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

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ABSTRACT: *In this paper, the performance comparison between two different cycles has been numerically studied. 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). In the present numerical solution, the heat source temperature variation is taken from 70°C to 90°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, if any one bed (3^{rd} 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. Results show that the cooling capacity (CC) and coefficient of performance (COP) of the cycle1 is much better than that of the cycle2 in the range of heat source temperature from 70^0C to 90^0C.*

KEYWORDS: silica gel-water, mass recovery, cooling capacity, coefficient of performance, renewable energy sources.

INTRODUCTION

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.

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.

Adsorption chillers are more environmentally sustainable than other types of chillers but the trade-off between price and performance makes it impossible for them to seize a significant market share in cooling. At a maximum COP of 1 and maximum Specific Cooling Power of 300 W kg^{-1}, the specific selling price of a Silica gel adsorption chiller is €1018 per kW of cooling power by Al-Hasni and Santori [2023]. Experimental study of a three-bed adsorption chiller with desalination function explained by Sztekler et al. [2020] and reported that the COP increased from 0.20 to 0.58 when the heating water temperature increased from 57^0 to 85^0C.

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 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.

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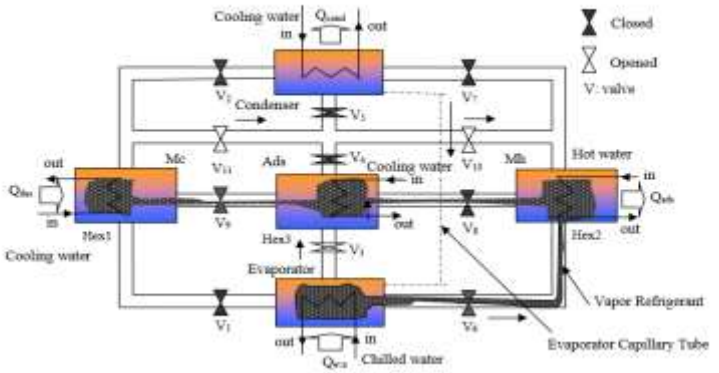


Figure1: Schematic of three bed chiller with mass recovery (cycle1).

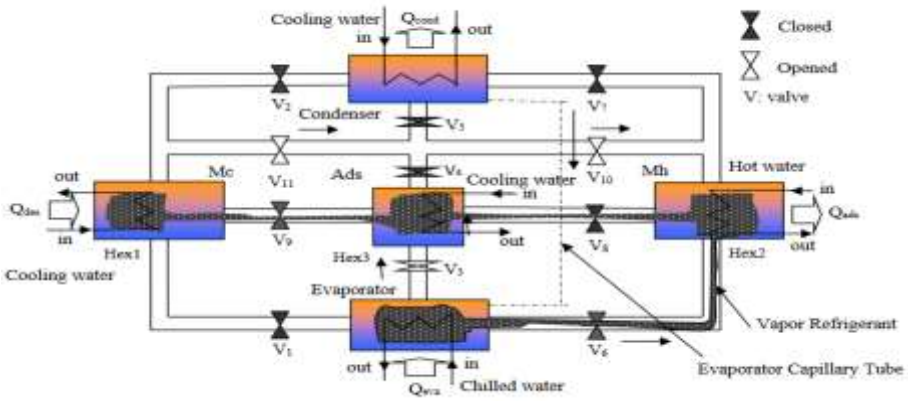
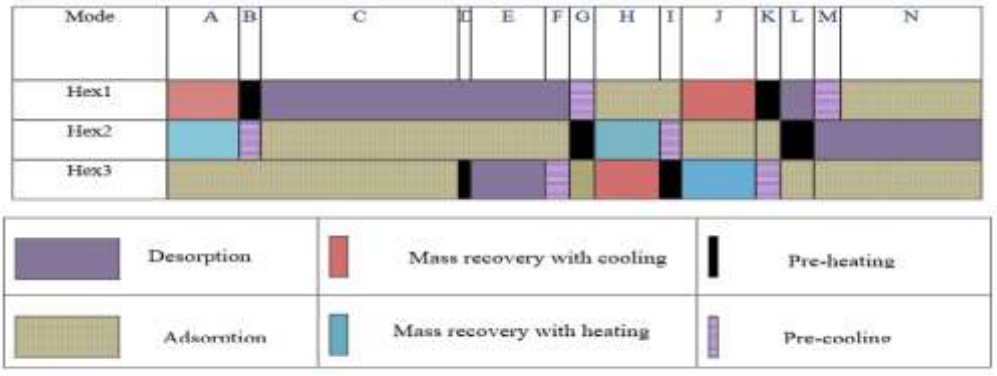


Figure2: Schematic of three bed chiller with mass recovery (cycle2).

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 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:

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

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

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

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

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

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.

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	16	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	70 ~ 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.

Comparison of the result between two cycles

Figures 3-5 show the comparison of the numerical results between the cycle1 and the cycle2. Both of the cycles were tested at the same conditions based on the input parameters. From the figure 4, it is clearly found that COP of the cycle1 is higher than that of the cycle2 if heat source temperature is 85^0C. It should be noted that the cooling capacity (CC) of the cycle1 is much better than that of the cycle2 (see Fig.3) in the range of heat source temperature from 70^0C to 90^0C.

