Photovoltaic Driven Adsorption Refrigeration Cycle

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Abstract—**The study investigated the cycle optimization of four-hex, silica gel-water adsorption with re-heat cycle, which is desorber (upper–hex) and adsorber (lower-hex) always interact with condenser and evaporator, to exploit low heat source temperature. A photovoltaic system designed and implemented in order to produced hot water which is used as solar driven or heat source in the adsorption refrigeration cycle. In this paper, the working principle of re-heat cycle introduced and a simulation model of re-heat adsorption cycles has developed as well. The optimization of the cycle time including adsorption/desorption time, mass recovery time and pre-heating/pre-cooling time, with chilled water outlet temperature fixed has observed during simulation. The proposed cycle was compared with the four-hex without re-heat cycle in terms of COP and cooling capacity and will be the performance indicator of the cycle. The result shows that the performance of re-heat cycle is superior to that of four-hex without re-heat especially for low heat source temperature. For low heat source temperature (55-65ºC) both COP and cooling capacity of re-heat cycle with optimization raised significantly compared to the high heat source temperature (70-80 ºC)**

Keywords—photovoltaic driven; adsorption; re-heat cycle; optimization; COP; cooling capacity

I. INTRODUCTION

Adsorption refrigeration which is good for environment become took attention nowadays because of its advantages such as use low temperature driven, good energy saving, there is no CFCs or HCFCs, simple maintenance and safe.

Adsorption cooling systems are considered not only as an alternative to reduce the use of CFCs and HCFCs but also as an energy efficient technology [1]. Meanwhile, the adsorption cycle has its own advantages compare to another systems in its ability to be driven by relatively low heat source temperature can be recovered, which is investigated by Kashiwagi et al. [4]. The advanced adsorption refrigeration performances, known as re-heat cycle has been investigated Alam et al. [5], Uyun et.al [2] and Khan et al. [8], without concerning in cycle optimization and not-fixed chilled water outlet condition. Arranging a fixed chilled water outlet temperature is a good effort to improve the efficiency and to maximized the cooling capacity [3]. Waste heat below 100ºC is considered for driving heat source due to effective cooling production. Therefore, silica gel-water is chosen because the regeneration temperature of silica gel is low than that of activated carbon and water has large latent heat of vaporization. For example, zeolite/water et.al [7] and silica gel/water [6].

In this paper, a photovoltaic system designed and implemented in order to produced low heat source temperature (55-65 ºC) as a driven heat for the propoused cycle. A simulation program using MATLAB and PSO are developed to shown the cycle optimization value of re-heat cycle adsorption chiller performances, repectively. The optimization of four-hex re-heat cycle focusing in adsorption/desorption time, mass recovery time and pre-heating/pre-cooling time, especially in chilled water out temperature 9 ºC.

The research investigation shown that mass flow rate should be controlled to fixed chilled water out temperature and optimization in cycle time of re-heat cycle has informing better performance in both COP and cooling capacity. The optimization in both COP and cooling capacity reached 80% for heat source temperature 55ºC. For low heat source temperatures, applying cycle time integration must be chosen wisely.

II. OPERATIONAL STRATEGY OF RE-HEAT ADSORPTION CYCLE

Figure 1 shows re-heat adsorption cycle draft. It's consists of four heat exchangers (HEX), an evaporator and one condenser. Adsorption, mass recovery with cooling, pre-heating, desorption, mass recovery with heating and pre-cooling are the six processes operated in a full cycle. During adsorption process, evaporator vaporized water/refrigerant at the evaporator temperature (T_{eva}) and seized heat (Q_{eva}) from the chilled water isobarically and the evaporation process occurs which is produces cooling effect. The heat of evaporation is supplied by flowing chilled water at low heat source temperature. In first half cycle, HEX1 is heated by hot water and HEX3 is cooled by cooling water. Since the pressure of HEX1 and HEX3 nearly equal, then both are connected by opening the connecting valve, allowing vapor flow from HEX1 into HEX3, whichi is known as mass recovery process. Heating and cooling process are continued during mass recovery process and HEX1 and HEX3 is still heated up and cooled by hot water and cooling water to provide more cooling capacity. In this process, there is no refrigerant circulation because all refrigerant valves are in closed position and known as pre-heating/pre-cooling process. If the pressures of HEX1 and HEX3 are nearly equal to the pressures of condenser and evaporator, then the valve between HEX1 and condenser or the valve between HEX3 and evaporator is opened, allowing refrigerant to flow and starting the adsorption and desorption process again. In this process, refrigerant water from HEX1 will be transferred to the condenser and it will condensed by releasing heat to heat tank. In the end, the liquid refrigerant flows from condenser to evaporator throughout u shape tube in

