



## Simulation and experimental verification on re-heat two-stage adsorption refrigeration cycle

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### Abstract

In this paper, an experimental investigation of re-heat two-stage adsorption cycle is verified by MATLAB simulation, and the working principle of the cycle introduced as well. The objective is to verify the effect of heat source temperature on the performance if chilled water outlet temperature is fixed at 9 °C in simulation and compared with the experiment. Coefficient of performance and cooling capacity are the performance indicator of the cycle.

**Keywords:** Re-heat adsorption cycle; COP; cooling capacity; desorber; and adsorber

### 1. Introduction

Adsorption refrigeration system is one of the environmentally friendly cooling systems because of not only as an alternative for reducing CFCs and HCFCs uses but also as an energy efficient technology and contributes for the green technology [1]. When compared to other cycles, the adsorption cycle has advantages in terms of its ability to use a relatively low heat source which is close to the environment temperature so that temperatures below 100 °C can be used, which are investigated by Kashiwagi et al [2]. One of the adsorption cycles namely reheat two-stage has been studied by Alam et al [3] and Khan et al [4].

However, chilled water outlet temperature is arranged in fluctuated. Thong et al [5] alleged that it is also important to maintain a constant chilled water outlet temperature in order to increase the conversion efficiency of the system and Wirajati et al [6] conducted the experiment by implementing the fixed chilled water outlet conditions. In this paper, a MATLAB program is developed and compared with the experiment to shown the performance of the cycle. The results show that the performance increased along with heat source temperature and cycle times 2000 – 2500s produces highest cooling capacity.

### 2. Working Principle of the Cycle

Figure 1 (a) show the reheat two-stage adsorption cycle scheme while Figure 1 (b) shows the P-T-X diagram for standard conditions. The adsorbent heat exchangers of the chiller are operated in a cycle through six thermodynamic

processes, namely: adsorption (1-2), mass recovery with cooling (2-3), pre-heating (3-4), desorption (4-5), mass recovery with heating (5-6), and pre-cooling (6-1). In the adsorption-evaporation process, refrigerant (water) in evaporator is evaporated at the temperature ( $T_{eva}$ ) and seized heat ( $Q_{eva}$ ) from the chilled water. At the end of each half-cycle, one heat exchanger (HEX-1) is cold and the other one (HEX-2) is hot. Simultaneously, HEX-1 is at low pressure and must be pressurized up to condenser pressure; HEX-2 is at high pressure and must be depressurized down to evaporator pressure. Making up and down of this pressure, vapor is transferred from desorber to adsorber.

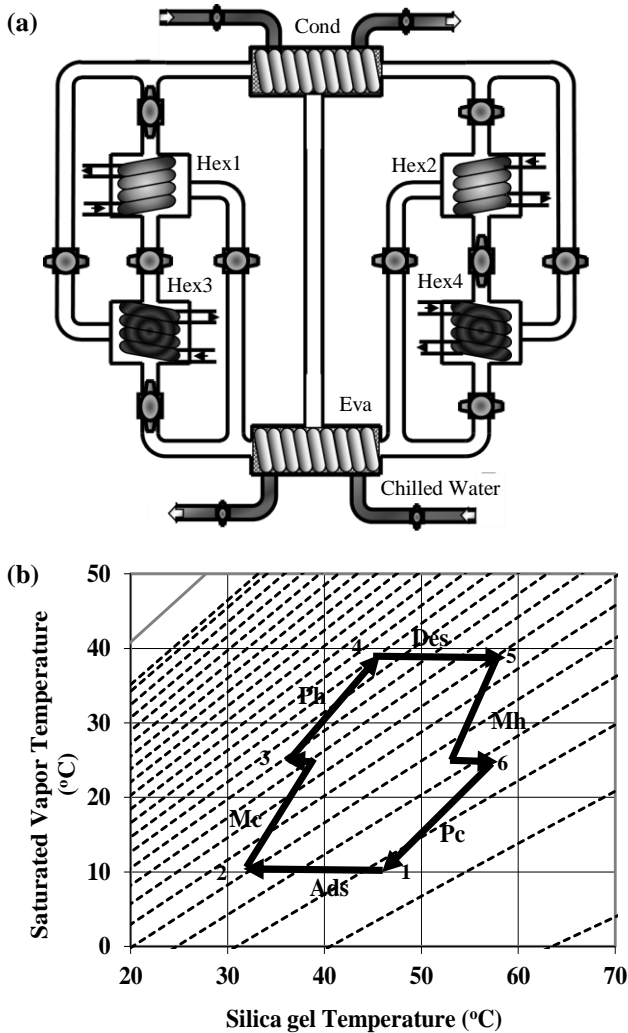
This process is known as mass recovery process. Adsorption/desorption process will occur automatically due to a difference in heat exchanger's pressure. HEX-2 pressure increases while HEX-1 pressure decreases. Both HEX pressures reach the same point. To provide more cooling capacity, desorber temperature (HEX-2) is still at high temperature or continuing heating process. Refrigerant release is still occurring from HEX-2 to HEX-1. It causes HEX-2 concentration to decrease. Afterwards, HEX-1 is heated up by hot water and HEX-2 is cooled down by cooling water. During this process, refrigerant circulation is stopped by closing all refrigerant valves. This process is known as pre-heating/pre-cooling process. When the pressures of HEX-1 and HEX-2 are nearly equal to the pressures of condenser and evaporator, the valve between HEX-1 and condenser (as well as the valve between HEX-2 and evaporator) is opened, allowing refrigerant to flow.

