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Exergy Analysis of a Double-effect Parallel-flow Commercial Steam Absorption Chiller

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Abstract: Exergy analysis of a double-effect parallel flow commercial absorption chiller is presented in this study. Generally a major obstacle for developing model of a commercial absorption chiller is lack of available component specifications. These specifications are commonly proprietary of the chillers manufacturers and normally the available information is not sufficient. This study presented a double-effect parallel-flow-type steam absorption chiller model based on mass and energy equations. The chiller studied is 1250 RT (Refrigeration Tons) using lithium bromide-water solution as working pair. For refrigerant and absorbent properties, set of efficient formulations are used. The model gives the required information about temperature, concentration, entropy, exergy and flow rate at each state point of the system. The model calculates the heat load at each component as well as the performance of the system. The profile of the exergy destructions for various components is plotted against the heat load in the range of 20-100% of cooling capacity. The results showed that the high temperature generator has the greatest exergy destruction followed by the absorber and high temperature solution heat exchanger. Further, it was found that the Coefficient of Performance (COP) increased with increasing with load factor. However, the exergetic efficiency was found to decrease while increasing the load factor.

Key words: Absorption chiller, coefficient of performance, exergy analysis

INTRODUCTION

Absorption cooling systems use thermal power as a driving force to produce cooling. Although, these systems have a lower coefficient of performance compared to the vapour compression systems, absorption cooling systems have been gaining a considerable attention in recent years due to their driving forces which, could be from industrial waste heat, renewable energy, or other heat sources for which the cost of supply is negligible in many cases. Furthermore, absorption systems use environmental friendly working fluids which do not contribute on ozone depletion and global warming (Gomri, 2010). The most common challenge for modeling commercial absorption chiller is the limitation of configuration data which are confidential to the chiller manufacturer. Many researchers studied the performance of absorption chiller based on second law analysis. Most of the previous works dealt with fixed capacity of the machine and no study in literature for second law analysis under partial load conditions.

Kaushik and Arora (2009) developed a model for water-lithium bromide absorption systems that investigates exergy and energy under single and series flow double effect configurations. Their findings pointed out that Coefficient of Performance (COP) lies in the range of 0.6-0.75 and 1-1.28 for single and double effect systems, respectively. Irreversibility is the highest in the absorber in both systems when compared to other system components.

Gebreslassie *et al.* (2010) conducted an exergy analysis for single, double, triple and half effect absorption cycles which use Water-Lithium bromide as a working fluid. In their study, they only considered the unavoidable exergy destruction and they concluded that the COP increases while increasing the cycle effect from double lift to triple. However, there was no significant effect on exergetic efficiency at various configurations. For exergy destruction rates, the effect of the heat source temperature has similar effect for same type of components. Nevertheless, the quantitative contributions were dependent on the flow configuration and cycle type. The absorbers and generators have the largest exergy destruction.

Sencan *et al.* (2005) reported exergy analysis of a single-effect lithium bromide/water absorption system for cooling and heating applications. They found out that the heat loads and exergy losses from the condenser and evaporator were less than those of the absorber and generator. This happened because of the heat of mixing in

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the solution which could not be present in pure fluids. The results show that the cooling and heating COP of the system increase slightly when increasing the heat source temperature. However, they reported that increasing the heat source temperature decreased the exergetic efficiency for both cooling and heating applications.

Kilic and Kaynakli (2007) developed a mathematical model based on the first and the second law of thermodynamics to analyze the performance of a single-stage water-lithium bromide absorption refrigeration system. The model used to assess the system performance, exergy loss of each component and total exergy loss of all the system components. Their study showed that increasing the generator and evaporator temperatures increased the performance of the absorption refrigeration system. However, the performance was decreased while increasing the temperature of absorber and condenser. The generator had the highest exergy loss irrespective of operating conditions, indicating that it's the most essential component of the cycle. Most of the previous works dealt with fixed capacity of the machine and to the best of our knowledge, no study in literature has been reported that considers the exergy analysis of absorption chillers under partial load conditions. Hence, our objective in this study is to develop thermodynamic model for a commercial absorption chiller and evaluate the chiller performance based on second low analysis under different load conditions.

