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Performance Assessment of LiBr-H_2O Absorption Chiller for Air Conditioning Purposes

تقييم أداء مثلج ماء امتصاصي يعمل بمحلول(ماء + بروميد الليثيوم) لأغراض تكييف الهواء

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Abstract

The thermodynamic analysis of a 4TR single stage absorption chiller is executed numerically using Engineering Equation Solver (EES) software. In this chiller, water and lithium bromide mixture is used as a working fluid and supplies by hot water from electrical boiler at any temperature. The investigation is done to assess the effect of varying the exit temperatures of the absorber, evaporator, generator, and condenser on the absorption chiller cycle performance. The cycle simulation is based on the operating temperature ranges and fixed parameters which include as follows: evaporating exit temperature within a range of 2-11 °C, generator exit temperature within a range of 80-89°C, condenser exit temperature range from 30 to 48°C, absorber exit temperature range from 20 to 38°C, three magnitudes of effectiveness of heat exchanger (0.6, 0.65 and 0.7), strong solution flow rate 0.05 kg/s. The results depicted that the performance parameters are affected by the operation temperatures of main components and heat exchanger effectiveness.

Keywords: EES, LiBr-H_2O Absorption Chiller, COP, thermodynamic analysis.

الخلاصة

تم اجراء دراسة عددية ببرنامج EES على مثلج ماء امتصاصي بسعة تتراوح 4 طن تثليجي . هذا المثلج يعمل بمحلول ماء و بروميد الليثيوم كمائع تشغيلي ويجهز بالمائع الحار عن طريق غلاية كهربائية. الهدف من هذا البحث، دراسة تاثير تغير درجات الحرارة الخارجة من الماص و المبخر و المولد والمكثف على أداء مثلج الماء. المحاكاة العددية تمت عند معدلات درجات حرارية مختلفة وكانت كالآتي: درجات الحرارة الخارجة من المبخر بين 2 و11°م، درجات الحرارة الخارجة من المولد بين 80 و89°م ، درجات الحرارة الخارجة من المكثف بين 30 و 48°م و درجات الحرارة الخارجة من الماص بين 20 و38°م. كذلك تم دراسة تأثير تغير قيم فعالية المبادل الحراري على أداء المثلج وكانت على التوالي 0,6 و 0,65 و0,7. النتائج المستحصلة بينت ان أداء المثلج يتأثر بتغير درجات الحرارة التشغيلية للمكونات الأساسية للنظام بالإضافة الى تأثره مع تغير قيم فعالية المبادل الحراري.

الكلمات المفتاحية: برنامج EES، مثلج ماء امتصاصي يعمل بمحلول ماء و بروميد الليثيوم، معامل الأداء، ةتحليل ثرموداينمك.

Nomenclature		Subscripts	
C	Specific heat capacity (kJ/kg.K)	a	absorber
h	Enthalpy [kJ/kg]	c	condenser
H_2O	Water	e	evaporator
m	Mass flow rate [kg/s]	g	generator
p	Pressure(kPa)	s	Strong solution
Q	Heat transfer rate(kW)	r	Refrigerant
T	Temperature (C)	w	Weak solution
f	Circulation ratio(-)	Abbreviations	
W	Work (kW)	COP	Coefficient of performance
X	Concentration	EES	Engineering Equation Solver
		HE	Heat exchanger
Greek symbols		HE	LiBr
ϵ	Effectiveness	SHX	Solution heat exchanger

1. Introduction

The conventional refrigerants such as CFCs and HCFCs used by vapor compression refrigeration systems cause global warming potential and ozone depletion potential. This problem can be cured by utilizing the eco-friendly cooling systems such as absorption, desiccant and adsorption chillers. In addition these systems have the important advantage being driven by many kinds of low level energy sources such as waste energy from various industrial processes and solar energy. The most common solutions employing for absorption chillers are water-ammonia (H_2O-NH_3), and lithium bromide-water (LiBr-H_2O). For water-ammonia solution are used in refrigeration applications where ammonia uses as a refrigerant and water as absorbent. On the other hand, lithium bromide-water solution are limited for refrigeration systems and good for air conditioning applications since water uses as a refrigerant and air conditioning applications require cooling at temperature above 0 °C. There are three type of absorption chillers which are depended on number of stages such as single, double and triple stages. Most models presented in the literature showed that the COP of single stage absorption chillers was about 0.6-0.8 **[1]**, COP of double stage was about greater than 1.0-1.3 **[2]**. And COP of triple stage was about 50% than that of the conventional double-effect cooling systems **[3].**

Grossman and Zaltash, [4] have made a computer ABSIM code for the flexible and modular form simulation of absorption schemes with different working fluids. **Joudi and Lafta, [5]** offered a computational model to describe the influence of several operating cases on the function of each component and to find the absorption refrigeration system performance working on LiBr–H_2O solution. **Florides et al., [6]** formed a mathematical model based on balance of mass and energy equations written for each components of absorption cycle with 1 kW cooling capacity. **Mehrabian and Shahbeik, [7]** developed the computer study for a single effect absorption chiller using solution consisted of lithium bromide and water as a working fluid. The program provides the thermodynamic properties of all state points and the overall cycle performance. **Jena and Mishra [8]**analyzed the potential of an engine exhaust driven LiBr–H_2O based absorption system for air-conditioning. A small scale LiBr-water based absorption system can be feasible to operate using exhaust heat energy from a diesel engine. The effects of generator, condenser, evaporator and absorber temperatures on the energy of the absorption system were observed. The results indicated that the COP increases with increasing in evaporator temperature, but decreases with increasing in absorber and condenser temperature. **Haresh et al., [9]** presented a numerical simulation of single-stage absorption with 140 kW cooling load using LiBr–H_2O solution. Researchers used energetic analysis for their simulation. The result showed that the heat load on generator and absorber increases with rise of generator and condenser exit temperature and it reduces when both evaporator and generator exit temperature are simultaneously increased. COP value is found high at lower condenser exit temperature and the average value of COP reduces by 8.1 % when condenser temperature is increased along with generator exit temperature.