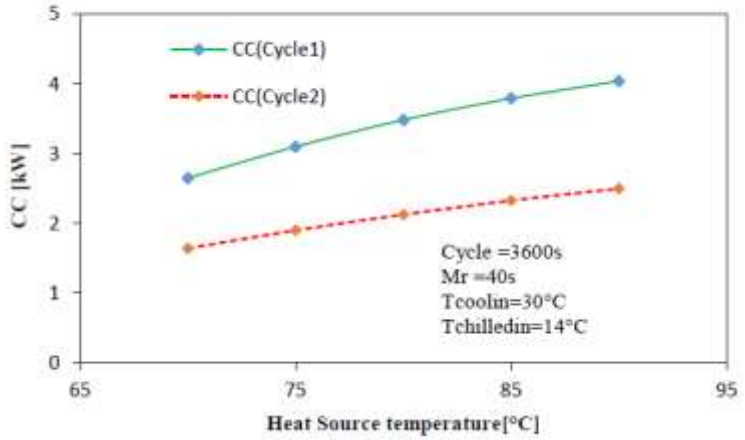


Fig 3: Performance comparison of CC between the cycle1 and cycle2

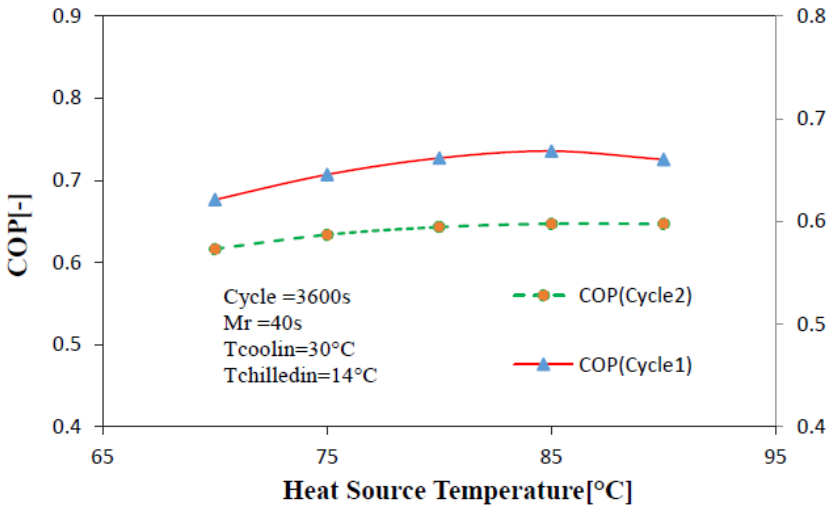


Fig 4: Performance comparison of COP between the cycle1 and cycle2

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 cycle1 is much better than that of the cycle2 because the chilled water outlet temperature of the cycle2 is higher than that of the cycle1 as shown in Figure 4.1(c). According to Figure 4.1(c), the cycle1 is able to produce chilled water at lower temperature than that of the cycle2.

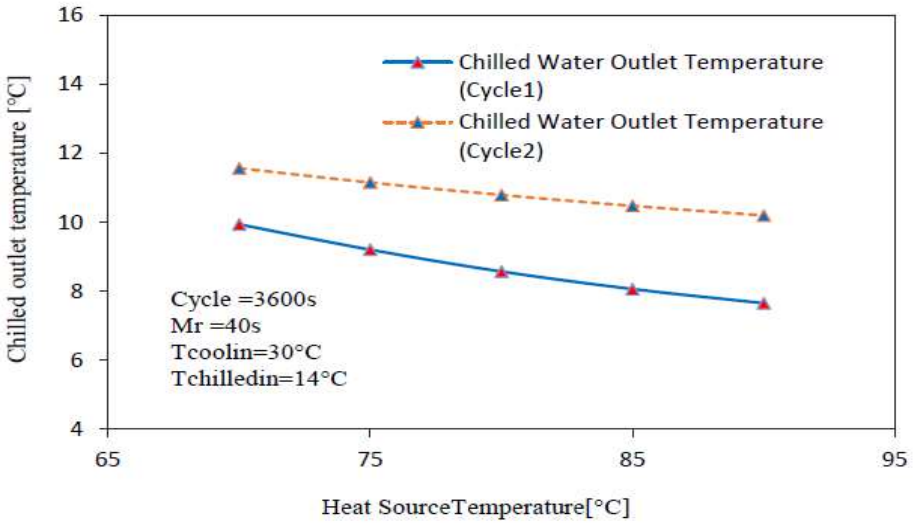


Fig 4.3(c): Performance comparison of outlet chilled water between the cycle1 and cycle2

CONCLUSION

The comparison of the numerical results between the cycle1 and the cycle 2 are discussed in the present study. The following possible outcomes can be drawn from the present analysis:

(i) The cooling capacity (CC) and coefficient of performance (COP) of the cycle1 is much better than that of the cycle2 in the range of heat source temperature from 70^0C C to 90^0C.

(ii) The optimum COP value is obtained for hot water inlet temperature at 85^0C.

(iii) The delivered chilled water temperatures are obtained at 8.0626^0C for cycle1 and 10.4704^0C for cycle2, especially for hot water inlet temperature at 85^0C.

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