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Effect of Chilled Water Outlet Temperature on the Performance of a Three-Bed Adsorption Chiller

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Abstract: *In this paper, the effect of the chilled water outlet temperature on the performance of 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 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. The configuration of beds in the three-bed chiller with mass recovery were taken as uniform in size. Results show the performance of the cycle with mass recovery is much better than that of the cycle without mass recovery because the chilled water outlet temperature of the cycle without mass recovery is higher than that of the cycle with mass recovery.*

Keywords: adsorption chiller, CC, COP, chilled water, silica gel-water, mass recovery.

INTRODUCTION

The energy consumption of household appliances increases in proportion to its usage. Among these appliances, the refrigerator is one of the most energy-consuming devices [68]. It is estimated that more than 45% of the world food production would go waste if not for the refrigerators' cold storage and distribution [68]. Thus, improving their energy efficiency, efficient energy consumption, and prolonged life becomes imperative [67, 68]. Energy and exergy analysis of a domestic refrigerator: Approaching a sustainable refrigerator described by Shikalgar and Sapali [69]. Experimental and Numerical Study on Performance Enhancement by Modifying the Flow Channel in the Mechanical Chamber Room of a Home Refrigerator explained by Dong Kyun Kim [70].

In hot climatic regions, particularly in the Middle East and North Africa (MENA), there is a growing demand for air conditioning. This is due to the warming climate, increased internal loads in structures, and increased demand for thermal comfort by users; as a result, it is becoming one of the most significant sources of energy consumption [71]. Refrigeration cycles and, in particular, air-conditioning systems are playing an important role in domestic, agricultural and industrial sectors. It has been indicated by the International Institute of Refrigeration (IIR), there are roughly 3 billion refrigeration, air-conditioning, and heat pump (HP) systems in use globally [72]. Furthermore, the refrigeration industry utilizes around 17% of all power used globally. Residential consumption accounts for over 45% of total consumption, making it one of the most energy-intensive sectors in the world [72]. Such statistics provided by the IIR give a clear indication on the importance of the decarbonisation of refrigeration cycles. For air conditioning systems, they can be classified as thermally or mechanically driven. An adsorption heat pump is an example of thermal driven heat, has workability that can employ thermal energy such as solar energy and the process/waste heat generated by industrial applications. Evaluation and Design of Large-Scale Solar Adsorption Cooling Systems Based on Energetic, Economic and Environmental Performance explained by Abdullah Ahmed Bawazir and Daniel Friedrich [73]. The study shows that solar driven adsorption cooling systems can significantly reduce the operational costs and CO2 emissions of cooling system in the desert climate of Saudi Arabia. An Experimental Study with Condenser Embedded Adsorber of an Adsorption Chiller explained by Gamze Gediz Ilis and Hasan Demir [74].

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 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.

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 Table 1.

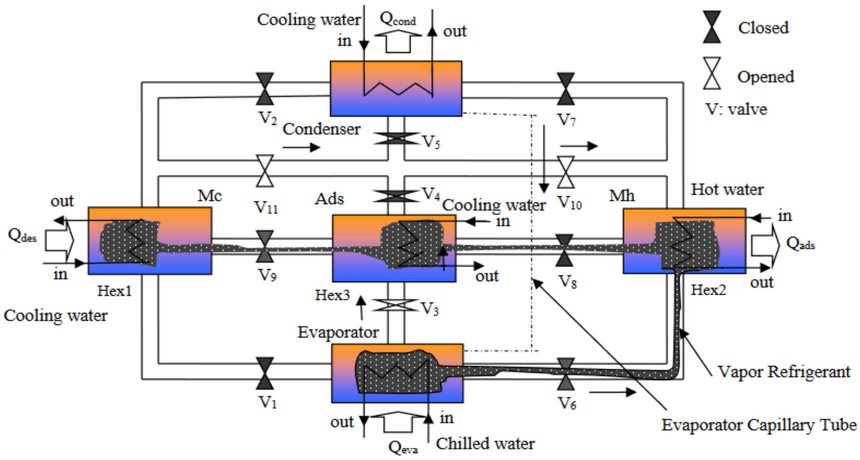
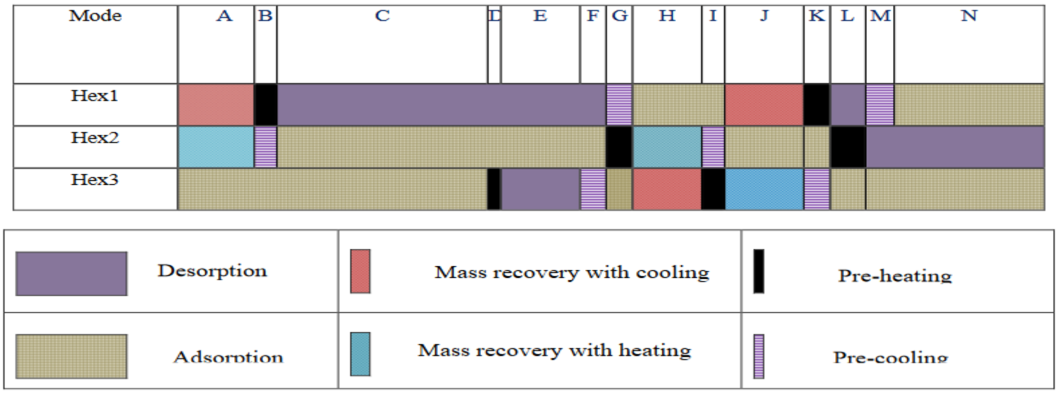


Figure1: Schematic of three bed chiller with mass recovery.

Table 1: 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

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

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

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

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 transfers 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 transfers 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.

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.