The objective of this study can be divided in two parts. The first part is developed a computer program to simulate all components of single stage absorption chiller, the second part is to investigate the effect of various operating conditions including the exit temperatures of the evaporator, condenser, generator and absorber and hot water mass flow rate on the performance of the absorption chiller cycle.

2. Steady State Analysis of Absorption Single Stage Chiller

2.1. The system configuration description

The single stage absorption chiller consists of several components such as: generator, absorber, expansion device, evaporator, condenser, pump, control system and auxiliary system. Three auxiliary system are connected to absorption chiller which are electrical boiler (heat source), cooling tower to cool the refrigerant for both the condenser and absorber, and storage tank with air-handling unit to conditioning space below ambient conditions. Absorption chiller system photograph is indicated in **fig. 1**.

2.2. Operational cycle of the system

The current study, the system operates by using two working fluids, a refrigerant (water) and an absorbent (LiBr). Various state points for LiBr-H_2O absorption system are depicted in **fig. 2** . In the evaporator, refrigerant vapor at low pressure and low quality (state point 10) enters the absorber where it is absorbed by the lithium bromide solution (state point 6) forming the dilute solution (lithium bromide-water mixture). The heat of absorption is removed from absorber by the cooling water circuit (i.e., cooling tower). The resulting cold dilute solution (state point 1) which is pumped to the generator using a solution pump (state point 3) where it is heated by hot-water coming electrical boiler. This heat helps to separate the refrigerant vapor (water) and concentrated lithium bromide solution. The hot concentrated lithium bromide solution (state point 4) is cooled by rejecting heat to the dilute solution entering the generator through a solution heat exchanger (state point 5). After that concentrated lithium bromide solution is throttled to the absorber and returned to the absorber at low pressure and temperature (state point 6). Refrigerant vapor leaves the generator and enters the condenser at high pressure and temperature (state point 7) where it is condensed to liquid refrigerant by rejecting heat of condensation to the cooling water circuit. The liquid refrigerant leaving the condenser then passes through a throttling valve (state point 8) which drops it from the high to the low pressure level, also reducing the temperature. Then, refrigerant vapor flows to evaporator at low pressure (state point 9) where heat is removed from the cooled medium to produce chilled water which is pumped to the air-handling unit to produce cooled air for the conditioning purposes. Refrigerant leaves the evaporator as vapor (state point 10) at low pressure and temperature. Refrigerant vapor enters again the absorber to complete the cycle.

2.3. Mathematical modeling

Analysis of the system is carried out to determine system parameters as a function of different values of operation variables. This analysis includes the following assumptions:
1. The chiller system operates under steady state conditions,
2. Pressure losses due to friction across the chiller components are ignored,
3. Only pure refrigerant boils in the generator,
4. Refrigerant vapor leaving of both the evaporator and the condenser as well as the solution leaving of both the generator and the absorber are assumed in a saturated state.
5. Isenthalpic throttling processes occur in expansion valves.
6. The specific heats fluid are constant.

In this cycle, the mass flow rate, species and energy balances for the components are recognized as follows:

Mass balance

$$\sum \dot{m}_{in} = \sum \dot{m}_{ex} \qquad (1)$$

Species balance

$$\sum X_{in} \dot{m}_{in} = \sum X_{out} \dot{m}_{ex} \qquad (2)$$

Energy balance

$$\sum \dot{Q} + \sum \dot{W} + \sum \dot{m}_{in} h_{in} - \sum \dot{m}_{out} h_{out} = 0 \qquad (3)$$

From first law of thermodynamics,

$$Q_e + Q_g - Q_c - Q_a + W_p = 0 \qquad (4)$$

The circulation ratio (f) is defined as the ratio of weak solution flow rate to refrigerant flow rate. Mathematically can be written as:

$$f = \frac{\dot{m}_w}{\dot{m}_r} \qquad (5)$$

Or, in concentrations term

$$f = \frac{X_{gen}}{X_{gen} - X_{abs}} \qquad (6)$$

The COP represents the coefficient of performance for absorption chiller cycle and is given by the following formula.

$$COP = \frac{chiller\ load}{Energy\ \ input} = \frac{Q_e}{Q_{gen} + W_p} \qquad (7)$$

2.4. Component analysis

The thermodynamic analysis is carried out across each component by applying the mass, species and energy balances. The cycle was treated as an independent element for each component with a certain number of input values. Eight standard components of absorption chiller can be illustrated in **Fig. 3**. The components with their state points are: (1) condenser. (2) Refrigerant expansion valve. (3) Solution expansion valve, (4) Evaporator, (5) Absorber, (6) Solution pump, (7) Solution heat exchanger and (8) Generator.

2.4.1-Condenser

The refrigerant vapor leaves the generator from point (7) and passes to the condenser where it condenses to liquid and exits from point (8). The liquid refrigerant is returned to the evaporator through expansion valve. The mass and energy balance across the condenser is given by

$$m_r = m_8 = m_7 \qquad (8)$$

$$Q_c + m_8 h_8 = m_7 h_7$$

$$Q_c = \dot{m}_r .(h_7 - h_8) \qquad (9)$$

2.4.2. Refrigerant expansion valve

$$m_8 = m_9 = m_r \qquad (10)$$

$$h_8 = h_9 \qquad (11)$$

2.4.3. Solution expansion valve

$$m_5 = m_6 = m_s \qquad (12)$$

$$h_5 = h_6 \qquad (13)$$

2.4.4. Evaporator

In the evaporator, the refrigerant from the condenser enters from point (9) and the liquid refrigerant starts to evaporate at low temperature and pressure. Refrigerant vapor leaves the evaporator at state point (10). The vaporization heat of the refrigerant produces the cooling effect of the whole system. The mass and energy balances for the evaporator can be given by:

$$m_r = m_9 = m_{10} \qquad (14)$$

$$Q_e + m_9 h_9 = m_{10} h_{10}$$

$$Q_e = \dot{m}_r \left(h_{10} - h_9\right) \qquad (15)$$

The value Q_e is chilled water or so-called cooling effect.