Description of double- effect absorption chiller cycle: Figure 1 shows the schematic of a double-effect steam absorption chiller. The circulation of the solution inside the system is assured by the solution pump. The weak solution (in LiBr) from absorber is subjected to flow to the high and low temperature generators (HTG and LTG, respectively) through low and high temperature solution heat exchangers (LTX and HTX, respectively). At HTG, the solution is heated by steam that circulates in the tube side, as a results the refrigerant vapor (water) is generated. The vapor from HTG is used as heat input for the LTG. Once this vapor is condensed, it is throttled to the condenser pressure. The vapor generated by LTG is also condensed in the condenser (Gordon and Ng, 2000).

The strong solutions leaving the HTG and LTG are combined at LTX for transferring heat to the weak solution that came from the absorber and then the combined stream enters the absorber. At the absorber spraying nozzles, the strong solution pressure drops to the absorber pressure. The refrigerant vapor produced in HTG and LTG is condensed in condenser and throttled to the evaporator pressure. In evaporator, liquid refrigerant is evaporated taking its latent heat from chilled water that circulates in the tube side and produce the cooling effect. Then the refrigerant that vapors in the evaporator is absorbed in the absorber (Ahmed and Ul-Haq Gilani, 2011).

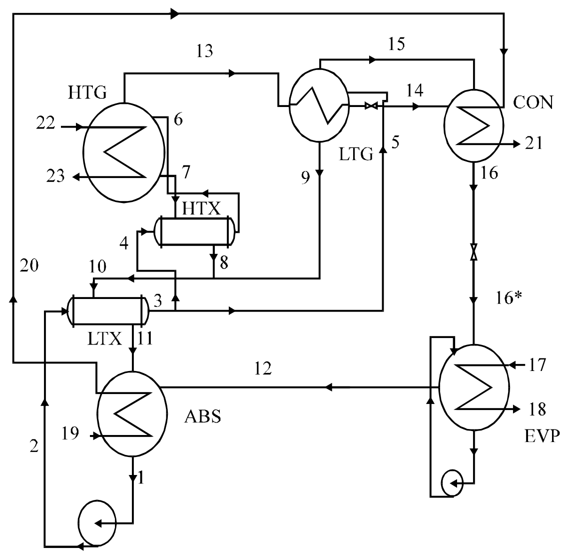

Fig. 1: Schematic presention of a double-effect steam absorption chiller, HTG: High temperature generator, LTG: Low temperature generator, CON: Condenser, EVP: Evaporator, ABS: Absorber, HTX: High temperature solution heat exchanger, LTX: Low temperature solution heat exchanger, 1, 2, 3...23: State points of entering and leaving streams

MATERIALS AND METHODS

A computer code for the simulation of a double-effect absorption chiller has been written using Matlab software. The model is based on mass and energy balances, heat transfer equations and equation of state. For thermal properties of LiBr solutions and steam used in the calculations are obtained from Herold *et al.* (1996), Chua *et al.* (2000), Talbi and Agnew (2000) and (Kreith and Goswami, 2007). The initial conditions consist of steam inlet pressure, cooling and chilled water inlet temperatures and flow rates and ambient conditions.

By applying mass balance, energy balance, heat transfer equations and equation of state for the LiBr-H_2O solution for each component of double effect steam absorption chiller, the following set of equations are obtained.

The following assumptions were employed to properly represent the absorption chiller cycle:

- The solution leaving the absorber is saturated
- The enthalpy change across the pump is very small and can be omitted
- The temperatures of the vapor generated in generators are equal to the average temperature of the entering and leaving temperatures of the solutions from which it generated
- The water entering the evaporator is saturated
- Expansions are isenthalpic
- The strong solution entering the absorber is saturated
- The simulation is under steady state

Mass balance: For each chiller component, the steady state total mass balance equation for refrigerant, chilled water, cooling water and lithium bromide can be expressed as:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{1}$$

where, m is the mass flow rate and in and out are the stream entering and leaving each of the chiller components.

The mass balance of LiBr-H_2O streams:

$$\sum \dot{m}_{in} * X_{in} = \sum \dot{m}_{out} \times X_{out} \tag{2}$$

where, x is the concentration of LiBr solution.

