The Energy and Exergy Analysis of Single Effect Absorption Chiller

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Received 17 June 2011; Revised 08 August 2011; Accepted 10 September 2011

Abstract: The first and second laws of thermodynamics have been employed to evaluate energy and exergetic efficiency of the single effect absorption chiller which is used for air conditioning purpose. The performance analysis has been carried out by developing a computer program in EES and modeling the chiller and its components. To evaluate entropy of the water/lithium bromide solution at any point, an empirical correlation has been utilized. Exergy destruction and thermodynamic properties at any point in the cycle are evaluated by using related equations or build in property data. The results showed that maximum exergy destruction was occurred in the generator and the absorber at various operating conditions and these components had greater effect on the energy and exergetic efficiency rather than condenser and evaporator. Thus, it can be clearly stated that the generator and absorber are the most important components of the absorption chiller. The results also showed the exergetic efficiency was less than the energy efficiency due to exergy destruction taking place within the absorption chiller. Therefore, it can be concluded that the exergy analysis has been proven to be a more powerful tool in pinpointing real losses and can be used as an effective tool in designing an absorption chiller and obtaining optimum operating conditions.

Keywords: Air Conditioning, Absorption Chiller, Energy Analysis, Exergy Analysis, Optimize Conditions

Reference: F. Panahi Zadeh and N. Bozorgan, (2011), 'The Energy and Exergy Analysis of Single Effect Absorption Chiller', Int J Advanced Design and Manufacturing Technology, Vol. 4/ No. 4, pp. 19-26

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1 INTRODUCTION

The ban of certain chlorofluorocarbon (CFC) and hydrochlorofluorocarbons (HCFCs) has encouraged engineers and researchers to give more consideration to absorption systems [1, 5]. The absorption chillers are becoming more attractive nowadays, especially because of their environmental friendliness. There are, of course, other advantages such as utilizing low-grade energies like solar, geological, and waste heat discharged from various industrial processes. The absorption chillers are still less efficient, bulkier, and more expensive than vapor compression systems. The absorption chillers, including those using LiBr/H2O and NH3/H2O solutions as refrigerant–absorbent combinations, have been studied extensively from both theoretical and experimental points of view. In recent years, there has been a growing interest in the use of the principles of thermodynamics second law for analyzing and evaluating the thermodynamic performance of thermal systems as well as their technologies [1]. First and second law analysis of absorption systems for cooling and heating applications were reported in Lee and Sherif in the year 2001.A number of researchers also have used exergy analysis of refrigeration systems such as Arzu Sencan and Yakut in the year 2005 [15]. A theoretical analysis is given by Bejan in the year 1996, based on entropy generation minimization. Exergy analysis of an absorption LiBr–H_2O refrigeration cycle was carried out by Talbi and Agnew in the year 2000 [16].

2 DESCRIPTION OF AN ABSORPTION CHILLER

An absorption chiller is heat operated refrigeration machine that operate on one of the earliest known principles of refrigeration. The cycle uses a refrigerant (known as the primary fluid) and an absorbent (known as secondary fluid). The refrigerant (primary fluid) is chemically and physically absorbed by the absorbent (secondary fluid) for the purpose of transferring heat. The evaporation of the primary fluid removes heat, this providing the refrigeration effect. The absorption cycle uses a heat operated generator, heat rejection absorber and a liquid solution pump. Many single effect LiBr/water absorption chillers using low pressure steam or hot water as the heat source have been installed in commercial building to produce chilled water for air conditioning [6].

A typical water lithium bromide single effect absorption chiller is shown in Fig. 1 but with a simple modification to increase the efficiency of chiller. In this modification the cooling tower water inlets of condenser and absorber have been paralleled to increase the efficiency of chiller especially when the ambient weather relative humidity more than 40%.