2.4.5. Absorber

The refrigerant vapor leaves the evaporator and enters the absorber from point (10) where refrigerant vapor is absorbed by the strong solution in absorber (point 6) to form a weak solution point (1). The mass and energy balances for absorber are given by:

$$m_1 = m_w = m_{10} + m_6 \quad (16)$$

$$Q_a + m_1 h_1 = m_{10} h_{10} + m_6 h_6$$

$$q_a = h_{10} + \frac{m_6}{m_{10}} h_6 - \frac{m_1}{m_{10}} h_1$$

$$q_a = h_{10} + \left(\frac{m_1 - m_{10}}{m_{10}} \right) h_6 - \frac{m_1}{m_{10}} h_1$$

$$q_a = h_{10} + (f - 1) h_6 - f . h_1 \quad becouse \quad f = m_1 / m_{10}$$

$$q_a = (h_{10} - h_6) + f\ (h_6 - h_1) \quad (17)$$

2.4.6. Solution pump:

The combined refrigerant and absorbent liquid enter the pump from point (1) and leaves from point (2) where the pump raises the pressure of solution. The mass and energy balances for the pump are given by Equations 4-6:

$$m_w = m_1 = m_2 \quad (18)$$

$$W + m_1 h_1 = m_2 h_2$$

$$W = m_w\ (h_2 - h_1) \quad (19)$$

2.4.7. Solution heat exchanger:

To avoid risks of irreversibilities due to high temperature at the generator, solution heat exchanger are employed. This component operates to preheat the cold diluted solution coming from the absorber and to cool the hot concentrated solution coming from the generator. The mass flow rate remains the same at the inlet and exit of the SHX, i.e. m_2=m_3, m_4=m_5, and heat transfer rate from the hot fluid to the cold fluid in the heat exchanger, Q_{hx} is determined from energy balance:

$$C_{hot} .(T_4 - T_5) = m_s\ (h_4 - h_5) \quad (20)$$

$$C_{cold} .(T_3 - T_2) = m_w\ (h_3 - h_2) \quad (21)$$

$$Q_{hx} = m_w\ (h_3 - h_2) = m_s\ (h_4 - h_5) \quad (22)$$

Heat exchanger effectiveness is given by

$$\varepsilon_{SHX} = \frac{\dot{Q}_{act}}{\dot{Q}_{max}} = \frac{(h_4 - h_5)}{(h_4 - h_2)}$$

or

$$\varepsilon_{SHX} = \frac{(T_4 - T_5)}{(T_4 - T_2)} \quad (23)$$

2.4.8. Generator:

In the generator, the weak solution entering from point (3) is regenerated. The weak solution starts to boil and generates vapor bubbles which, along with the liquid, leaves the generator from points (7) as water vapor and (4) as strong solution . The mass and energy balances for the generator are given by :

$$m_3 = m_7 + m_4 \quad (24)$$

$$Q_{gen} + m_3 h_3 = m_7 h_7 + m_4 h_4$$

$$q_{gen} = h_7 + \frac{m_4}{m_7} h_4 - \frac{m_3}{m_7} h_3$$

$$q_{gen} = h_7 + \left(\frac{m_3 - m_7}{m_7} \right) h_4 - \frac{m_3}{m_7} h_3$$

$$q_{gen} = h_7 + (f - 1).h_4 - f .h_3$$

$$q_{gen} = (h_7 - h_4) + f \left(h_4 - h_3 \right) \quad (25)$$

Also energy balance between heat source (electrical boiler) and generator gives

$$Q_{gen} = m_{11} \left(h_{11} - h_{12} \right) \quad (26)$$

$$\varepsilon_{gen} = (T_{11} - T_{12}) / (T_{11} - T_7) \quad (27)$$

3. Validation

To validate the solution procedure, the numerical results obtained from present study were compared with results published by **Haresh et al. (2016)** for single stage absorption chiller with cooling capacity of 140 kW. As shown in **Table 1,** close agreements were observed between the present results and the presented in **Haresh et al. (2016)**.

Table 1 shows validation between present study and **Haresh et al.(2016)**

Data	Haresh et al.(2016)	Present Study	Difference(%)
Temp. Of Weak Solution Leaving The Absorber (°C)	40	40	-
Temp. Of H2O Vapour Leaving The Generator (°C)	80	80	-
Temp. Of H2O Liquid Leaving The Condenser (°C)	40	40	-
Pressure Of H2O Liquid Leaving The Condenser (kPa)	7.3844	7.381	-0.046
Temp. Of H2O Vapour Leaving The Evaporator (°C)	13	13	-
Temp. Of Strong Solution Leaving The Generator(°C)	80	80	-
Heat Capacity Of VAM Machine (kW)	140	140	-
Efficiency Of Solution Heat Exchanger	0.5	0.5	-
Results			
Heat Capacity Of Generator (kW)	186.9	190.236	1.78
Heat Capacity Of Condenser (kW)	147.02	146.692	-2.23
Heat Capacity Of Absorber (kW)	181.57	183.878	1.27
Pump Work (kW)	1.6	1.79	11.87
Coefficient of Performance (COP)	0.7491	0.738	-1.48

4. Results and Discussions

The thermodynamic properties of various state points such as temperature, pressure, enthalpy, mass flow rate, and LiBr concentration are calculated as delineated in **Table 2**. The input data to the simulation of absorption chiller cycle are absorber, evaporator, condenser and generator temperatures equal to 32.9°C, 7.6°C, 39.9°C and 89.4°C, respectively. The strong solution mass flow rate is set to 0.05 kg/s and solution heat exchanger effectiveness is 0.65. The hot water temperature enters to the generator at 100°C with mass flow rate of 0.7kg/s. The performance parameters results and heat transfer rates generated by EES for absorption chiller cycle are reported in Table 3.