Energy balance: The energy balance for each chiller components is expressed as:

$$\dot{Q} + \sum \dot{m}_j * h_j = 0 \tag{3}$$

Where:
Q = The quantity of heat transfer to or from the system
h_j = Enthalpy of each stream

For the absorption process in the absorber:

$$Q = m_r\, h_r + m_c\, h_c - m_d\, h_d \tag{4}$$

Where:
r = For refrigerant
c = Concentrate solution
d = Dilute solution

Heat transfer equations: The log mean temperature difference method (LMTD) is used to evaluate the product of overall heat transfer coefficient U and heat transfer surface area A:

$$UA = \frac{\dot{Q}}{\Delta T_{LMTD}} \tag{5}$$

The log mean temperature difference is expressed as:

$$\Delta T_{LMTD} = \frac{(T_{hot,in} - T_{cold,out}) - (T_{hot,out} - T_{cold,in})}{\ln \frac{T_{hot,in} - T_{cold,out}}{T_{hot,out} - T_{cold,in}}} \tag{6}$$

Exergy analysis: The exergy method, known as the second law analysis, calculates the exergy loss caused by irreversibility which is an important thermodynamic property that evaluates the useful work that, can be produced by a substance or the amount of work needed to complete a process. The exergy analysis is a useful tool for thermodynamic analysis of energy-conversion systems.

The exergy content of a pure substance is generally given by:

$$\psi = (h-h_0)-T_0(S-S_0) \tag{7}$$

ψ = Exergy (kJ kg^{-1})
S = Entropy (kJ kg^{-1} K^{-1})
S_0 and h_0 = Enthalpy and entropy at environmental temperature T_0, respectively

The exergy of the solution is calculated by:

$$\psi = (h\,(T, X)-h_0)-T_0(S(T, X)-S_0) \tag{8}$$

The exergy loss in each component under steady state condition and neglecting the potential and kinetic energies is calculated by:

$$\Delta\psi = \sum m_i \psi_i - \sum m_o \psi_0 - Q\left(1 - \frac{T_0}{T}\right) - W \tag{9}$$

The first term on the right-hand side is the sum of the exergy input; the second is the sum of exergy output while the third term is the exergy of heat Q which is transferred at constant temperature T. The last term is mechanical work transfer to or from the system.

The total exergy loss ($\Delta\psi_T$) of the system is the sum of exergy loss in each component:

$$\Delta\psi_T = \Delta\psi_{HTG}+\Delta\psi_{LTG}+\Delta\psi_{CON}+\Delta\psi_{EVP}+\Delta\psi_{ABS}+\Delta\psi_{HTX} \tag{10}$$

The exergetic efficiency τ is given by:

$$\tau = \frac{-Q_{EVP}\left[1-\frac{T_0}{T_{EVP}}\right]}{Q_{HTG}\left[1-\frac{T_0}{T_{HTG}}\right]} \tag{11}$$

Where:

HTG = High temperature generator
LTG = Low temperature generator
CON = Condenser
EVP = Evaporator
ABS = Absorber
HT = High temperature solution heat exchanger
LTX = Low temperature solution heat exchanger

RESULTS AND DISCUSSION

The mathematical equations that govern the operation of the steam absorption chiller are developed. A computer program which is written in MATLAB environment was developed. Simulation was performed in order to get the various state points properties such as, temperature, concentration, mass flow rate, entropy and exergy. Table 1 shows the properties at each state point at the design condition. The exergy flow has a maximum value at state point 22 which is the input heat source (saturation steam) and followed by the state point 7 where the strong solution left the HTG. The exergy loss and exergetic efficiency are calculated based on the previous state points properties.