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**Nomenclature**

A	Area (m <sup>2</sup> )	q*	Concentration equilibrium (kg <sub>ref</sub> kg <sub>ad</sub> <sup>-1</sup> )
C	Specific heat (kJ kg <sup>-1</sup> °C <sup>-1</sup> )	Q <sub>st</sub>	Iso-steric heat of adsorption (J kg <sup>-1</sup> )
D <sub>0</sub>	Pre-exponential constant (m <sup>2</sup> s <sup>-1</sup> )	R	Gas constant (J mol <sup>-1</sup> K <sup>-1</sup> )
E <sub>a</sub>	Activation energy (J mol <sup>-1</sup> )	R <sub>n</sub>	Average radius of a particle (m)
L	Latent heat of vaporization (J kg <sup>-1</sup> )	T	Temperature (K)
ṁ	Mass flow rate (kg s <sup>-1</sup> )	t	Time (s)
P <sub>s</sub>	Saturated vapor pressure (Pa)	U	Overall heat transfer coefficient (W m <sup>-2</sup> K <sup>-1</sup> )
q	Concentration (kg <sub>ref</sub> kg <sub>ad</sub> <sup>-1</sup> )	W	Weight (kg)

Adsorption and desorption process then starts. In this process, refrigerant from HEX-1 will be liquefied in condenser by releasing heat condenser to heat sink. Refrigerant liquid flows from condenser to evaporator. In evaporator, refrigerant will be adsorbed iso-barically by HEX-2. Evaporation process occurs and produces cooling effect. Evaporation heat is supplied by flowing chilled water at low heat source temperature. To complete one cycle, the next process is the same as the previous half-cycle. Only, the position of HEX-1 is as desorber and HEX-2 is as adsorber.



**Figure 1.** (a) Reheat two stage adsorption scheme and (b) P-T-X Diagram

**Table 1.** Operational strategy

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

Ads = adsorption, Des = desorption, Mh = mass recovery heating, Mc = mass recovery cooling, Ph = pre-heating, Pc = pre-cooling

**3. Developing Equation**

*3.1. Heat Transfer in Evaporator, Condenser and Heat Exchanger*

Heat transfer in evaporator, condenser and heat exchanger describes as follow:

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

$$T_{chill,o} = T_{eva} + (T_{chill,i} - T_{eva}) \exp\left(-\frac{U_{eva} \cdot A_{eva}}{\dot{m}_{ch} \cdot C_{ch}}\right) \tag{2}$$