The computed state point results of the cycle are summarized in **Table 2**.

State point	From	To	Temperature(C)	Pressure (kPa)	Enthalpy (kJ/kg)	MFR(Kg/s)	LiBr (X%)
1	Absorber	Pump	32.9	1.044	72.5	0.05	52.9
2	Pump	SHX	32.9	7.342	72.5	0.05	52.9
3	SHX	Generator	59.8	7.342	129.6	0.05	52.9
4	Generator	SHX	89.4	7.342	221.3	0.0424	62.46
5	SHX	SEV	53.3	7.342	154	0.0424	62.46
6	SEV	Generator	51.4	1.044	154	0.0424	62.46
7	Generator	Condenser	69.3	7.342	2629	0.0076	0
8	Condenser	REV	39.9	7.342	167.1	0.0076	0
9	REV	Evaporator	7.6	1.044	167.1	0.0076	0
10	Evaporator	Absorber	7.6	1.044	2514.5	0.0076	0
11	Boiler	Generator	100	-	419.1	0.7	-
12	Generator	Boiler	81.93	-	386.5	0.7	-

Table 3 reported the performance parameter results of the cycle.

Parameter	Values
Heat absorber, Q_{abs}(kW)	21.951
Heat condenser, Q_{cond}(kW)	18.647
Heat generator, Q_{gen} (kW)	22.818
Heat evaporator, Q_{evap}(kW)	17.78
Solution heat exchanger, Q_{SHX}(kW)	2.86
Solution pump, W_p(W)	0.203
LiBr strong solution(%)	56.6
LiBr weak solution(%)	62.46
COP(-)	0.779

When the generator exit temperature increases, the cold diluted solution coming from the absorber is preheated which leads to reduce the heat input at the generator. Consequently, the values of the chiller COP improve with increasing in generator exit temperature as depicted in **Fig 4.** On the other hand, increasing in generator exit temperature leads to heat the refrigerant entering to the absorber and increasing absorption rates of the refrigerant from the evaporator. This is explained by increasing in cooling capacity with generator exit temperature. **Fig. 5** shows that the amount of heat transfer for all main components except SHX of absorption system increases linearly with increasing generator exit temperature. The circulation ratio reduces with increase of generator exit temperature as shown in **Fig. 6**. This requires pumping less LiBr concentration from the absorber to generator for working absorption cycle at generator exit temperature rise.

Fig 7 shows the absorber exit temperature as a function of chiller COP and cooling capacity. The COP drops as absorber exit temperature increases because absorption rate the refrigerant is reduced at absorber and less heat is transferred to refrigerant entering the evaporator. This reduces cooling capacity as well COP. **Fig. 8** illustrates the decrease of heat transfer rates with increasing in absorber exit temperature. **Fig. 9** shows the effect of absorber exit temperature on circulation ratio and LiBr concentration. It is observed that values of circulation ratio and LiBr concentration increase with increase in absorber exit temperature.

Fig. 10 displays the variation of COP and cooling capacity of the absorption chiller for different evaporator exit temperatures. It can be seen that at an evaporator exit temperature of 5°C, the COP of the cycle is 0.758, and its cooling capacity is 14.6 kW (4 RT). Also, both are found to increase gradually with an increase in evaporator exit temperature. This is because a higher evaporator exit temperature requires a higher pressure in the evaporator and absorber, thus requiring a lower pressure and temperature lift, and a lower heat input for evaporator to maintain the same cooling capacity. **Fig. 11** shows the effect of evaporator exit temperature on rates of heat transfer. **Fig. 12** shows the circulation ratio and LiBr concentration as a function of evaporator exit temperature. This figure displays that the circulation ratio and LIBR concentration (weak and strong solution) decrease at evaporator exit temperatures between 2 and 11°C.

Fig. 13 shows that increase of condenser exit temperature is escorted by drop of system COP and cooling capacity. **Fig. 14** exhibits the effect of condenser exit temperature on heat transfer rates of components. As shown in **Fig. 15**, raise of condenser exit temperature was followed by increase of circulation ratio which is due to raise of input mass flow from condenser.

The effect of generator exit temperature on COP for different effectiveness's of heat exchangers are revealed in **Fig. 16**. This figure exposes the increase of **COP** with increasing in both generator exit temperature and effectiveness's of heat exchangers.

Fig. 17 shows the COP is best when the low pressure increases. While the COP reduces with decreasing of the high pressure. Generally, For maximum COP, the pressure difference between the high and low pressure side is kept as small as possible. The cycle performance of water cooled chiller, as functions of cooling capacity and hot water mass flow rate is shown **Fig. 18**. The COP is not influenced by any change in the water flow rate.

5. Conclusions

The model solves using computer software EES which contains the thermodynamic properties of various working fluids, to find the performance of the absorption chiller cycle. The results show that the cycle performance is dependent on a number of variables including: the exit temperatures of absorber, condenser, generator, evaporator, the mass flow rate of the LiBr and effectiveness of the heat recovery. According to the simulation results, it is concluded that

1- The cooling capacity and COP of the system increase when the generator exit temperature increases.

2- Higher COP values are obtained for a lower circulation ratio.

3-The condensing exit temperature has a higher influence on the system performance compared with the absorber exit temperature.

4- the COP improves when the condenser and absorber exit temperature declines.

5- The increase in effectiveness of heat exchangers causes increasing of system COP .

6-The pressure difference between the high and low pressure side should be kept as small as possible.

