Energy and Exergy analysis of Triple Effect Vapor Absorption Air Conditioning System

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Abstract: Energy and Exergy analysis of an Air-Conditioning plant which is running for the last four and half year is presented in this paper. This plant is actually a demonstration project installed by Thermax and Ministry of New and Renewable Energy at National Institute of Solar Energy for research purpose. Triple effect vapor absorption chiller is utilized to produce cooling and the input heat is provided by solar energy with the help of parabolic trough collector. Mathematical modeling of vapor absorption chiller is done for formulating the required relations for evaluation. Energy and exergy balance equations of chiller are clearly presented. The results of analysis of chiller shows that the two heat exchangers, (HX I) and (HX II) are the biggest source of exergy destruction, destroying 16.40 % and 8.60 % of exergy respectively. Deviating from the previous published results in literature, absorber is not the component where maximum exergy is destroyed. The components that need to be optimized are the three generators. The COP is also calculated from energy balance and it comes out to be 1.27. Exergetic efficiency of chiller obtained is 9.2 %.

Keywords: Energy, Exergy, Generator, Heat exchanger, Triple effect.

I. INTRODUCTION

Absorption cycles have been used in air-conditioning applications for over 50 years .In the late 1950s the first working double-effect lithium bromide – water absorption chiller was built. In the 1960s the natural gas industry was very effective in promoting this alternative to electric-driven cooling. Absorption cooling and gas absorption chillers were successfully marketed on the basis of lower operating costs, and better system performance. Counter acting this, innovations in compressors, electric motors, and controls increased the performance and decreased the cost of electric cooling systems.

Additionally, and perhaps more importantly, the gas crunch of the seventies curtailed gas cooling promotion and forced prospective buyers to remain with conventional electric systems. Since 1987 when the Montreal Protocol first came into existence many issues surrounding electric cooling including the use of CFC refrigerants and electric utility rates, have become increasingly complicated. Coincident with these electric cooling issues, gas costs have remained relatively stable while the technology itself has improved. Since 1995 several factors have helped the absorption cooling market including the opening of large natural gas equipment manufacturing plants in the United States, major developments in equipment financing and performance contracting.

A basic three-condenser-three-generator triple-effect cycle was patented in 1985. An alternate triple-effect cycle, the double-condenser coupled (DCC) cycle, was patented in 1993. As of the end of 1997, two U.S .manufacturers were conducting research and development (R&D) programs aimed at producing triple-effect absorption chillers.

II. LITERATURE SURVEY

Bajpai [1] designed a single effect absorption system with evacuated tube collector for heat input. He showed all the calculations in his paper and he proved the feasibility of solar powered absorption system. His results include the heat input required to run the 1TR vapour refrigeration system, for the operating conditions designed, is about 304.2 KJ/min. This heat in the generator is supplied by the hot water coming from the solar flat plate water heater. Output temperature of his system was 84° C and COP he got is 0.69. **A.I.Shahata, M. M. Aboelazm [2]** did the energy and exergy analysis of a single and double effect lithium bromide-water absorption cycle .They presented clear relations for finding the enthalpy and entropy of LiBr-water solution at different concentrations.

They concluded that the maximum COP and Exergetic efficiency is achieved at lower values of the generator and absorber temperatures for both single and double effect systems. The double effect system has higher COP and Exergetic efficiency compared with the single effect system. The maximum COP and exergetic efficiency for single effect is 0.78 and 11.48 while the maximum COP and exergetic efficiency for double effect system is 1.3736 and 11.5766. The absorber has highest exergy loss rate among the different components of 49.511% for single effect and 27.511% for double effect system. **Khaliq and Kumar [3]** analysed the performance of a solar thermal driven LiBr-H2O absorption refrigeration system for single effect cooling and evaluated the entropy generation in each component as well as the energetic and exergetic COP of the system. They proved that exergy destructions were significantly larger in generators, absorbers, evaporator and heat exchangers as compared to those in