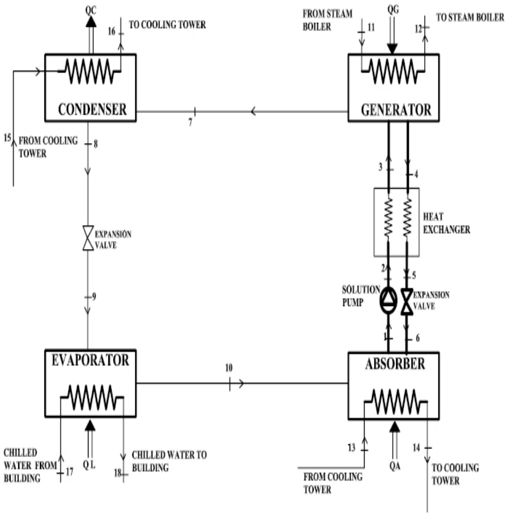

Fig. 1 The flow diagram of single effect absorption chiller

3 ENERGY AND EXERGY ANALYSIS

Energy can be transformed from one form to another while its quality changes. According to the first law of thermodynamics, which is a principle concerned with conservation, the total quantity of energy is constant during any transformations. However, from experimental evidences, loss of energy always gets the outlet energies less valuable than those of the inlet during any processes [12, 14]. The main aim in realizing energy analysis is to determine the used and lost energies. The energy efficiency of a process may be expressed as the ratio of energies leaving the process to the energies entering the process. On the other hand, energy analysis does not indicate the way of energy transformation and the location of energy degradation. In the last few years, a growing interest is observed in a special principle for measuring the ability of different types of energy to work, popularly known as exergy. By definition, the maximum work achievable from a given form of energy, while transforming from one thermodynamic state to another that is in equilibrium thermodynamics, it is possible to infer the true potential of different kinds of energies. Due to thermodynamic irreversibilities, the exergy efficiency of a process is often low in spite of a high energy efficiency, which indicates the quality degradation of different energies [13]. Considering Fig. 1, mass balance equation of the solution and lithium bromide at the generator can be written as follows [7]:

$$\dot{m}_{DS} = \dot{m}_{CS} + \dot{m}_{R} \tag{1}$$

Where $\dot{m}$ is the mass flow rate, the indexes DS, CS indicating dilute and concentrated solution respectively and R, refrigerant. By considering the lithium bromide concentration as X, this equation could be rewritten in generator (energy balance) [7] as below:

$$\dot{m}_{DS} X_{DS} = \dot{m}_{CS} X_{CS} \tag{2}$$

The ratio of solution mass flow rate through the pump to the mass flow rate refrigerant defined as the circulation ratio (CR) and expressed as follows [7]:

$$CR = \frac{\dot{m}_{DS}}{\dot{m}_{R}} \tag{3}$$

The coefficient of performance defined as a follows [7]:

$$COP = \frac{\dot{Q}_L}{\dot{Q}_G + \dot{W}_P} \tag{4}$$

Where $\dot{Q}$ is the heat transfer rate, $\dot{W}$ the pump power, L the evaporator, G the generator, A the absorber, C the condenser. Mass flow rate of circulated refrigerant can be calculated as follows [7]:

$$\dot{m}_R = \frac{\dot{Q}_L}{q_L} \tag{5}$$

Considering Fig. 1, the equations for the first law of thermodynamic (energy balance) for components of the absorption chiller could be written as follows [7]:

$$\begin{aligned} \dot{Q}_A = \dot{m}_R[h_{10} + (CR-1)h_6 - CR(h_1)] = \\ \dot{m}_{CTW}(h_{14} - h_{13}) \end{aligned} \tag{6}$$

$$\dot{Q}_C = \dot{m}_R[h_7 - h_8] = \dot{m}_{CTW}(h_{16} - h_{15}) \tag{7}$$

$$\dot{Q}_G = \dot{m}_R[h_7 + (CR-1)h_4 - CR(h_3)] = \dot{m}_{ST}(h_{11} - h_{12}) \tag{8}$$

$$\dot{Q}_L = \dot{m}_R[h_{10} - h_9] = \dot{m}_{CW}(h_{17} - h_{18}) \tag{9}$$

$$\dot{Q}_{HX} = \dot{m}_R(CR-1)(h_4 - h_5) = \dot{m}_R CR(h_3 - h_2) \tag{10}$$

$$\dot{W}_P = \dot{m}_R CR(h_2 - h_1) = \dot{m}_R CR \upsilon_R (P_C - P_E) / \eta_P \tag{11}$$