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Source: http://www.thermaxglobal.com/thermax-absorption-cooling-systems/vapour-absorption-machines/steam-fired-chillers/

Fig. 1 Absorption chiller system (source),

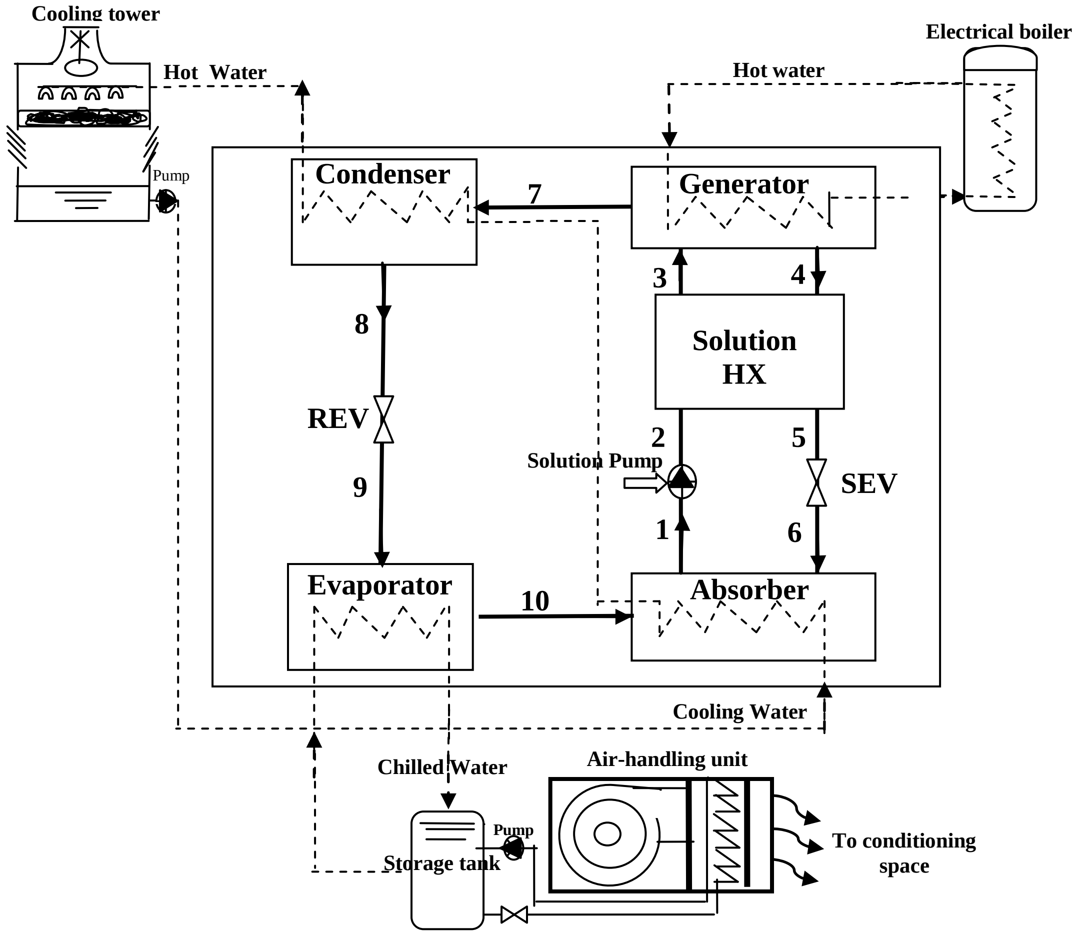

Fig. 2 Schematic of LiBr-H_2O absorption system with state points

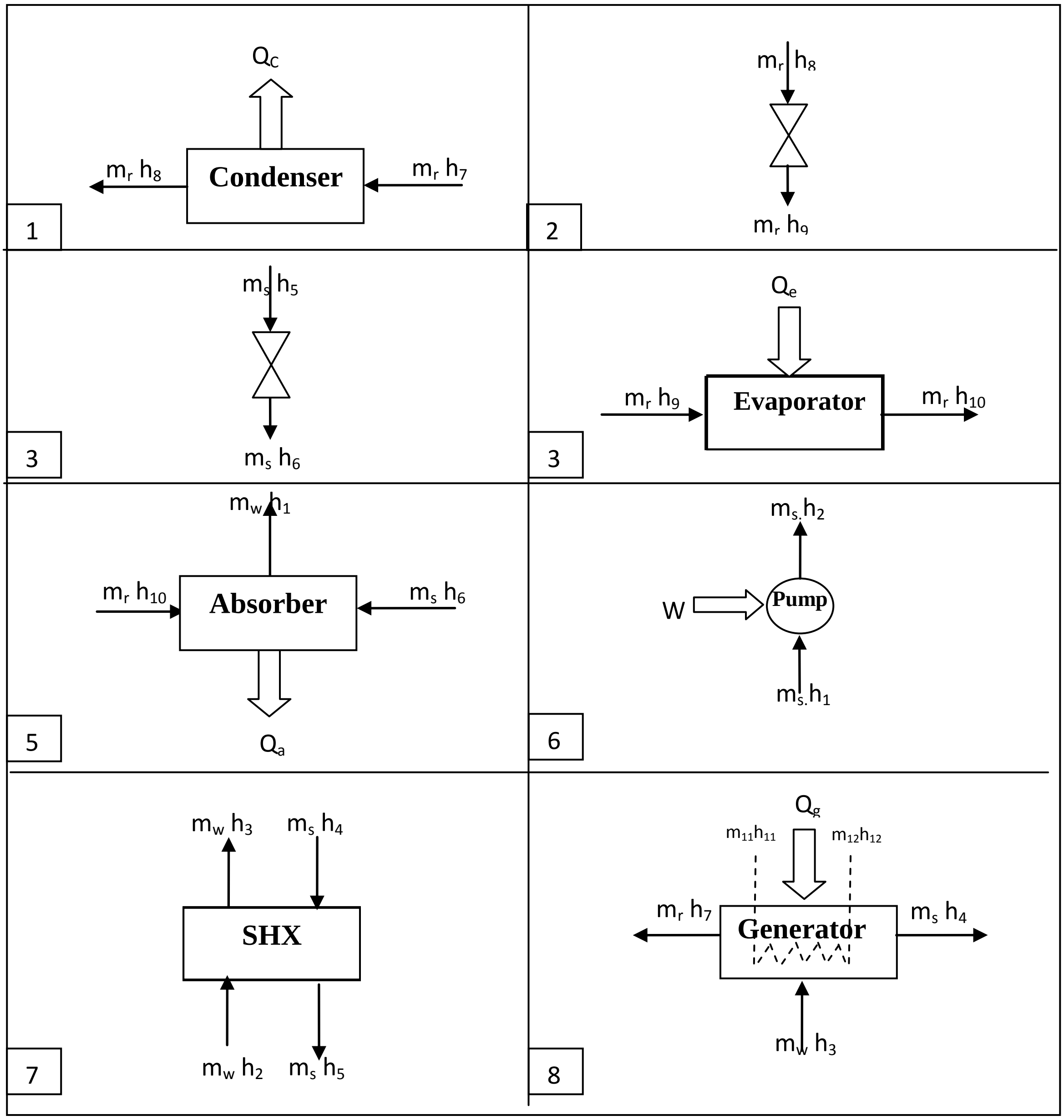

Fig. 3 Sketch of individual components for absorption chiller

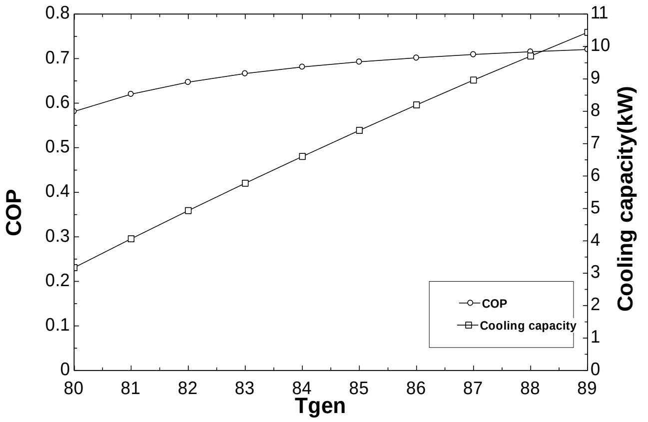