condenser, evaporator, throttling valves, and expansion valves. **J.Aman [4]** observed that large scale heat-driven absorption cooling systems are available in the marketplace for industrial applications but the concept of a solar driven absorption chiller for air-conditioning applications is relatively new. Absorption chillers have a lower efficiency than compression refrigeration systems, when used for small scale applications and this restrains the absorption cooling system from air conditioning applications in residential buildings. The potential of a solar driven ammonia-water absorption chiller for residential air conditioning application is discussed and analysed in his paper. A thermodynamic model was developed based on a 10 kW air cooled ammonia-water absorption chiller driven by solar thermal energy. Both energy and exergy analyses was conducted to evaluate the performance of this residential scale cooling system. The analyses uncovered that the absorber is where the most exergy loss occurs (63%) followed by the generator (13%) and the condenser (11%). Furthermore, the exergy loss of the condenser and absorber greatly increase with temperature, the generator less so, and the exergy loss in the evaporator is the least sensitive to increasing temperature. **Gomri [5]** analysed a triple effect vapor absorption system. He wrote in his paper that an analysis method is developed and implemented on a computer code to simulate the operation of triple effect absorption refrigeration system under different conditions. Exergy loss of each component is calculated. The absorber has the highest exergy loss rate. For commonly used condenser and absorber cooling water temperature (25°C/30°C) and chilled water temperature (12°C/7°C) the maximum exergetic efficiency value of the triple effect refrigeration system is about 35.1 % .For a given HPG temperature (here 190°C) the effect of LPG temperature is more important than the MPG temperature. The maximum COP and η_{exergy} are obtained for a maximum value of LPG and MPG temperatures. For a given MPG temperature there is an interval of LPG temperature for which the triple effect absorption system can operate. Out from this interval of temperature the system does not function any more. The second law analysis used in this study facilitates the identification of the system components with high exergy loss. The results of the exergy analysis presented in this paper can be used in thermo-economic optimization of triple effect absorption refrigeration system.

III. EXPERIMENTAL SETUP

A solar powered air-conditioning system designed for heating and cooling typical for National Institute of Solar Energy of average occupied area of 288 m^2 in India was put into operation at centre by Ministry of New and Renewable Energy in 2011.

About 170° C prevailing heat is supplied to the generator of a 100 kW nominal cooling capacity (LiBr/H_2O) absorption chiller, which operated in vacuum. This is to boil a weak solution of solvent and refrigerant (lithium bromide and water), that resulted in a strong solution. The refrigerant vapor is condensed on the condenser tubes. The

condensate is then throttled through an expansion device obtaining two-phase refrigerant; the liquid refrigerant evaporated under low pressure in the evaporator, thus producing cooling. Chilled water flowing through the evaporator tubes is supplied to the fan coil units at about 7˚C. Meanwhile, the strong solution from the generator passes through a counter flow heat exchanger to preheat the weak solution entering the generator. In the absorber, the refrigerant vapor from the evaporator is absorbed in the strong solution. The heat of condensation and absorption is removed from the system by means of cooling water entering/leaving the chiller at about 30/35˚C flowing through the tubes of the absorber and condenser in parallel connected to a forced draft cooling tower. The solution is circulated by a mechanical pump. However, pumps are used to circulate water between the collector array and the plate heat exchanger, plate heat exchanger and storage tank, storage tank and generator, cooling tower and absorber/condenser and fan coil units and evaporator. Thermal energy is supplied entirely by solar collectors

3.1 Calculation procedure for obtaining specific enthalpy and specific entropy of LiBr water solution:-

Since strong water-lithium Bromide solution deviates from ideal solution behavior, it is observed that when water and anhydrous lithium bromide at same temperature are mixed adiabatically, the temperature of the solution increases considerably. This indicates that the mixing is an exothermic process a negative heat of mixing. Hence the specific enthalpy and entropy of the solution given by:

$h = \xi.h_L + (1-\xi)h_w + \Delta h_{mix}$

Where h_L=specific enthalpy of pure LiBr

h_w=specific enthalpy of Water

ξ= mass fraction of LiBr in solution= $m_L/(m_L+m_w)$

So enthalpy and entropy both have to be determined for proper analysis. The lack of pre-established methodology has led several authors to perform exergy calculations reporting widely varied exergy values for LiBr-H_2O solution. Some of these studies are limited to the calculation of irreversibility and exergy efficiency of overall system considering only pure water properties. Thus there is a need to adopt unique methodology for obtaining these values. In this analysis tables developed by **Chua at el [6]** are used.
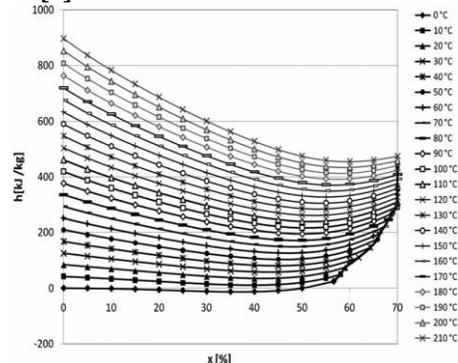
Figure1. Enthalpy of lithium bromide–water solutions as a function of the concentration for different temperatures (adapted from Chua et al)
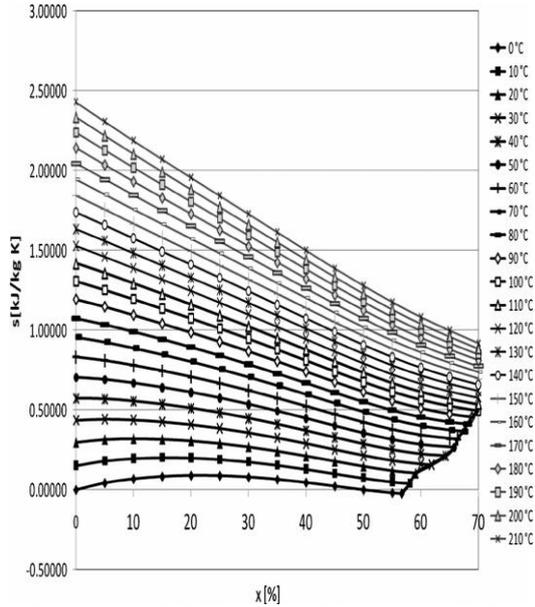
Figure2. Entropy of lithium bromide–water solutions as a function of the concentration for different temperatures (adapted from Chua et al)

3.2 Equations used in the analysis

Energy and Exergy analysis is carried out throughout the triple effect vapor absorption system .For that, enthalpy & entropy as well as mass flow rate of all points or states in the system have to be obtained.

The following equations will serve the purpose:
First law (Energy balance)

$$\left(\Sigma \dot{m}_i h_i - \Sigma \dot{m}_o h_o\right) + \left(\Sigma \dot{Q}_i - \Sigma \dot{Q}_o\right) + \dot{w} = 0 \quad [7]$$

Exergy balance

$$\dot{E}_{destroyed} =$$

$$\dot{E}_{destroyed} \Sigma\left(1 - \frac{T_o}{T_k}\right)\dot{Q}_k + \Sigma\left(m_i \psi\right)_{in} - \Sigma\left(m_o \psi\right)_{out} + \dot{w}$$

Flow exergy is calculated at every state as

$$\psi = \left(h - h_o\right) - T_o\left(s - s_o\right), \quad COP = \frac{Q_{eva}}{Q_g + W_p}$$

Non dimensional exergy loss $= \dfrac{\dot{E}_{destroyed}, i}{\dot{E}_{destroyed}, total}$

Then, COP_E (Reversible cycle) is determined by

$$COP_E = \left(1 - \frac{T_o}{T_{gen}}\right)\left(\frac{T_{eva}}{T_o - T_{eva}}\right) \quad [4]$$