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

In this case, T indicates the temperature. The temperature and concentration of the liquid in both Hex, evaporator and condenser are assumed uniform. Specific heat from refrigerant (water) in the liquid phase because the system works in the low concentration range. The temperature of fluid (water), T<sub>i</sub> and T<sub>o</sub> fluid heat transfer shows cold water and hot water when the process of adsorption and desorption. U and A in the formula state the heat transfer parameters, namely the overall heat transfer coefficient and heat transfer area

*3.2. Energy Balance in Evaporator, Condenser and Heat Exchanger*

Energy balance in evaporator, condenser and heat exchanger express below:

$$\begin{aligned} (W_s \cdot C_s + W_s \cdot C_w \cdot q + W_{bed} \cdot C_{bed}) \frac{dT}{dt} = \\ W_s \cdot Q_s \frac{dq}{dt} - W_s \cdot C_v \cdot \delta [\gamma (T - T_{eva}) + (1 - \gamma) (T - T_{ww})] \frac{dq}{dt} + \\ \dot{m}_w \cdot C_w \cdot \epsilon_{bed} (T_i - T) \end{aligned} \tag{4}$$

$$\begin{aligned} (W_{eva,w} \cdot C_w + W_{eva,bed} \cdot C_{eva,bed}) \frac{dT_e}{dt} = \\ \dot{m}_{chill} \cdot C_{chill} \cdot \epsilon_{eva} (T_{chill,i} - \\ T_{chill,o}) W_s \left( \frac{dq_{ads}}{dt} + \frac{dq_{des}}{dt} \right) (L + C_v (T_{con} - T_{eva})) \end{aligned} \tag{5}$$

$$(W_{con,w} \cdot C_w + W_{con,bed} \cdot C_{con,bed}) \frac{dT_c}{dt} = \dot{m}_{cw} \cdot C_w \cdot \varepsilon_{con} (T_{cw,i} - T_{cw,o}) - W_s \left( \frac{dq_{des}}{dt} + \frac{dq_{ads}}{dt} \right) (L + C_v (T_{des} - T_{con})) \quad (6)$$

Where  $\delta$  either 0 or 1 depends on whether the adsorbent functions as desorber or adsorber and  $\gamma$  either 1 or 0 depending on whether Hex is connected to the evaporator or with another Hex. The left side of the adsorber/desorber energy balance equation in equation (4) gives the amount of sensible heat needed to cool or heat the silica-gel (s), water (w) and the heat exchanger (hex) metal part during the adsorption or desorption process. This term takes into account the sensible heat input / output required when the cycle operates in accordance with the stages of the process. The first term on the right side of equation (4) is the release of heat from adsorption or heat desorption input, while the second term for sensible heat from steam is adsorbed. The last term on the right side of equation (4) refers to the total amount of heat released into cooling water after the adsorption process or provided by hot water for the desorption process. Equation (4) does not take into account the loss of external heat to the environment because all layers are considered well isolated. The term  $\varepsilon$  in equations (4.5 and 6) states the effectiveness of the heat exchanger derived from the log difference in the average temperature of the heat exchanger (hex, evaporator and condenser) in the flow system.

The left side of Equations (5 and 6) represents the sensible heat needed by liquid refrigerant and metal tube heat exchanger in the evaporator and condenser. The first term on the right side of equation (5) represents the total amount of heat from cold water and in equation (6) gives the amount of heat released into the cooling water. The second term in equation (5) describes explaining the latent heat of evaporation (L) for the amount of adsorbed refrigerant ( $dq_{ads}/dt$ ) and the sensible heat needed to cool the incoming condensate from the  $T_{con}$  condensation temperature to the  $T_{eva}$  evaporation temperature, while the second term equation (6) describes the latent heat of evaporation (L) for the amount of refrigerant absorbed ( $dq_{des}/dt$ ) and the amount of heat carried by the liquid condensate when it leaves the condenser to the evaporator