Fig. 4 Effect of generator exit temperature on COP and cooling capacity.

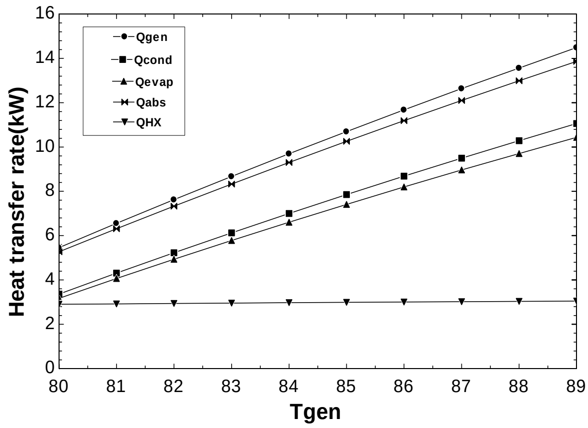

Fig. 5 Effect of generator exit temperature on heat transfer rates.

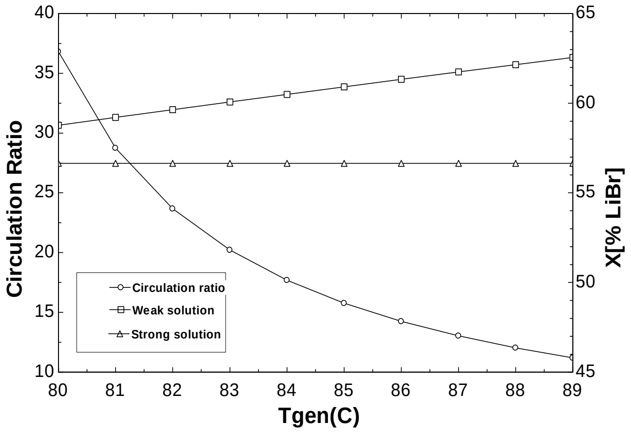

Fig. 6 Effect of generator exit temperature on circulation ratio and LIBR concentration

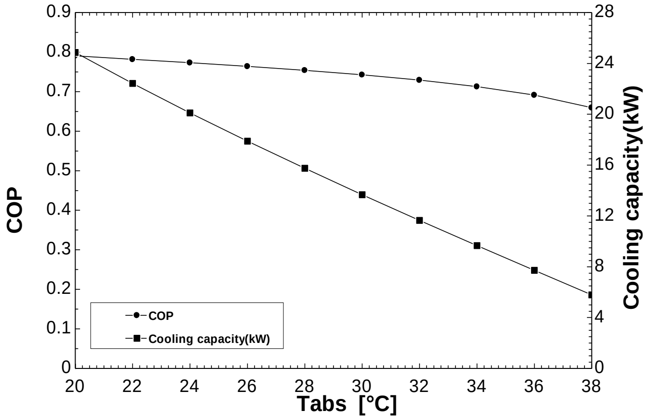

Fig. 7 Effect of absorber exit temperature on COP and cooling capacity.

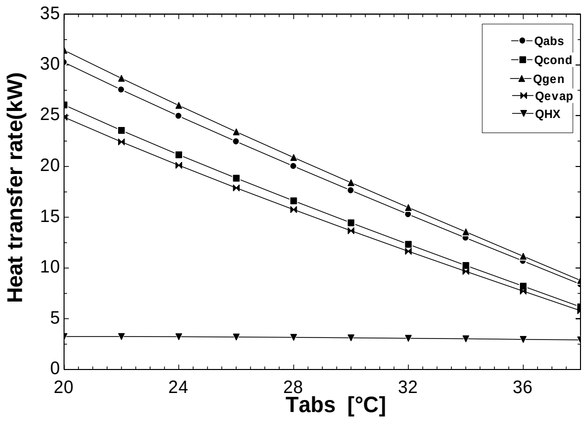

Fig. 8 Effect of absorber exit temperature on heat transfer rates.