Exegetic efficiency, therefore is

$$\eta_{exergy} = \eta_{II} = \frac{COP}{COP_E}$$
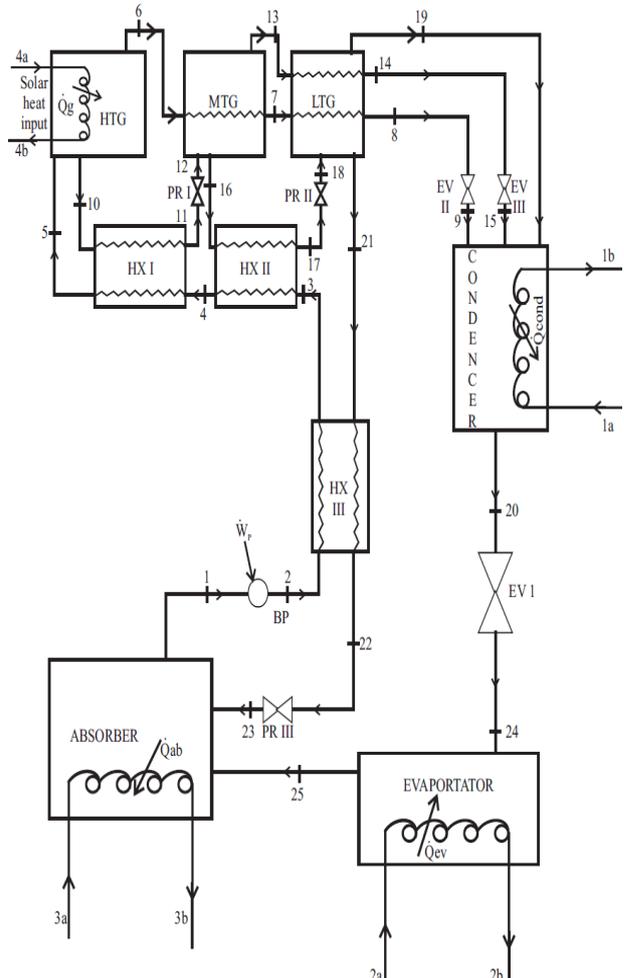
Figure3. Flow diagram of triple effect vapor absorption system

In absorber the LiBr-H_2O solution is off 50% concentration each. The temperature in absorber is fixed at 35°C. The solution is pumped by Booster pump (BP) to the Heat Exchanges III (HXIII) where it takes heat energy from the strong solution coming out from Low temperature Generator (LTG) through counter how heat exchange Afterwards, it again passes through two more heat exchangers (HXII) and (HXI), where the 50% solution gains more heat from the fluid coming directly from MPG and LPG in Counter heat exchange manner. In High temperature Generator (HTG) the heat energy is supplied from solar field at 210°C temperature pressurized water. This water loses its sensible heat to the LiBr-H_2O Solution and leaves the generator at 200°C. The LiBr-H_2O solution takes this heat and since the evaporation temperature of H_2O is less, some mass of H_2O boils off as a superheated Vapor at around 180°C and 4 bar pressure. The remains solution passes through (10) and then HXI to MTG. Since some mass to H_2O is boils off, the concentration of new solution will be around 57/43 i.e. 57% LiBr & 43% H_2O. In medium temperature generator, the superheated Vapor is made to pass through it where it loses its latent heat to get convert in saturated liquid at (7) with 143°C temperature. The 57/43 concentration solution takes this heat and again some mass of water boils of at 120°C temp & 0.9 bar pressure. Then same process is

repeated in LTG and finally at (8) and (14) Saturated liquid and at (19) saturated vapor is produced. The remaining solution in LTG is Send back to absorber after passing through (HXIII). (8) and (14) are expanded to condenser pressure of 0.1 bar and then passes through condenser where it releases its heat to cooling water at 30-35˚C and condenses into saturated liquid. Then it is throttled in EV I to evaporator pressure of 0.01 bar and finally entered into evaporator where sudden decrease in pressure cause evaporation of liquid water and in order to do that it needs latent heat of vaporization and this heat it extract from the chilled water flowing through it at temperature of 12˚C and hence the temperature of chilled water further decreases to 7˚C. The vaporized water is sucked by the absorber which in same assembly as evaporator. The vapor is absorbed by LiBr creating a vacuum inside the evaporator and new cycle is ready is being.