order to control pressure difference between condenser and evaporator. The next process is the same as the first half-cycle to complete a full cycle. Only, the position of HEX3 and HEX1 is as desorber and adsorber, respectively.

Table 1 represents the strategy work of re-heat cycle and consists of 10 modes (mode A-J). The special characteristic of the strategy is in mode C and mode H because there are two HEXs doing adsorption and desorption process simultaneously.

The parameter and standard operating conditions applied in simulation refers to the Table II and Table III, respectively.
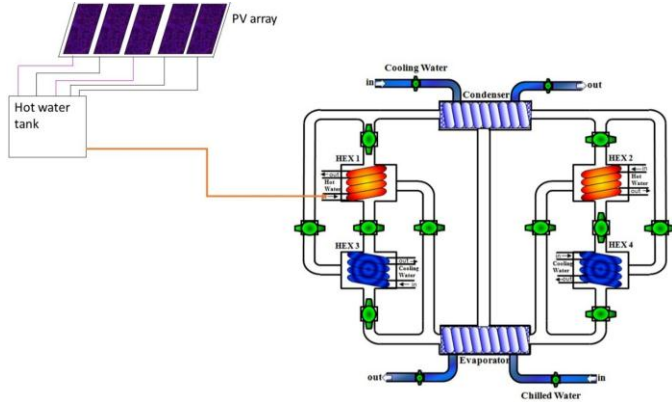

Fig. 1. Re-heat adsorption cycle scheme

TABLE I.   OPERATIONAL STRATEGY OF RE-HEAT TWO STAGE CYCLE

Hex	Mode									
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**
1		Des		Mrh	Pc		Ads		Mrc	Ph
2	Mrh	Pc		Ads		Mrc	Ph		Des	
3		Ads		Mrc	Ph		Des		Mrh	Pc
4	Mrc	Ph		Des		Mrh	Pc		Ads	

Ads = adsorption
Des = desorption
Mrh = mass recovery heating
Mrc = mass recovery cooling
Pc = pre-cooling
Ph = pre-heating

III. SIMULATION EQUATION

A. Energy Balance in Adsorber/Desorber

The heat transfer formulation of adsorbent hex described as follows:

$$T_o = T + (T_i - T) exp\left(\frac{U_{hex} \cdot A_{hex}}{\dot{m}_w \cdot C_w}\right) \tag{1}$$

Here, T states hex-temperature. It's assumed that temperature, pressure, and concentration of hex-adsorbent are to be uniform in all hex-adsorbents. Due to our system works in a low concentration range so that the specific heat of refrigerant (water) in the liquid phase has taken. Term T_i and T_o denotes heat transfer fluid (water) temperature cooling water upon adsorption and hot water upon desorption.

TABLE II.   SIMULATION PARAMETERS

Symbol	Value	Unit
C_s	924	J/kgK
C_v	1.89E+03	J/kgK
C_w	4.18E+03	J/kgK
D_o	2.54-4	m²/s
E_a	4.20E+04	J/kg
L_w	2.50E+06	J/kg
Q_s	2.86E+06	J/kg
R	8.314	J/kgK
R_p	3.00E-04	m
UA_{ads}	2001	W/m²K
UA_{des}	2233	W/m²K
UA_{eva}	2360.75	W/m²K
UA_{con}	4061.86	W/m²K
W_s	16	kg
$W_{con,w}$	5	kg
$W_{eva,w}$	25	kg