### 3.3. Performance Indicator

The performance of a re-heat two-stage adsorption chiller is mainly characterized by cooling capacity (CC), coefficient of performance (COP), and can be measured by the following equations:

$$\text{Cooling Capacity} = \dot{m}_{chill} C_w \int_0^{t_{cycle}} (T_{chill,in} - T_{chill,out}) dt / t_{cycle} \quad (5)$$

$$\text{COP} = \frac{\dot{m}_{chill} C_w \int_0^{t_{cycle}} (T_{chill,in} - T_{chill,out}) dt}{\dot{m}_{hot} C_w \int_0^{t_{cycle}} (T_{hot,in} - T_{hot,out}) dt} \quad (6)$$

### 3.4. Total Energy Balance

The total mass balance of refrigerant (water) can be expressed as:

$$W_{eva,w} = -W_s \left( \frac{dq_{des-con}}{dt} + \frac{dq_{ads-eva}}{dt} \right) \quad (7)$$

### 3.5. Adsorption Rate

The combination of silica-gel adsorption rate was modeled as a function of temperature [7]:

$$\frac{dq}{dt} = k_s a_p \cdot (q^* - q) \quad (8)$$

The overall mass transfer coefficient,  $k_s a_p$ , was estimated by Eq.(9) and (10), as below:

$$k_s a_p = \frac{15D}{R_p^2} \quad (9)$$

$$D = D_0 \exp(-E_a/RT) \frac{dq}{dt} = k_s a_p \cdot (q^* - q) \quad (10)$$

The amount adsorbed in equilibrium,  $q^*$ , is predicted by equation as follows:

$$q^* = \frac{0.8 \times [P_s(T_w)/P_s(T_s)]}{1 + 0.5 \times [P_s(T_w)/P_s(T_s)]} \quad (11)$$

where  $P_s(T_w)$  and  $P_s(T_s)$  are the saturation vapor pressure at temperature  $T_w$  (water vapor) and  $T_s$  (silica gel), respectively. The saturation vapor pressure and temperature are correlated by Antoine's equation, as follows:

$$P_s = 133.32 \times \exp\left(18.3 - \frac{3820}{T - 46.1}\right) \quad (12)$$

## 4. Results and Discussion

The MATLAB simulation program was developed to identify the performance and compared with the experiment. Both simulation and experiment were operated based on the Table 1 and Table 2.

### 4.1. Temperature Histories of Heat Exchanger (Bed)

Figure 2 has shown the temperature histories of Bed in both simulation and experiment. Heat source temperature 75°C and total cycle time 1300s are chosen

**Table 2.** Standard operating conditions of the simulation and experiment

	Temperature (°C)	Flow rate (simulation) (kg.s <sup>-1</sup> )	Flow rate (experiment) (kg.s <sup>-1</sup> )
Hot water	75	0.364	0.51
Cooling Water	30	0.8	1.4
Chilled water	14	0.364	0.51
Cycle time	1300 s = (420 + 30 + 200) x 2 (Ads/Des + Ph/Pc + Mc/Mh) x 2		

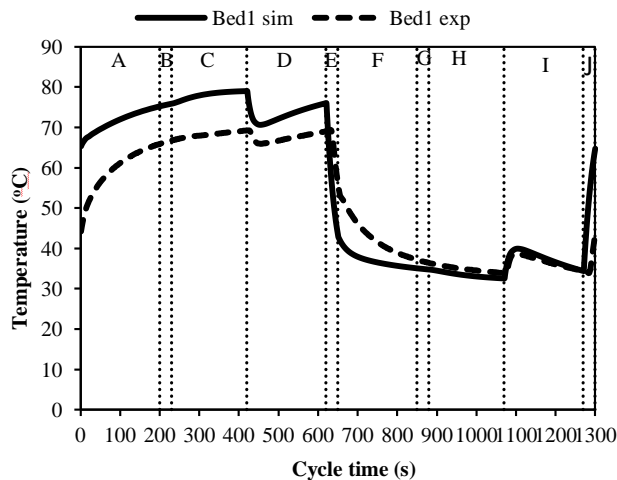
Ads/Des : Adsorption-Desorption time  
Ph/Pc : Preheating-Precooling time  
Mc/Mh : Mass recovery cooling & heating time

In the beginning (420s), mode A into mode C, Bed1 in desorption process, and therefore the temperature of HEX1 increased. In mode D, Bed1 in mass recovery with heating process. The temperature of Bed1 decreased suddenly and after that the temperature of Bed1 is increased due to heating by hot water. In mode E, Bed1 in pre-cooling process, so that temperature of Bed 1 decreased.