3.3 Mathematical Modeling of VAM
Energy and Exergy balance equations for each component are formulated as;

Heat exchanger III:-

$$\dot{m}_2 h_2 + \dot{m}_{21} h_{21} = \dot{m}_3 h_3 + \dot{m}_{22} h_{22}$$

$$\dot{E}_{destroyed} = \left(\dot{m}_2 \psi_2 + \dot{m}_{21} \psi_{21} \right) - \left(\dot{m}_3 \psi_3 + \dot{m}_{22} \psi_{22} \right)$$

Heat exchanger II:-

$$\dot{m}_3 h_3 + \dot{m}_{16} h_{16} = \dot{m}_4 h_4 + \dot{m}_{17} h_{17}$$

$$\dot{E}_{destroyed}$$

$$\left(\dot{m}_3 \psi_3 + \dot{m}_{16} \psi_{16} \right) - \left(\dot{m}_4 \psi_4 + \dot{m}_{17} \psi_{17} \right)$$

Heat exchanger I:-

$$\dot{m}_4 h_4 + \dot{m}_{10} h_{10} = \dot{m}_5 h_5 + \dot{m}_{11} x_{11}$$

$$\dot{E}_{destroyed} = \left(\dot{m}_4 \psi_4 + \dot{m}_{10} \psi_{10} \right) - \left(\dot{m}_5 \psi_5 + \dot{m}_{11} \psi_{11} \right)$$

High temp Generator:-

$$\dot{Q}_g + \dot{m}_5 h_5 = \dot{m}_6 h_6 + \dot{m}_{10} h_{10}$$

$$\dot{Q}_g = m_{4a} C_p \left(T_{4a} - T_{4b} \right)$$

$$\dot{E}_{destroyed} =$$

$$\left(1 - \frac{T_o}{T_g} \right) \dot{Q}_g + \dot{m}_5 \psi_5 - \dot{m}_6 \psi_6 - \dot{m}_{10} \psi_{10}$$

T_g = Generator temp

Medium temp Generator:-

$$\dot{m}_6 h_6 + \dot{m}_{12} h_{12} = \dot{m}_{13} h_{13} + \dot{m}_7 h_7 + \dot{m}_{16} h_{16}$$

$$\dot{E}_{destroyed} =$$

$$\left(\dot{m}_6 \psi_6 + \dot{m}_{12} \psi_{12} \right) - \left(\dot{m}_{13} \psi_{13} + \dot{m}_7 \psi_7 + \dot{m}_{16} \psi_{16} \right)$$

Low Temp Generator:-

$$\dot{m}_{13} h_{13} + \dot{m}_7 h_7 + \dot{m}_{18} h_{18} = $$
$$\dot{m}_{14} h_{14} + \dot{m}_{19} h_{19} + \dot{m}_{21} h_{21} + \dot{m}_8 h_8$$

$$\dot{E}_{destroyed} =$$

$$\left(\dot{m}_{13} \psi_{13} + \dot{m}_7 \psi_7 + \dot{m}_{18} \psi_{18} \right) - \left(\dot{m}_8 \psi_8 + \dot{m}_{14} \psi_{14} + \dot{m}_{19} \psi_{19} + \dot{m}_{21} \psi_{21} \right)$$

Condenser:-

$$\dot{m}_9 h_9 + \dot{m}_{15} h_{15} + \dot{m}_{19} h_{19} = \dot{m}_{20} h_{20} + \dot{Q}_{cond}$$

$$\dot{Q}_{cond} = m_{1a} C_p \left(T_{1b} - T_{1a} \right)$$

$$\dot{E}_{destroyed} =$$

$$\left(\dot{m}_9 \psi_9 + \dot{m}_{15} \psi_{15} + \dot{m}_{19} \psi_{19} \right) - \left(1 - \frac{T_o}{T_{cond}} \right) \dot{Q}_{cond} - \left(\dot{m}_{20} \psi_{20} \right)$$