Where h is specific enthalpy, υ specific volume, P pressure, η efficiency, CW chilled water, ST steam, CTW cooling tower water, HX heat exchanger. Exergy is defined as the maximum amount of work potential of material or an energy stream in relation to the surrounding environment. The exergy of a fluid stream or exergy stream can be defined [7]:

$$\Psi = (h - h_0) - T_0(S - S_0) \tag{12}$$

Where Ψ is the exergy of fluid stream or exergy stream at temperature T, the terms h and S are enthalpy and entropy of fluid. Whereas h_0 and S_0 are enthalpy and entropy of fluid at environmental temperature T_0, in all cases absolute temperature is used in ${}^0K$ and in this study T_0 was taken as $298.15\,{}^0K$. To simplify the modeling of system, several assumptions were made:

- The system operates in steady state
- Pressure drop along the fluid flow is negligible
- In the condenser the refrigerant condenses to a saturated liquid, while in the evaporator the refrigerant evaporates to saturated vapor
- Each main component of concerned absorption chiller such as absorber, generator, is insulated well thus heat transfer between it and environment is negligible

The exergy transfer to a steady flow system is equal to the exergy transfer from it plus the exergy destruction within the system. The Exergy balance for the steady flow system could be expressed as follow [10]:

$$\sum_{in}\dot{Q}(1-\frac{T_0}{T}) - \sum_{out}\dot{Q}(1-\frac{T_0}{T}) - \dot{W} + \sum_{in}\dot{m}\psi - \sum_{out}\dot{m}\psi - \dot{X}_{destroyed} = 0 \tag{13}$$

First and second terms of the Eq. (13) are the exergy associated with heat transferred from the source maintained at temperature T. The third term is the exergy of mechanical work added to control volume which usually consider zero because for absorption chiller, the solution pump has a very low power requirement. The fourth and fifth terms are the exergy of the inlet and outlet streams of the control volume and the next term is exergy destruction which is happen in control volume.

Considering Fig. 1, the equations for the exergy losses calculation for each main component of absorption chiller could be expressed as follows:

$$\Delta\Psi_A = \dot{m}_{10}\Psi_{10} + \dot{m}_6\Psi_6 + \dot{m}_{13}\Psi_{13} - \dot{m}_1\Psi_1 - \dot{m}_{14}\Psi_{14} \tag{14}$$

$$\Delta\Psi_G = \dot{m}_3\Psi_3 - \dot{m}_4\Psi_4 + \dot{m}_{11}\Psi_{11} - \dot{m}_7\Psi_7 - \dot{m}_{12}\Psi_{12} \tag{15}$$

$$\Delta\Psi_{L} = \dot{m}_9\Psi_9 - \dot{m}_{10}\Psi_{10} + \dot{m}_{17}\Psi_{17} - \dot{m}_{18}\Psi_{18} \quad (16)$$

$$\Delta\Psi_{C} = \dot{m}_7\Psi_7 - \dot{m}_8\Psi_8 + \dot{m}_{15}\Psi_{15} - \dot{m}_{16}\Psi_{16} \quad (17)$$

The exergetic efficiency (ECOP) defined as the ratio of the useful exergy obtained from a system to that which is supplied to the system. Thus the exergetic efficiency of the absorption chiller for the cooling is the ratio of the chilled water exergy at the evaporator to exergy of heat source at the generator and can be written as [10]:

$$ECOP = \frac{\dot{m}_{17}(\psi_{18} - \psi_{17})}{\dot{m}_{11}(\psi_{11} - \psi_{12})} \quad (18)$$

As mentioned previously, this study has been carried out to evaluate energy and exergy performance of concerned absorption chiller. The chiller is used for air conditioning purpose. The operating data of the concerned chiller on 30th June 2009 were measured with infra red thermometer and are listed in table 1.