The exergy destructions for various components are plotted versus heat load starting from minimum heat load till full load (20-100%). The high temperature generator has the greatest exergy destruction followed by the absorber and high temperature solution heat exchanger as shown in Fig. 2. The exergy destruction in the first two is

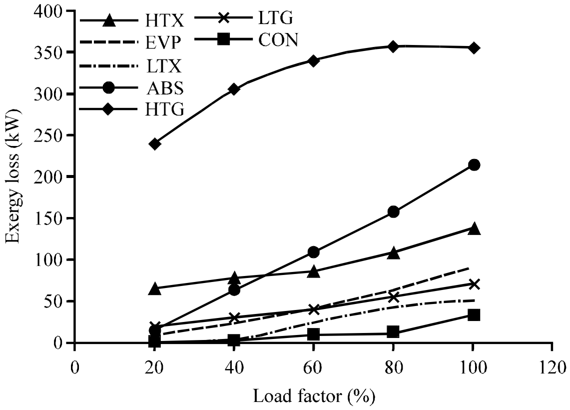

Fig. 2: Exergy loss under various load conditions, HTG: High temperature generator, LTG: Low temperature generator, CON: Condenser, EVP: Evaporator, ABS: Absorber, HTX: High temperature solution heat exchanger, LTX: Low temperature solution heat exchanger

Table 1: Properties of state point values of double-effect steam absorption chiller at design condition

State point	T (°C)	Entropy (kJ kg^{-1} K^{-1})	X (%)	m (kg sec^{-1})	Entholpy (kJ kg^{-1} K^{-1})	ψ (kJ kg^{-1})	Exergy (kW)
Evaporator							
16*	4.62	171.620	-	1.880	0.61290	-8.1200	-15.256
17	13.50	56.700	-	140.000	0.20238	0.9322	130.508
18	6.50	27.300	-	140.000	0.09856	2.4872	348.208
12	4.62	2519.350	-	1.880	9.03400	-179.6020	-337.650
Absorber							
1	37.00	96.290	57.70	18.000	0.21500	34.0930	516.060
11	48.67	136.630	63.96	16.120	0.25800	61.6400	993.640
19	32.00	134.400	-	255.550	0.46440	0.5080	129.870
20	37.25	155.910	-	255.550	0.53590	0.6623	169.250
High temperature G.							
6	136.90	302.110	57.7	9.540	0.76600	75.5700	720.937
7	163.52	375.128	64.9	8.419	0.79510	140.2200	1180.512
13	150.20	2780.000	-	1.021	7.83000	447.4000	456.790
22	169.30	2768.390	-	1.528	6.67460	784.0380	1198.010
23	169.30	716.360	-	1.528	2.03200	114.4350	174.857
Low temperature G.							
5	80.00	187.610	57.7	8.460	0.46700	50.4000	453.600
9	97.12	242.500	62.9	7.602	0.51410	91.3060	694.108
15	88.90	2684.010	-	0.858	8.55400	138.0800	118.472
14	89.96	376.780	-	1.021	1.19200	25.8700	26.413
Condenser							
16	41.00	171.580	-	1.880	0.58420	1.3830	2.412
20	37.25	155.910	-	255.550	0.53590	0.6623	169.250
21	39.22	164.155	-	255.550	0.56212	1.0880	278.140
HTX							
8	88.68	230.270	64.9	8.419	0.45790	95.7690	806.280
LTX							
4	69.38	162.970	57.7	18.000	0.40530	44.1640	794.950

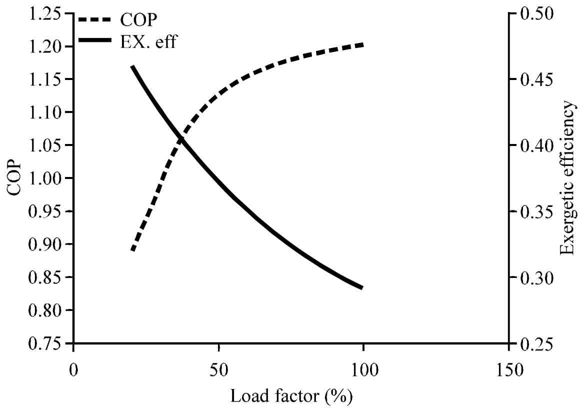

Fig. 3: Exergy efficiency and COP under various load conditions

due to heat of mixing and separation in the absorber and first generator, respectively. For high temperature solution heat exchanger, the exergy loss is due to large terminals temperature difference. For single and series flow double effect lithium bromide-water absorption systems, it is found that the highest exergy loss occurs in the absorber (Kaushik and Arora, 2009; Gebreslassie *et al.*, 2010). For double effect parallel flow chillers, (Gebreslassie *et al.*, 2010) also found that the highest exergy loss occurs in the high temperature generator which well matches our results.