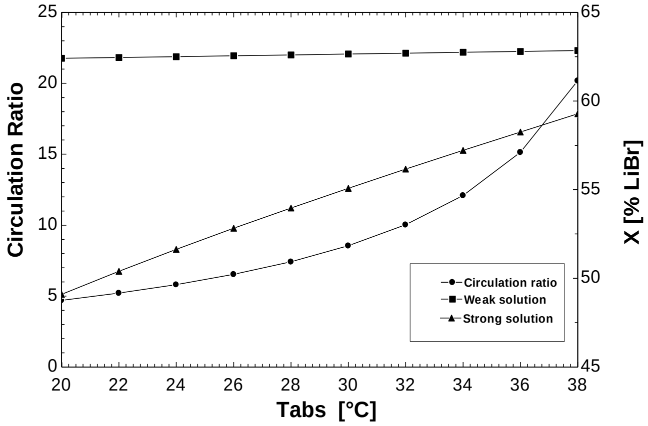

Fig. 9 Effect of absorber exit temperature on circulation ratio and LIBR concentration

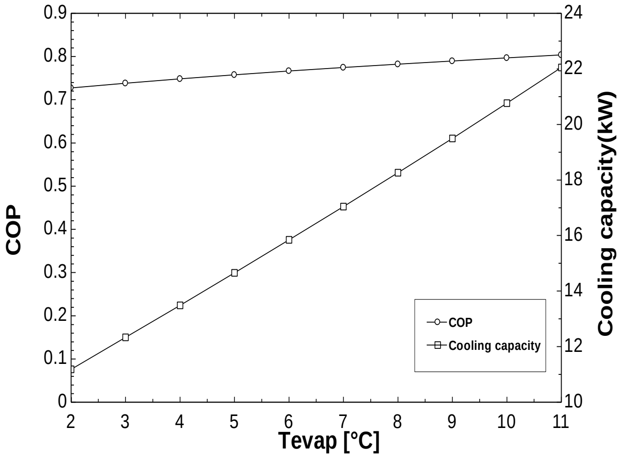

Fig. 10 Effect of evaporator exit temperature on COP and cooling capacity

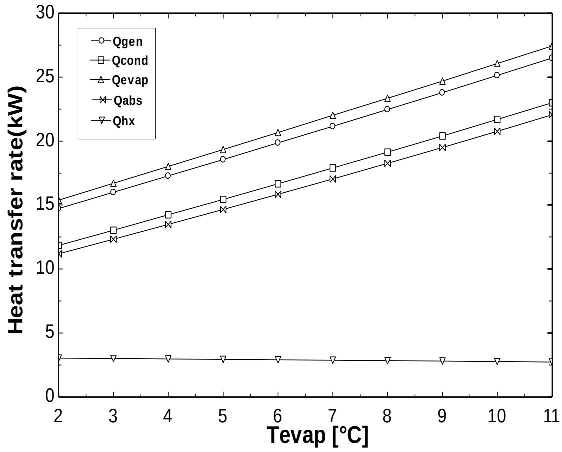

Fig. 11 Effect of evaporator exit temperature on heat transfer rates.

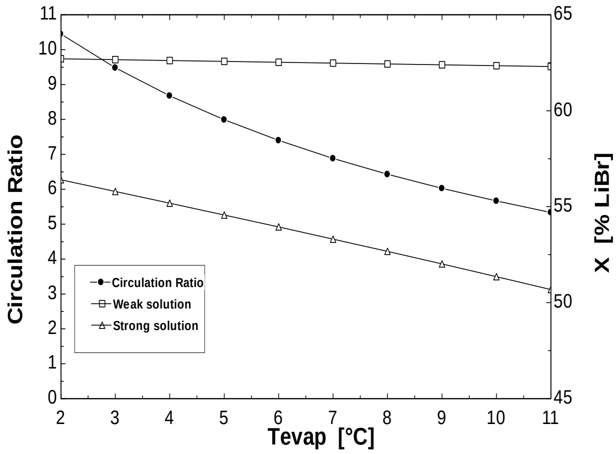

Fig. 12 Effect of evaporator exit temperature on circulation ratio and LIBR concentration

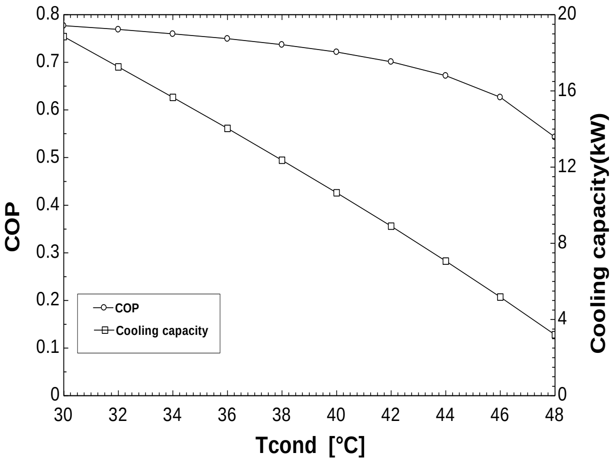

Fig. 13 Effect of condenser exit temperature on COP and cooling capacity

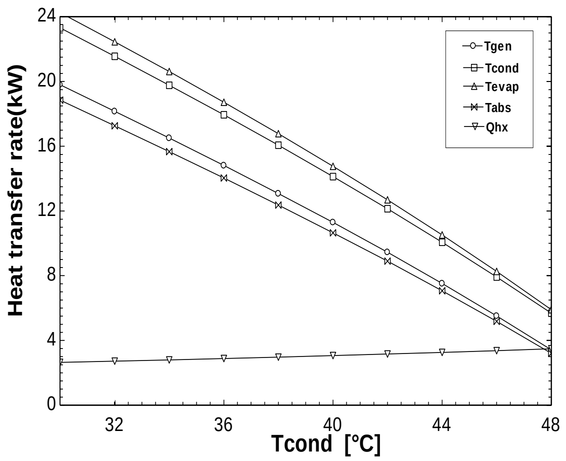

Fig. 14 Effect of condenser exit temperature on heat transfer rates of components.