Table 1 Data measured on the site

Chilled water inlet temperature	14 ^{0}C
Chilled water outlet temperature	9 ^{0}C
Chilled water flow rate	65 kg/s
Ambient temperature	45 ^{0}C
Cooling water inlet temperature (absorber)	28 ^{0}C
Cooling water outlet temperature (absorber)	33 ^{0}C
Cooling water flow rate (absorber)	55 kg/s
Cooling water inlet temperature (condenser)	28 ^{0}C
Cooling water outlet temperature (condenser)	32 ^{0}C
Condensed water temperature (condenser)	34 ^{0}C
Cooling water flow rate (condenser)	55 kg/s
Steam inlet temperature (generator)	115 ^{0}C
Steam outlet temperature (generator)	95 ^{0}C
Steam flow rate (generator)	0.83 kg/s
Concentrated solution temperature at generator outlet	82 ^{0}C
Diluted solution temperature at heat exchanger inlet	40 ^{0}C
Diluted solution temperature at heat exchanger outlet	65 ^{0}C

In this study, a computer program has been developed to investigate the first and second law behavior of the system. The computer program is developed in engineering equation solver (EES) software. As the EES build-in property database does not contain the entropy of LiBr/H2O mixture, a procedure is developed within the EES to calculate the entropy of the solution using two empirical correlations which proposed by Kaita and Feuerecker [8]. The empirical correlation proposed by Kaita could be employed for calculating entropy of LiBr/H2O mixture where the mixture temperature is greater than $40^{0}C$. This correlation could be written in below form:

$$S = \sum_{i=0}^{3} \sum_{j=0}^{3} B_{ij} X^{j} T^{i} \quad (19)$$

The correlation coefficients are given in table 2. Where S, kj/kg.k, $40 \le T \le 210\ ^{0}C$, $40 \le X \le 65$.

The above equation isn't suitable where the mixture temperature is less than $40^{0}C$. Feuerecker [8] has proposed the below equation for computing entropy of LiBr/H2O mixture:

$$S = A_1 + A_2 + A_3T^2 + A_4X + A_5XT + A_6XT^2 + A_7X^2 + A_8X^2T + A_9X^3 + A_{10}X^4 \quad (20)$$

Where the coefficients are as follow:

$A_1 = -1.01961E3, A_2 = 1.1011529E-1,$
$A_3 = -1.042150E-2, A_4 = 1.036935E2,$
$A_5 = -5.87032E-2, A_6 = 8.63107E-5,$
$A_7 = -3.266802, A_8 = -3.16683E-4,$
$A_9 = 4.10099E-2, A_{10} = -1.790548E-4$

The Subroutines for calculating the properties of water–lithium bromide solution are linked to the library file of the EES. The developed computer program is based on heat and mass balances, heat transfer equations and the state equations. The thermodynamic properties of LiBr/H2O solution such as enthalpy, concentration and entropy are calculated by using built-in property database or developed procedure for LiBr/H2O solution. It should be noted that, in general, one would expect the enthalpy of a mixture to depend on pressure as well as temperature and mass fraction. For LiBr/H2O, the pressure dependence is small and it is ignored in the property models used here.

The initial conditions read into the program include the data measured at the site, with given parameters, the program calculates at all points of cycle the values of temperature, enthalpy, entropy, mass flow rate, concentration and exergy of the mixture. The results are presented in tables 3 and 4. In order to validate the present EES model, the results for the enthalpy and entropy of LiBr/H2O solution which are calculated by using EES model have been compared with available numerical data reported by Feuerecker and Kaita. It is observed that differences are within ±2%.

It can be seen from table 4, that the generator heat transfer rate is the highest and solution pump power is the lowest. Therefore, the solution pump effect on total energy is negligible. By using the computer program, the exergy losses of each component of the concerned absorption chiller are calculated and listed in table 5.

The atmospheric condition is considered as dead state with $T_0 = 25^0 C(298.15^0 K)$, $P_0 = 1atm$.