TABLE III.   OPERATING CONDITIONS

	Temperature (ºC)	Flow Rate (kg/s)
Hot water	60	1
Cooling water	30	1(ads) + 0.8(des)
Chilled water	14	0.8
Cycle time (Ads/Des+Mr+Ph/Pc)	(420 + 200 + 30) s	

Noted:
Ads/Des = adsorption/desorption
Mr= mass recovery
Ph/Pc = pre-heating/precooling

The energy balance of the adsorbent hex is:

$$(W_s.C_s + W_s.C_w.q + W_{hex}.C_{hex})\frac{dT}{dt} = W_s.Q_s\frac{dq}{d_t}W_s.C_v.\delta[\gamma(T - T_{eva}) + (1-\gamma)(T - T_{wv})]\frac{dq}{dt} + \dot{m}_w.C_w.\varepsilon_{hex}(T_i - T) \tag{2}$$

where δ is 0 or 1 depending on whether the hex adsorbent functions as desorber or adsorber and γ is 1 or 0 depending on whether the hex is connected to another evaporator or hex. Eq. (1) states the importance of heat transfer parameters, namely heat transfer area A_{hex} and overall heat transfer coefficient U_{hex}. The left hand side of Eq. (2) provides the amount of sensible heat required to cool or heat the silica-gel (s), water (w) as well as metallic (hex) parts of the heat exchanger during adsorption or desorption. This term describes the input / output of sensible heat needed by batch-cycle operations. On the right hand side of Eq. (2) constitutes the release of adsorption heat or the input of desorption heat and the terms for the sensible heat of the adsorbed vapor. The last term on the right hand side of Eq. (2) means the total amount of heat released to the cooling water upon adsorption or provided by the hot water for desorption. Eq. (2) does not take into account for external heat losses to the environment because all hexes are considered in good isolated. ε_{hex} in Eq. (2) states the heat exchanger effectiveness that came from log mean temperature difference of heat exchanger (HEX) in flow system.

B. Energy Balance in Condenser

Eq. (3) reflect as the heat transfer of condenser while Eq. (4) as energy balances for condenser, and can be writes as

$$T_{con,o} = T_{con} + (T_{cw,i} - T_{con}) exp\left(-\frac{U_{con}.A_{con}}{\dot{m}_{cw}.C_w}\right) \qquad (3)$$

$$(W_{con,w}.C_w + W_{con,hex}.C_{con,hex})\frac{dT_c}{dt} = \dot{m}_{cw}.C_w.\varepsilon_{con}(T_{cw,i} - T_{cw,o}) - W_s\left(\frac{dq_{des}}{dt} + \frac{dq_{des}}{dt}\right)(L + C_v(T_{des} - T_{con})) \qquad (4)$$

C. Energy Balance in Evaporator

Eq. (5) reflects the heat transfer of evaporator and Eq. (6) as energy balances for evaporator, respectively:

$$T_{chill,o} = T_{eva} + (T_{chill,i} - T_{eva}) exp\left(-\frac{U_{eva}.A_{eva}}{\dot{m}_{ch}.C_{ch}}\right) \qquad (5)$$

$$(W_{eva,w}.C_w + W_{eva,hex}.C_{eva,hex})\frac{dT_e}{dt} = \dot{m}_{chill}.C_{chill}.\varepsilon_{eva}(T_{chill,i} - T_{chill,o}) - W_s\left(\frac{dq_{ads}}{dt} + \frac{dq_{des}}{dt}\right)(L + C_v(T_{con} - T_{eva})) \qquad (6)$$

The right hand side of Eq. (6) informs the total amount of heat from chilled water while the second term states for the latent heat and the sensible heat of vaporization (L) of refrigerant adsorbed (dq_{ads}/dt) required to cooled condensate came from the condensation temperature T_{con} to evaporation temperature T_{eva}. ε_{eva} in Eq. (6) states the heat exchanger effectiveness from log mean temperature difference of heat exchanger (evaporator) in the system. The sensible heat requirement by the liquid refrigerant and the metal of heat exchanger tubes in the evaporator are represents in the left hand side of Eq. (6)