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

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

RESULTS AND DISCUSSIONS

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

Values Adopted in Simulation

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 ~ 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	

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

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[-]	$T_{chillout}$ [^{0}C]
With Mass Recovery (WMR)	3.7904	0.6685	8.0626
Without Mass Recovery (WOMR)	2.5082	0.6009	10.2418

Comparison of the results

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.

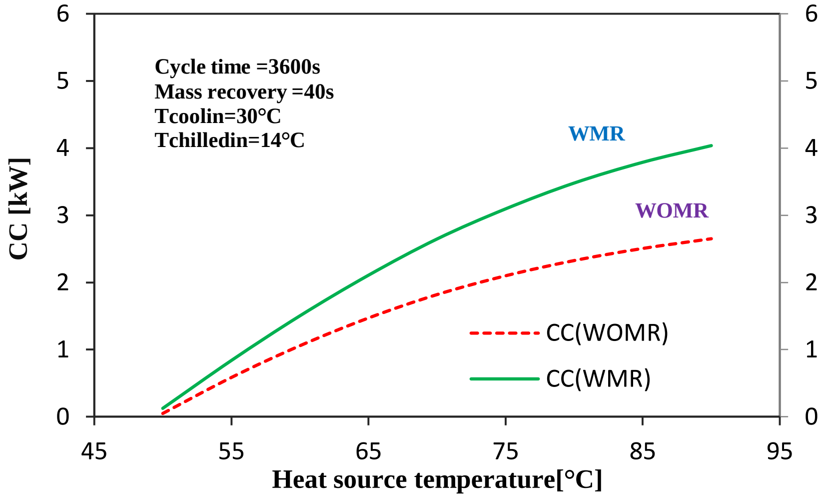

Figure 2: Performance comparison of CC between the three bed chiller with and without mass recovery process

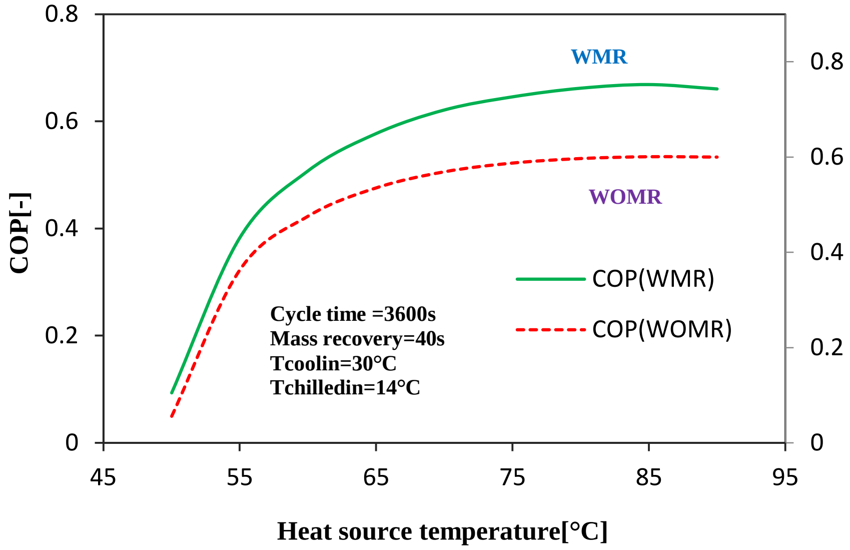

Figure 3: Performance comparison of COP between the three bed chiller with and without mass recovery process

The ability to produce a low chilled water outlet is one of the indicators to test the performance of the new cycle. The performance of the cycle with mass recovery is much better than that of the cycle without mass recovery because the chilled water outlet temperature of the cycle without mass recovery is higher than that of the cycle with mass recovery as shown in Figure 4. According to Figure 4, the cycle with mass recovery is able to produce chilled water at lower temperature than that of the cycle without mass recovery.

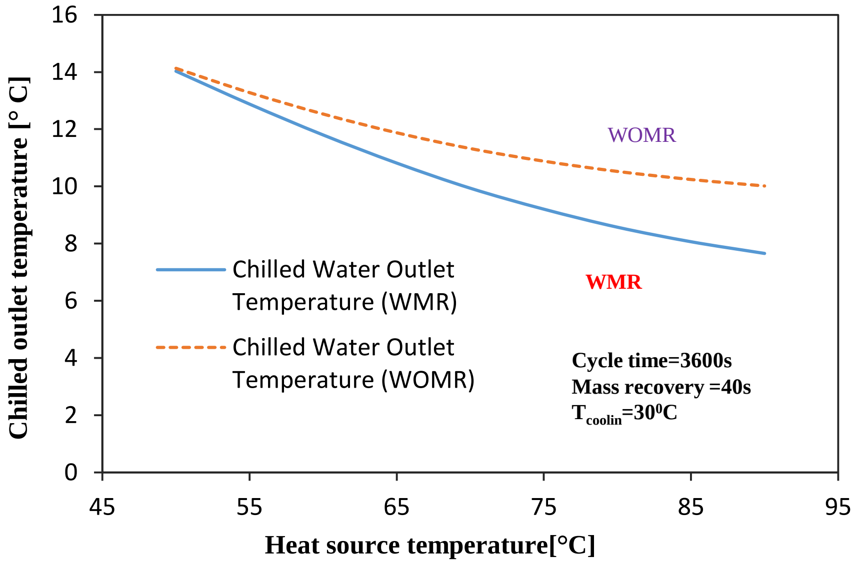

Figure 4: Performance comparison of outlet chilled water between the three bed chiller with and without mass recovery

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 85^0C.
(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 delivered chilled water temperatures are obtained at 8.0626^0C for cycle with mass recovery process and 10.2418^0C for cycle without mass recovery process, especially for hot water inlet temperature at 85^0C.

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