It can be seen from table 5, that the generator has the highest entropy generation and exergy loss. The next component which produces highest entropy generation and exergy loss is the absorber

Table 2 Coefficients of Eq. (19) calculated

i	B_{i0}	B_{i1}	B_{i2}	B_{i3}
0	5.12756E-1	-1.39395E-2	2.92415E-5	9.0357E-7
1	1.22678E-2	-9.1568E-5	1.82045E-8	-7.992E-10
2	-1.3649E-5	1.0689E-7	-1.38111E-9	1.53E-11
3	1.0215E-8	0	0	0

Table 3 Thermodynamic properties of each state point

omponent	Exergy Received, kw	Exergy Delivered, kw	Exergy Loss, kw	Exergy Loss, %
Evaporator	46.51	20.37	26.17	7.7
Absorber	196.3	91.67	104.7	30.86
Generator	591.3	429.6	161.8	47.69
Condenser	46.31	7.353	38.96	11.48
Heat exchanger	429.2	421.6	7.634	2.25
System	1309.72	970.59	339.264	

Table 4 Energy flows at various components of absorption chiller

State point	T, ^0C	X, %	h, kj/kg	S, kj/kg.k	Exergy, kj/kg
1	40	58.3	107.1	0.2379	6.403
2	40	58.3	107.1	0.2379	6.403
3	67	58.3	160.5	0.3986	11.9
4	81	61.76	202.7	0.4505	36.47
5	55	61.76	153.8	0.3087	29.88
6	55	61.76	153.8	0.3087	29.88
7	73.36		2632	8.599	72.72
8	34		142.4	0.5579	-19.27
9	5.002		142.4	0.5579	-19.27
10	5		2510	9.024	-176
11	115		2699	7.183	561.8
12	95		398	1.25	29.93
13	28		117.3	0.4088	0.06333
14	33		138.2	0.4777	0.443
15	28		117.3	0.4088	0.06333
16	32		134	0.464	0.3401
17	14		58.73	0.2097	0.8688
18	9		37.8	0.1361	1.862

. **Table 5** Exergy balance of the absorption chiller components

Component	Symbol	Energy flow, KW
Evaporator	Q_L	1360
Absorber	Q_A	1878
Generator	Q_G	1910
Condenser	Q_C	920.4
Heat exchanger	Q_{hx}	484
Solution Pump	P_{pump}	1.05

4 REAULTS AND DISCUSSIONS

It is clear from Fig. 2, by dividing the exergy loss of the generator and absorber to total exergy loss, that the generator has the highest exergy loss with the 47.69% and the next highest exergy loss or exergy destruction occurred in the absorber with the 30.86%. Since exergy losses in the solution, refrigerant pump and expansion valves are small then their effect on the total exergy loss could be neglected.

The variation of the generator exergy loss with the generator inlet steam temperature is shown in Fig. 3. It can be seen by increasing the inlet steam temperature while other components conditions kept constant, the generator exergy will be increased. Considering Fig. 3, one could conclude that an absorption chiller with hot water as heat source is more efficient than the one with steam as heat input.

The entropy generation for the generator is calculated using Eq. (21). The similar formulas could be developed for calculating entropy generation in the chiller other components.

$$\dot{S}_G = \dot{m}_R[S_7 + (CR-1)S_4 - CR(S_3)] + \dot{m}_{ST}(S_{12} - S_{11}) \quad (21)$$