D. Formula of the Performance

The performance of the re-heat adsorption cycle can be measured as Coefficient of performance (COP) and cooling capacity (CC):

$$COP = \dot{m}_{ch}C_w\int_0^{t_{cycle}}(T_{ch,i} - T_{ch,o})dt / \dot{m}_{hw} x \ C_w\int_0^{t_{cycle}}(T_{hw,i} - T_{hw,o})dt \qquad (7)$$

$$CC = \dot{m}_{ch}C_w\int_0^{t_{cycle}}(T_{ch,i} - T_{ch,o})dt / t_{cycle} \qquad (8)$$

IV. Optimization Method

In this paper, MATLAB with ode-45 solver and Particle Swarm Optimization (PSO) are developed to obtain the performance of re-heat cycle based on the equation (1)-(8). All input parameters in Table II and standard operating condition in Table III were applied in simulation. PSO was applied to optimize the adsorption/desorption time, pre-heating/pre-cooling time and mass recovery time. COP and cooling capacity were chosen as the objective function and will be the performance indicator of the optimization.

V. Results and Discussion

A. Temperature Characteristics In Hex

The trend of temperature histories of the four-hex of the chiller with heat source temperature 60°C and total cycle time 1300s are plot in Figure 2. It is described here that in the beginning of the cycle (420s), shows that HEX2 and HEX4 are in mass recovery process where HEX2 and HEX4 is in heating and cooling process (mode A), respectively. It is mean that at the beginning, the temperature of HEX2 decreased and that of HEX4 increased. After that, the temperature of HEX2 is increased and HEX4 decreased because of heating and cooling by hot and cold water, simultaneously. By this time being, HEX2 and HEX4 start to desorb and adsorb water vapor. During mode B, HEX2 and HEX4 are in pre-cooling and pre-heating process, caused the temperature of HEX2 decreased and pressure decline. Oppositely, temperature of HEX4 increased. The next process is desorption process for HEX2 and adsorption process for HEX4 (mode C, D and E).

During this process, HEX2 and HEX4 are in evaporator and condenser pressure. HEX2 will adsorb refrigerant which is evaporated in evaporator. Meantime, adsorbed HEX4 refrigerant will be released to the condenser during the adsorption process and then condensed in a condenser. Mode E is a first half-cycle and the next cycle (mode F to J) is alike to mode A into mode E, only change the position of adsorber and desorber in every hex pairs, which is clearly seen in this picture
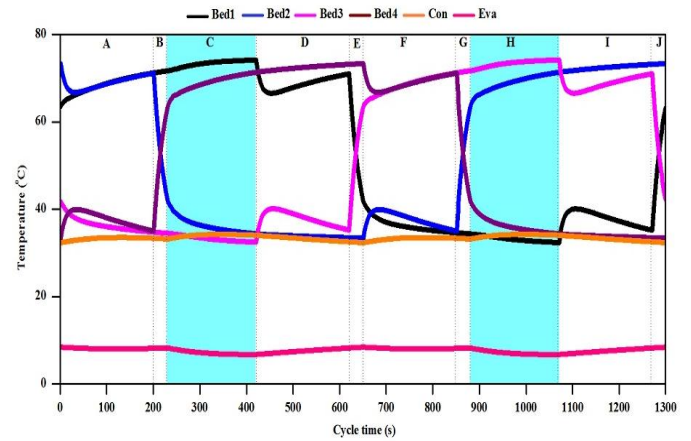