**Table 3.** Parameter's values in simulation

Symbol	Value	Unit
$C_s$	924	J/kg K
$C_v$	1.89E+03	J/kg K
$C_w$	4.18E+03	J/kg K
$D_o$	2.54E-4	m <sup>2</sup> /s
$E_a$	2.33E+06	J/kg
$L_w$	2.50E+06	J/kg
$Q_s$	2.86E+06	J/kg
$R$	4.62E+2	J/kg K
$R_p$	3.00E-04	m
$UA_{ads}$	2.00E+3	W/m <sup>2</sup> K
$UA_{des}$	2.23E+3	W/m <sup>2</sup> K
$UA_{eva}$	2.36E+3	W/m <sup>2</sup> K
$UA_{con}$	4.06E+3	W/m <sup>2</sup> K
$W_s$	16	kg
$W_{con,w}$	5	kg
$W_{eva,w}$	25	kg

The next process is adsorption process for Bed 1 (mode F, G and H). In this process, Bed 1 operates in evaporator pressure. Refrigerant in evaporator will be evaporated and adsorbed by Bed1. In mode I, Bed1 is in mass recovery with cooling process. The temperature of Bed 1 increased slightly and after that the temperature of Bed 1 is decreased due to cooling by cold water. In mode J, Bed1 in pre-heating process, so that temperature of Bed1 increased.

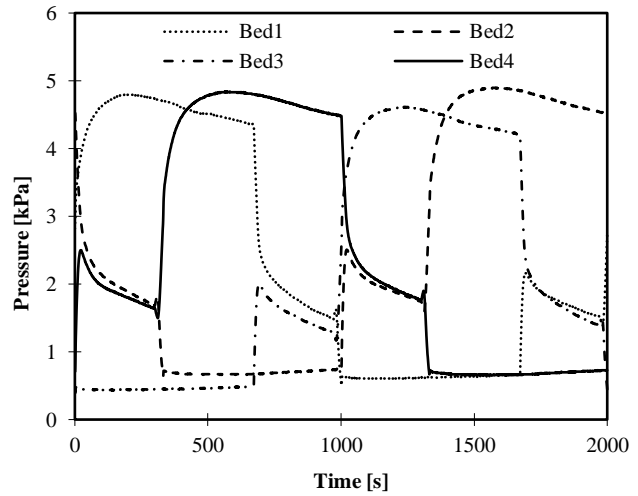


**Figure 2.** Temperature histories of bed

**4.2. Pressure Histories of Heat Exchanger (Bed)**

Figure 3 illustrates the pressure histories of the four adsorbent beds (heat exchangers) with heat source temperature is 60oC and total cycle time is 2000s. It is worth to mention here that in the beginning (300s) heat exchangers 2 and 4 are in mass recovery process (340s) where bed 2 is in heating mode and bed 4 in cooling mode (30s). It is seen that in the beginning of mass recovery process, the temperature of bed 2 decreased and that of bed 4 increased though the bed 2 and bed 4 are in heating and cooling mode, respectively. In the beginning of mass recovery process, the saturation pressures of beds change suddenly, so that bed 2 starts to desorb and bed 4 to adsorb water vapor very fast. Therefore, temperature of bed 2 decreased and that of bed 4

increased for few seconds in the beginning of mass recovery process and then the temperature of bed 2 starts to increased and that of bed 4 start to decreased. It is also seen that after half cycle (1000s), temperature of bed 1 and bed 3 did not reach near to inlet hot and cooling water temperature, respectively.