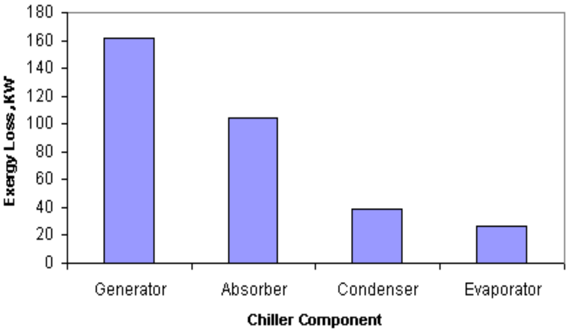

Fig. 2 The exergy losses of absorption chiller components

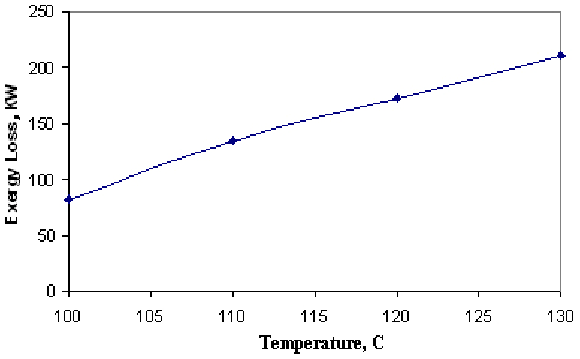

Fig. 3 The variation of generator exergy loss with the generator inlet steam temperature

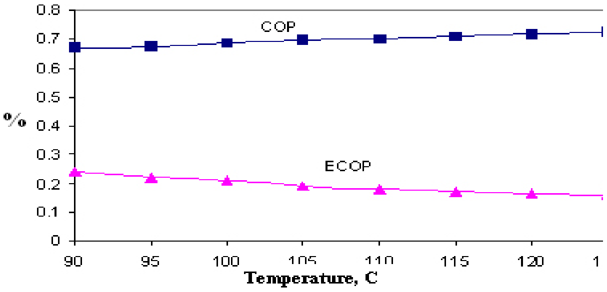

Fig. 4 The variation of COP and ECOP with the generator inlet steam temperature

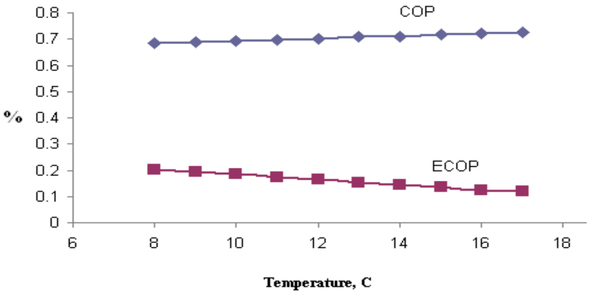

Fig. 5 The variation of COP and ECOP with evaporator inlet chilled water temperature

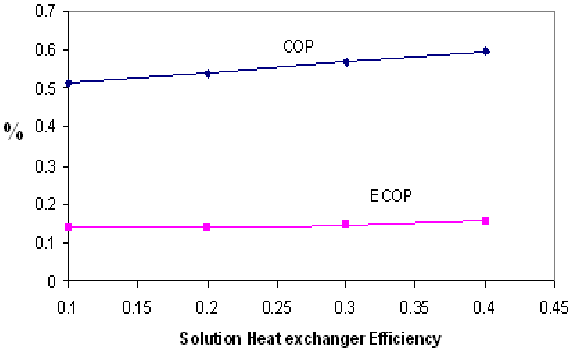

Fig. 6 The variation of COP and ECOP with solution heat exchanger efficiency

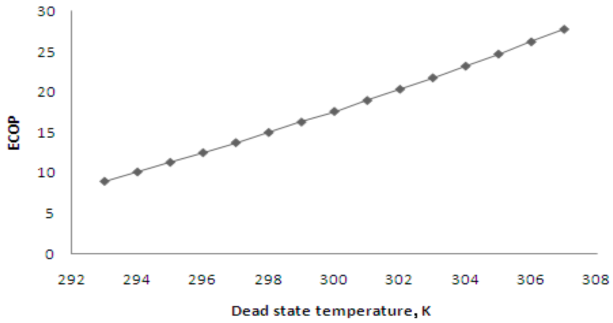

Fig. 7 The variation of COP and ECOP with dead state temperature (environmental temperature)

The variation of COP and ECOP of the concerned absorption chiller with the generator inlet steam temperature is shown in Fig. 4. It can be seen by increasing the inlet steam temperature due to increasing the cooling capacity which is produced at the evaporator, COP increased slightly but ECOP due to higher heat transfer irreversibility (higher temperature difference between hot and cold streams) decreased.