Fig. 2. Temperature characteristics of four-hex re-heat adsorption cycle

B. Water Content Characteristics In Hex

The tendency of variation water contents in adsorber/desorber of hex is shown in Figure 3. Heat source and chilled water outlet temperature at 60°C and fixed at 9°C are implemented. Water contents were decreased in hex1, hex2, hex3 and hex4 during desorption process (i.e., mode A to C for hex1, mode H to J for hex2, mode F to H for hex3 and mode C to E for hex4) and increased during adsorption process (i.e., mode F to H for hex1, mode C to E for hex2, mode A to C for hex3 and mode H to J for hex4). Water contents in all hexs were remained constant during pre-heating and pre-cooling process, due to all valves of the system were closed position (i.e., mode E for hex1 and mode J for hex3). During mass recovery with heating process, water content in hex1 decreased, mode D, because vapor transferred into hex3, therefore water content in hex3 increased, respectively. During mass recovery with cooling process, water content in hex1 increased, mode I), due to receive vapor from hex3, therefore water content in hex3 decreased in mode I.
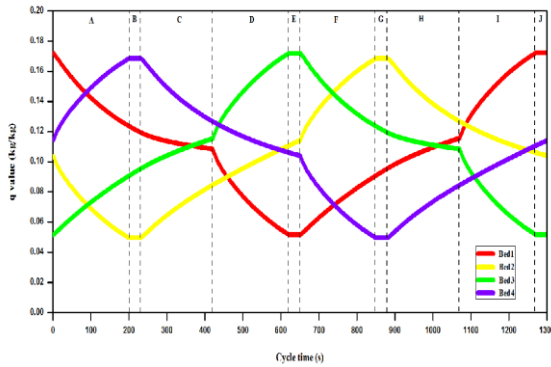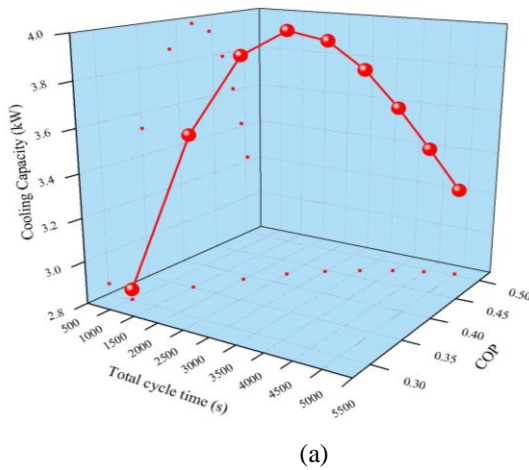
Fig. 3. The Tendency of water content in hex
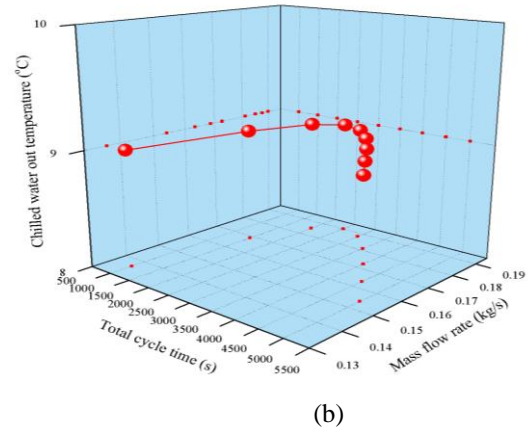

(b)

Fig. 4. Performance of cycle time

C. Cycle Time Performance

Figure 4 informed the relations of the effect of cycle time on the performance and the correlation among chilled water out temperature and mass flow rate of four- hex re-heat cycle.

Based on Fig.4 (a), it was mentioned that COP increased along with cycle time. Cycle time 1000s to 5000 s with 500s escalation is applied to shown the performance characteristic. Temperature of chilled water out applied in fixed condition at 9°C while controlled mass flow rate based on Fig. 4 (b). By this figure, can be said that mass flow rate increased due to gain the chilled water out temperature 9°C in cycle time from 1000s to 3000s and decreased when the cycle time more than 3000s. On the other hand, to gain chilled water outlet 9°C, cycle time from 2000s to 3000s required highest mass flow rate. Cycle time between 2000s and 3000s offering the highest cooling capacity and cycle time out of this range made cooling capacity lower. The reason can be said that the adsorption/desorption process cannot be occurred well within long cycle time. For the short cycle time, the process reaches its equilibrium state, which causes cooling capacity decline smoothly.