Figure 3 shows the exergetic efficiency (EX.eff) and COP under different load conditions. The exergetic efficiency decreases with increasing of the load factor while the COP increasing with the load factor till reached its highest value. This behaviour is mainly due to the increase in the heat input to the system which leads to increase the cooling effect in the evaporator and finally it increases the COP. But due to the rapid increase in heat input, the heat transferred in all components of the system is increased. The aforementioned increase in heat input result in an increase in irreversibility and thus reduces the exergetic efficiency. This result is in a very good agreement with the research work done by Sencan *et al.* (2005).

Figure 4 presents the variation of exergy loss of the main component in the system for different heat load. It is obvious from this figure that the exergy loss is increasing with the increasing of the load factor and it is increasing with load factor for all components. The first generator has the greatest exergy loss that, increasing with load factor. After 60 % load the increase in exergy loss is lower than that for load less than 60%. The absorber has the second higher exergy loss and its increases proportionally with load factor.

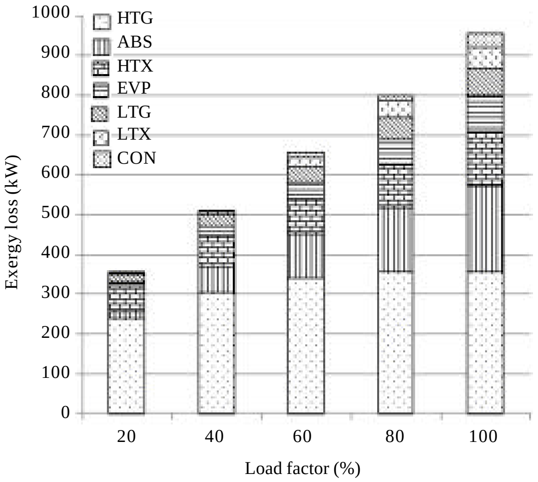

Fig. 4: Total exergy loss under various load conditions, HTG: High temperature generator, LTG: Low temperature generator, CON: Condenser, EVP: Evaporator, ABS: Absorber, HTX: High temperature solution heat exchanger, LTX: Low temperature solution heat exchanger

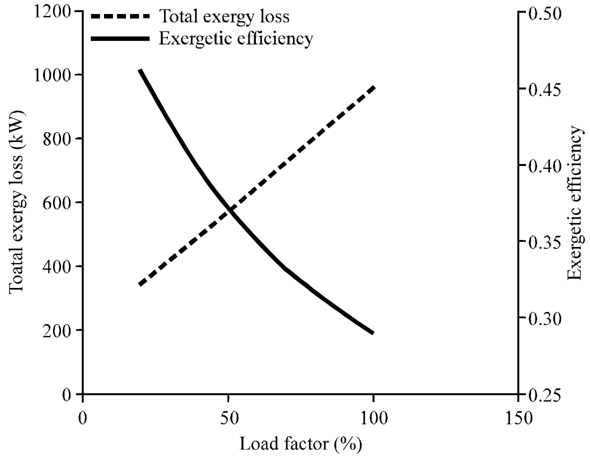

Fig. 5: Total exergy loss and exergetic efficiency under various load conditions

The total exergy loss is increasing with the load factor while the exergetic efficiency is decreasing as illustrated in Fig. 5. This manner is mainly due to increasing the heat input with respect to the load factor which leads to increasing the heat transferred in all the system components. Therefore, the increase in heat transfer results in an increase in the exergy loss in all components. Hence, it decreases the exergetic efficiency.

CONCLUSIONS

The model that represents the operation of the steam absorption chiller is developed. The properties of refrigerant and solution at each state point are calculated (temperature, enthalpy, concentration, flow rate, entropy and exergy). The exergy destruction in different system components is evaluated. The first generator has the greatest exergy destruction followed by the absorber and high temperature solution heat exchanger. Further, the performance of the system is evaluated by means of Coefficient of Performance (COP) and exergetic efficiency (second law efficiency). This model can be used as a tool for thermo-economic analysis of the absorption system.

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