Evaporator:-

$$\dot{Q}_{ev} + \dot{m}_{24} h_{24} = \dot{m}_{25} h_{25}$$

$$\dot{Q}_{ev} = \dot{m}_{2a} C_p \left(T_{2a} - T_{2b} \right)$$

$$\dot{E}_{destroyed} = \left(1 - \frac{T_o}{T_{ev}} \right) \dot{Q}_{ev} + \dot{m}_{24} \psi_{24} - \dot{m}_{25} \psi_{25}$$

Absorber:-

$$\dot{m}_{23} h_{23} + \dot{m}_{25} h_{25} = \dot{Q}_{ab} + \dot{m}_1 h_1$$

$$\dot{Q}_{ab} = m_{3a} C_p \left(T_{3b} - T_{3a} \right)$$

$$\dot{E}_{destroyed} =$$

$$-\left(1 - \frac{T_o}{T_{ab}} \right) \dot{Q}_{ab} + \left(\dot{m}_{23} \psi_{23} + \dot{m}_{25} \psi_{25} \right) - \dot{m}_1 \psi_1$$

Pump:-

$$\dot{m}_1 h_1 + \dot{W}p = \dot{m}_2 h_2$$

$$\dot{E}_{destroyed} = \left(\dot{m}_1 \psi_1 - \dot{m}_2 \psi_2 \right) + \dot{W}_p$$

Expansion Valve:-

$$\dot{m}_{20} h_{20} = \dot{m}_{24} h_{24}$$

$$\dot{E}_{destroyed} = \left(\dot{m}_{20} \psi_{20} - \dot{m}_{24} \psi_{24} \right)$$

Notations used are:-
$\dot{m}$ = mass flow rate in kg/sec
ψ = flow exergy in kJ/kg
η_{exergy} = exergetic efficiency
$\eta_{thermal}$ = thermal efficiency
$\dot{w}$ = rate of work done
h = specific enthalpy in kJ/kg
s = specific entropy in kJ/kg-k
Q_{eva} = heat energy transferred by evaporator
Q_g = heat energy supplied by HTG
χ = concentration of LiBr in solution by weight

T_{eva} = temperature of evaporator
Tg = temperature of HTG
T_o = ambient temperature
h_o = enthalpy at environment condition
s_o = entropy at environment condition

IV.   RESULTS AND ANALYSIS

The result after calculations can be summarized as**,**

State	m(kg/sec)	T(°C)	concentration(%)	h (KJ/Kg)	s(KJ/Kg-K)	ψ(kJ/kg)
1	0.374	35	50	70	0.24	0.297
2	0.374	37	50	80.4	0.26	-16.27
3	0.374	50.19	50	103.06	0.348	0.633
4	0.374	101.03	50	213.81	0.665	15.332
5	0.374	154	50	300.49	0.947	16.076
6	0.0152	148	0	2752	6.829	689.43
7	0.0152	105	0	444.4	1.376	34.09
8	0.0152	96	0	402.6	1.261	27.13
9	0.0152	35	0	402.6	0.505	256.21
10	0.346	145	54.2	350	0.83	82.59
11	0.346	102	54.2	240.6	0.6	42.883
12	0.346	102	54.2	240.6	0.6	42.44
13	0.0152	102.6	0	2677.5	7.413	437.98
14	0.0152	96.71	0	404.2	1.27	26.01
15	0.0152	35	0	404.2	0.505	257.81
16	0.342	105.9	56.1	250.6	0.65	26.77
17	0.342	65	56.1	140.5	0.41	-11.55
18	0.342	65	56.1	140.5	0.41	-11.55
19	0.0152	68.6	0	2584.78	7.77	237.09
20	0.043	35	0	191.8	0.649	1.77
21	0.332	65.8	57.9	170.6	0.36	22.02
22	0.332	40	57.9	110.7	0.2153	6.058
23	0.332	40	57.9	110.7	0.2153	6.058
24	0.043	4.5	0	191.8	0.068	174.35
25	0.043	4.5	0	2514.4	9.053	-222.03

Component	Energy flow and COP
HTG	50 kW
Condenser	43.30kW
Evaporator	99.87 kW
Absorber	99.84 kW
Pump	-28.239
COP	1.276

The COP of triple effect calculated in real time working conditions comes out to be 1.27 which is quite less as compared to 1.7 predicted by Thermax which is based on design conditions.