D. Optimization of Cycle Time

Figure 5(a) and Figure 5(b) informed the cycle time optimization of four hex re-heat cycle and the achievement of chilled water out temperature by controlling mass flow rate. There are adsorption/desorption time, mass recovery time and pre-heating/pre-cooling time in these optimizations. Heat source temperature 55 to 80 °C applied to observe its characteristic.

From the Fig.5(a & b) it is observed that cycle time is decreasing with heat source temperature and chilled water flow rate was increased with heat source temperature to maintain the chilled water outlet temperature at constant temperature., Its required longer cycle time to gain the optimum performance for heat source temperature 55°C. But, the opposite tendency occurred in the heat source temperature (80°C). It appears that, there is the highest increase of 80% in both COP and cooling capacity at temperatures of 55 °C, while 20% increment for heat source temperature 60°C and 7% increment for heat source temperature 65°C, respectively.

Unfortunately, heat source temperature between 70-80 °C, there is no significant improvement increment in both COP and cooling capacity in about 1%.

In this case, before optimization, cycle time selection based on Table III was not suitable for low heat source temperature to achieve the best performance. Then, the optimized cycle time based on Fig. 5(a) should be applied. For high heat source temperature the optimization of cycle time still offering better performance.

VI. CONCLUSION

In this study, the optimization of four hexs re-heat cycle while applying chilled water out temperature fixed has observed. Mass flow rate is required to control due to gain fixed chilled water out temperature. Cycle time below 3000s required mass flow rate higher than cycle time up to 3000s. Cycle time couse the COP increased along with. Cycle time between 2000s and 3000s give the highest cooling capacity values.

(a)
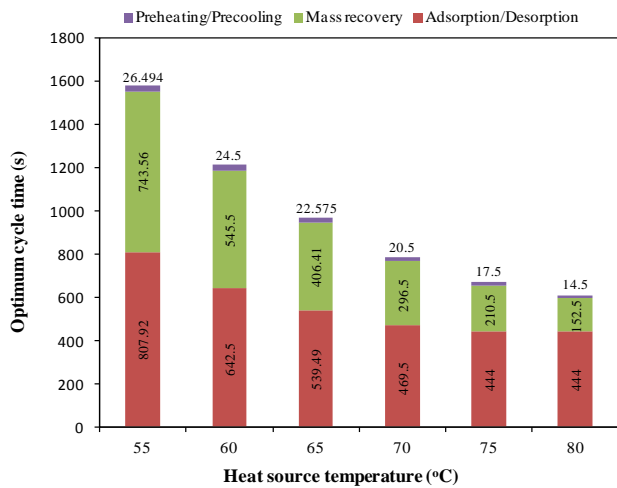
(a)
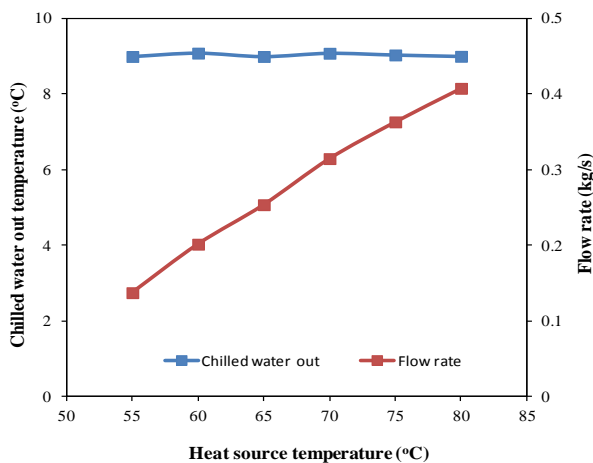
(b)

Fig. 5.   Cycle time optimization

Cycle optimization of re-heat cycle has offering better performance in both COP and cooling capacity. For heat source temperature 55ºC shown the highest increment of 80% raised in both COP and cooling capacity, while 20% increment for heat source temperature 60ºC and 7% increment for heat source

temperature 65ºC respectively. For relatively high heat source temperature (70-80ºC), although there was increment in both

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