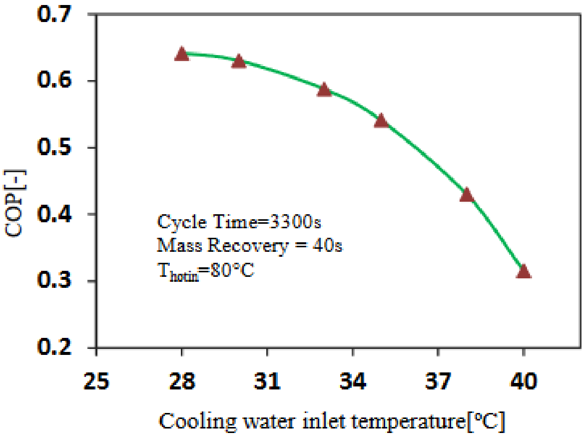


Figure 5. The effect of cooling water inlet temperature on COP

Effect of Mass Recovery Time on CC and COP

Mass recovery cycle is very simple but effective to operate. For operating conditions such as high-condensing temperatures, low-evaporation temperatures, or low-generation temperatures, mass recovery operation is strongly recommended by Wang [12].

Figure 6 shows the effect of mass recovery process time on CC and COP. It is shown that both CC and COP values are decreased with the increase of mass recovery time. Both CC and COP values are maximized when mass recovery time is 40s with 80^0C driving source temperature.

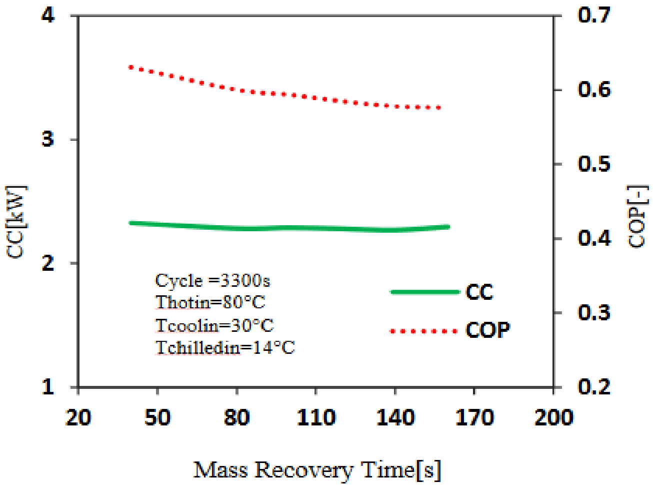


Figure 6. Effect of mass recovery time on CC and COP

Conclusion

The following possible outcomes can be drawn from the present analysis:

(i) The optimum COP value (0.6307) is obtained for hot water inlet temperature at 80^0C in combination with the coolant and chilled water inlet temperatures are 30^0C and 14^0C, respectively.

(ii) Cooling capacity of the three bed chiller is increased as heat source temperature is increased from 50^0C to 90^0C and cooling water inlet temperature is decreased from 40^0C to 28^0C.

(iii) We will observe mass recovery time in the presence of both CC and COP.

(iv) Adsorption/desorption cycle time is very sensitive to the heat source temperature. The highest CC values are obtained for cycle time between 3000s and 3600 s in the present study.

Acknowledgements

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