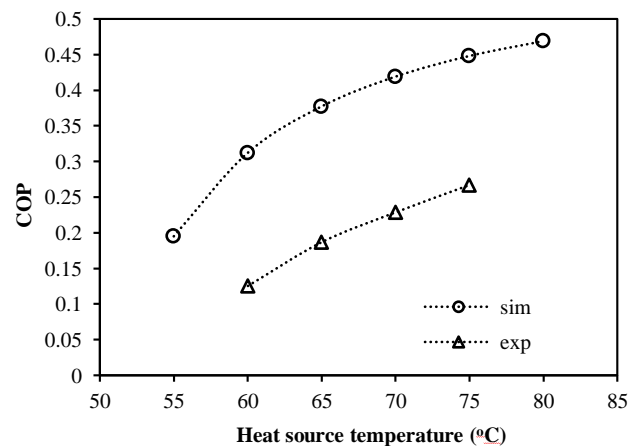


**Figure 3.** Pressure histories of bed

After mass recovery process, pre-heating and pre-cooling process will occur. Bed 2 is in cooling process and Bed 4 in heating process. Temperature of Bed 2 will decrease during the process of pressure decline and temperature of Bed 4 will increase respectively. The next process is desorption-adsorption process (mode C, D, E). In this process, Bed 2 operates in evaporator pressure. Refrigerant in evaporator 2 will be evaporated and adsorbed by Bed 2. Bed 4 operates in condenser pressure. Refrigerant will be released in desorption process and will be condensed in condenser. Up to mode E is a half-cycle, the next process (F-J) is similar to mode A-E, only adsorber and desorber position will change for each bed pairs.

**4.3. Effect of Heat Source Temperature on Performance**

The effect of heat source temperature on the coefficient of performance (COP) and cooling capacity are presented in Figure 4 and 5 respectively. Chilled water outlet temperature was 9 °C and total cycle time was 1300s. COP and cooling capacity both increased along with heat source temperature.



**Figure 4.** Effect of heat source temperature on COP

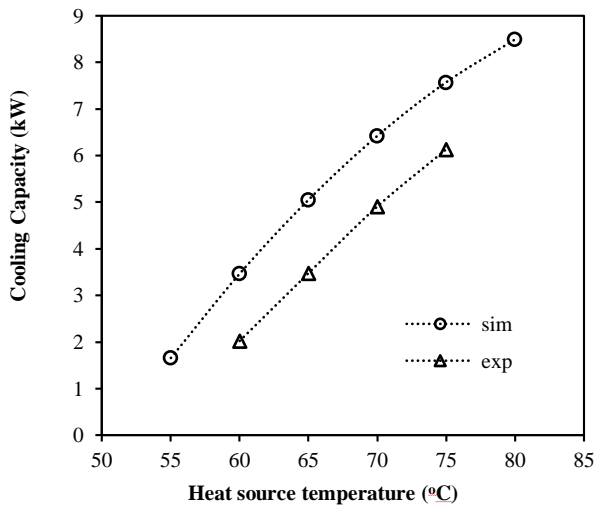


Figure 5. Effect of heat source temperature on performance

The same tendencies are shown in both simulation results compare with the experiment results. Performance simulation is bigger than experiment because there is always some heat loses to the environment in a real system, which is neglected in simulation model.

4.4. Effect of Cycle Time on Performance

The effect of cycle time on performance (COP and cooling capacity) described in Figure 6. Seven cycles times are chosen from 1000s to 4000s. As consideration, the experimental and simulation conditions were set up at the same condition as heat source temperature and chilled water outlet temperature were at 60°C and 9°C, respectively.