In the other hand, by increasing the inlet steam temperature the dilute solution concentration increases so according to the Eq. (2) and (3) the circulation ratio (CR) decreased thus the cooling capacity increased in the evaporator therefore the COP increased until the value of CR reached to the critical value after that increasing the inlet steam temperature cause crystallization which is reduced the COP rapidly.

The effect of decreasing CR causes the average temperature of the generator, absorber and condenser to increases. This increase in the average temperatures is accountable for the increase in the exegy destruction in the generator and absorber. It should be noted that, the exergy destruction increases in the condenser is small compared with the overall increase in the system exergy destruction.

The variation of COP and ECOP with inlet evaporator temperature is shown in Fig. 5, where it is clear that by increasing the evaporator inlet water (chilled water) temperature from 8 to 17 ^{o}C , the pressure in the evaporator and absorber increases from 0.609 to 1.084 Kpa. This will cause the heat transfer increases slightly. This means that the circulation ratio decrease and the COP increases. Unlike the COP by increasing the evaporator inlet water temperature the ECOP of the system decreases because the evaporator entropy generation increases rapidly. This means that the lower evaporator inlet water temperature has a more potential to create cooling effect at the same flow rate rather than higher temperature.

The absorber pressure is another important parameter which is affecting the ECOP. When the absorber pressure varies, properties such as enthalpy and entropy changed, by increasing the pressure, solution absorbs a greater amount of mass in order to maintain equilibrium with the water vapor exist at the absorber. Thus the outlet solution concentration decreased and causes the outlet exergy of the dilute solution decreased too. Hence, the irreversibility increases and total exergy decreases as the absorber pressure is increased.

It is clear from Fig. 6 that by increasing the solution heat exchanger efficiency the COP increases. This is because the dilute solution (before entering the generator) is preheated hence the heat demand in the generator decreased. Like COP, as the solution heat exchanger efficiency increases, the ECOP increases too. The increase in ECOP is due to decrease in the exergy destruction within the generator and absorber.

The less exergy destruction is due to regenerate heat of the concentrated solution by the weak solution returning to the generator and reducing circulation losses.

The variation of ECOP with the dead state (environment) temperature for the concerned chiller is shown in Fig. 7. It is observed the ECOP increases by increasing the dead state temperature. This could be discussed by looking at the Eq. (12), as the input exergy of fluid decreases hence total exergy destruction of system decreases too.

5 Conclusion

In this study, the energy and exergy analysis of an absorption chiller, are carried out. A computer program is developed to predict the performance of the concerned chiller. The conclusions drawn from the analysis are cited below:

1. The results showed that in spite of relatively high energy efficiency, the absorption chiller has low exergy efficiency. In fact, irreversibilities happen in the chiller's components due to heat and mass transfer processes are main factor that affect the exergy efficiency of the absorption chiller and tend to reduce it.

2. The exergy loss which is happened in the generator is a considerable fraction of the total exergy losses due to the temperature difference between the heat source and working fluid. Therefore, the generator is the most important component of the absorption chiller and has a greater effect on COP and ECOP of the system. So to produce less exergy loss within the chiller, the generator should be operated with lower temperature source.

3. The absorber is a next important component of absorption chiller as it produces 20-30% of the total exergy losses. In order to produce less exergy within the absorber, it should be develop more efficient.

4. The exergy destruction which is happened in the generator and absorber increase with the generator temperature as the concentration difference between weak and strong solution increases.

5. The condenser and evaporator exergy losses are much less than generator and absorber losses. The losses (within the condenser and evaporator) are mainly due to heat of mixing in the solution which is not present in pure fluid such as single refrigerant in vapor compression cycle. The effect of exergy losses in the solution, refrigerant pump and expansion valves on the total exergy losses are small and considered negligible.

6. The performance of the absorption chiller is strongly influenced by the operating temperatures. These results are very important in the improvement of the absorption chillers performance.

7. The ECOP and COP increase with the increase in the solution heat exchanger efficiency.

8. The ECOP increase with the increase in dead state (environment) temperature.

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