This can be attributed by the fact that pump is actually consuming more energy, 28.239kW which is higher than expected. The reason for this can be find out only by exergy analysis. That's the reason behind for exergy analysis.

One more thing that can be observed in energy analysis is that in condenser 43.30 kW of energy is taken away by cooling water and also 99.84 kW in absorber. This much energy can be used for process heat or cooking for sustainable energy model.

And the result of exergy analysis is;
Exergy destruction by each component of triple effect chiller

component	Exergy destructed(kW)	% destruction by individual component
HTG	6.82	8.05
MTG	8.83	10.43
LTG	8.49	10.00
condenser	5.15	6.10
Evaporator	5.75	6.79
Absorber	6.62	7.80
HX I	13.89	16.40
HX II	7.28	8.60
HX III	1.01	1.20
Pump	6.20	7.30
Expansion valve I	0.19	0.22
Expansion valve II	0.41	0.48
Expansion valve III	0.39	0.46
PR valve I	0.15	0.18
PR valve II	6.52	7.60
PR valve III	6.96	8.22

Heat exchanger I (HX I) destructed the maximum exergy 13.89 kW. Since the plant is running continuously for three years and the temperature is high in HX I, there may be problem of corrosion due the presence of LiBr. This results in reduced heat transfer and hence greater loss in exergy. The same reason applies for HX II where destruction is 7.28 kW of exergy. The next component where the exergy loss is high is set of three generators. HTG has minimum of exergy destruction which is actually not in line with the published literature where the maximum destruction is in HTG. In MTG the destruction is more than HTG because of the high percentage of LiBr in the solution. Also the heat transfer between aqueous LiBr solution which is at 0.9 bar pressure and the superheated steam passing through the solution at 4 bar pressure is affected due to their different temperature profile at different pressure. The next result which in not coming in accordance with the previous studies on this system is that most of the published results shows that the exergy destruction in pressure relieve valves is very small and can be neglected but in my study the exergy destruction in PR II and PR III is 6.92 kW and 6.52 kW, which is quite high. Pump is also showing high exergy destruction and this is the reason of getting lower COP than expected.

Exergetic efficiency of the triple effect system is calculated based on above data and using the equation developed in modeling section and it comes out to be 9.2 %.

$\eta_{exergy} = \eta_{II} = 9.2\%$
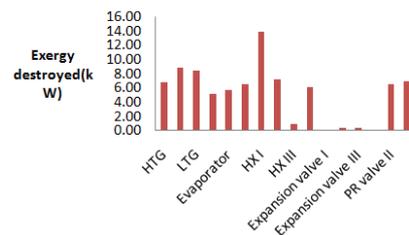
Figure4. Exergy destroyed by individual components

Figure 4 shows the exergy destroyed by each component in kW. It can be observed more clearly the respective loss in system. Figure 5 is showing same thing but in term of percentage.
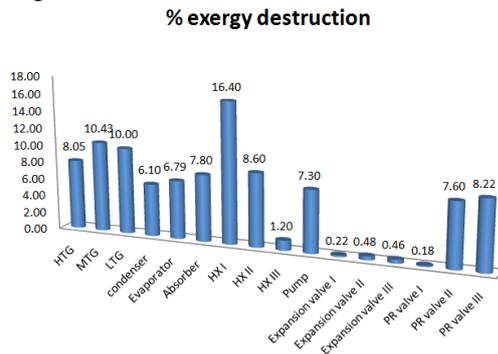
Figure5. Percentage exergy destruction by individual components

V. CONCLUSION

Exergy destruction by every component is calculated using the given data and exergy balance equations. Heat exchanger I (HX I) is showing the maximum amount of exergy destruction. Expansion valves EV I, EV II, EV III and pressure relieving valve PR I is destroying very less exergy and hence can be neglected. Finally the Exergetic efficiency of system comes out to be 9.2%, which shows the ample opportunity for improvement. The focus of proper designing and improvement should be on all three heat exchangers and generators.

ACKNOWLEDGEMENT

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