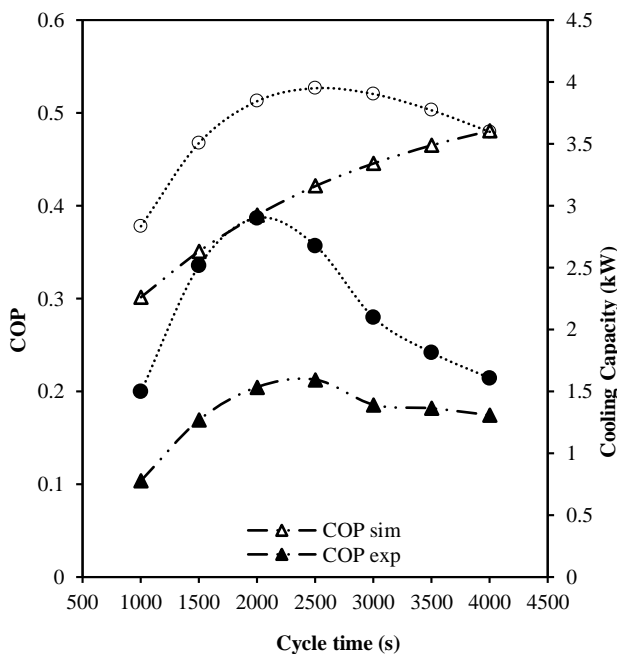


Figure 6. Effect of cycle time on performance

4.5. The average of chilled water out temperature and mass flow rate

As can be shown in simulation results that the trend of the average chilled water out is flat smoothly because it is easy

to give the mass flow rate values in simulation to reach the chilled water out 9°C. The tendency became different in the experiment results because it is a little bit difficulties to control mass flow rate to gain chilled water out 9°C. From Figure 2 (b) we can say that in order to gain chilled water out 9°C, we must increase mass flow rate if heat source temperature increased.

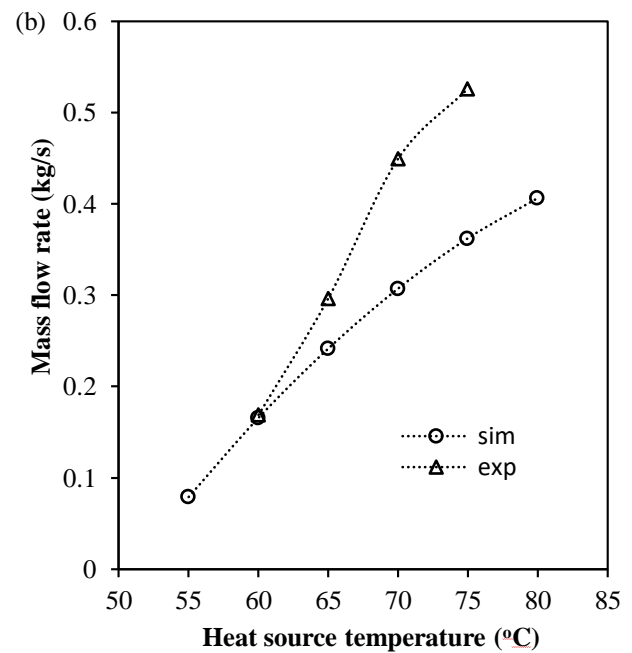
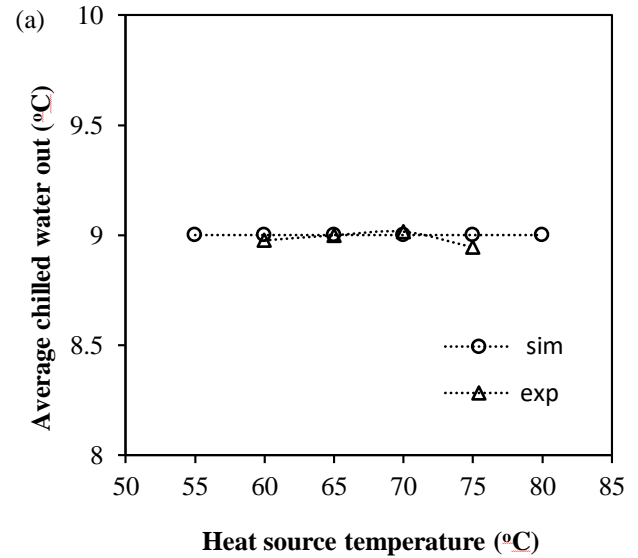


Figure 7. (a) Average chilled water out (b) Mass flow rate behavior of the chiller

5. Conclusions

The following concluding remarks can be drawn from the present study.

- (a) In both experiment and simulation are showing the same tendency results.
- (b) COP and cooling capacity increased along with heat source temperature.
- (c) Cycle times within 2000 – 2500s produces highest cooling capacity.

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