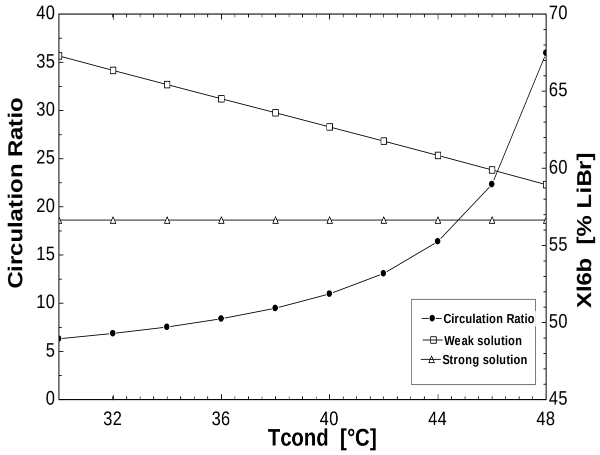

Fig. 15 Effect of condenser exit temperature on circulation ratio and LIBR concentration

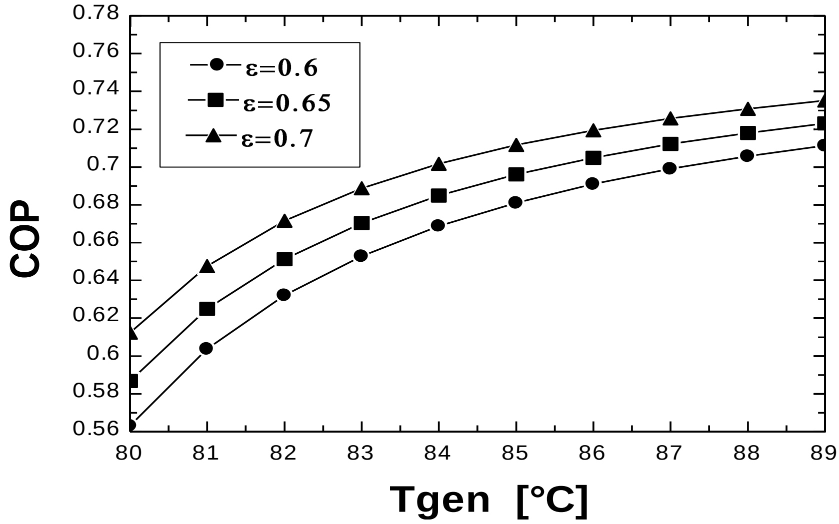

Fig.16 Effect of generator exit temperature on COP for different effectiveness

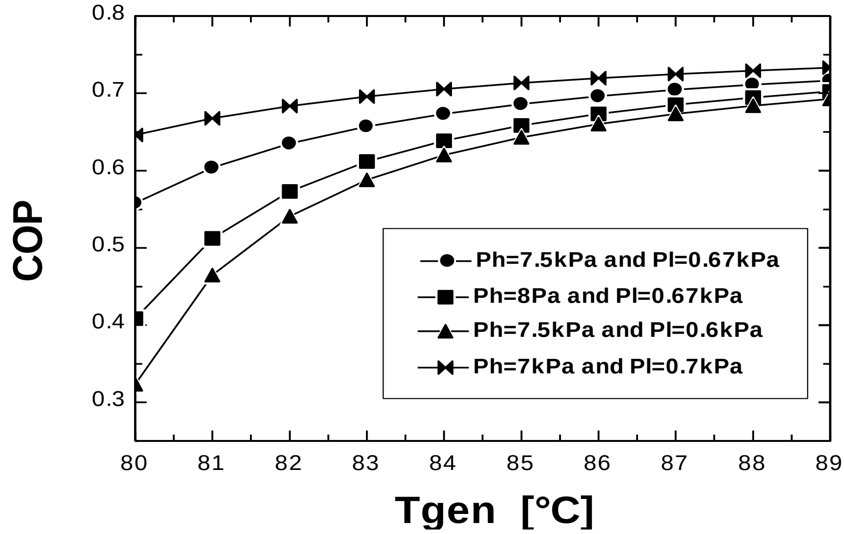

Fig.17 Effect of generator exit temperature on COP for different P_{high} and P_{low}

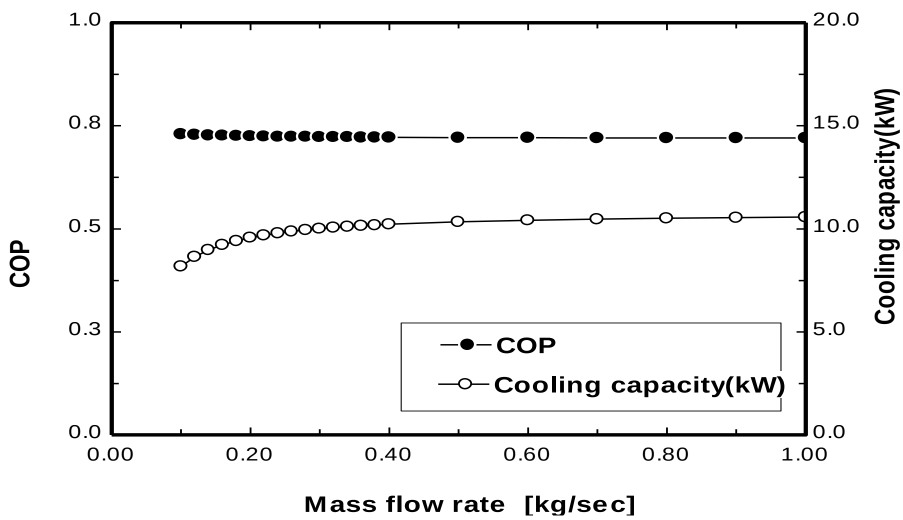

Fig.18 Effect of hot water flow rate at generator on COP and cooling capacity.