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Energy Analysis of LiBr-Water Single Effect Absorption Refrigeration System : Effect of Operating Conditions on System Performance

Sandeep S. Chevli[1], **Dimple Gandhi**[2], **Milli Hota**[3]
[1]Assistant Professor in Government Engineering College, Bhuj, Gujarat, India
[2]Assistant Professor in Government Engineering College, Valsad, Gujarat, India
[3]Assistant Professor in Government Engineering College, Surat, Gujarat, India

ABSTRACT

Energy based thermodynamic analysis and parametric study of the LiBr-Water single effect vapour absorption refrigeration system for 1 TR capacity is performed for 10oC evaporator, 35oC condenser and 40oC absorber temperature. The effect of operating temperatures on heat loads of all heat exchanger and Circulation Ratio (CR) of system are investigated. Operating temperatures effect on system Co-efficient of Performance (COP), Carnot COP and efficiency ratio has also been analysed. It is observed that the thermal load of generator and absorber is strongly influenced by CR of the system. It is concluded that thermal load of generator and absorber decreases with increase of temperature of generator and evaporator, whereas they increases with increase of absorber and condenser temperatures. System COP increases with rise in generator temperature up to optimum value. Maximum COP of the system is 0.7825 is obtained with optimum generator temperature of 85.3oC. Increase in system COP is observed with enhance of solution heat exchanger effectiveness. Further, Sensitivity analysis has been conducted to study the effect of generator temperature on COP for different values of operating temperatures of evaporator condenser and absorber.

Keywords : Refrigeration, Absorption, Lithium Bromide-Water, Single Effect

I. INTRODUCTION

Absorption systems has ability run with low grade heat such as that obtained from solar, geothermal, etc., helps in reducing electric demand in peak hours specially in summer season. Most widely used working fluid pair for absorption refrigeration system is ammonia-water when the required evaporating temperature is 0°C to -40°C. In this pair ammonia is used as a refrigerant having freezing point is -77°C, whereas water is used as an absorbent [1].This system requires the rectifier and analyser in order to remove the water traces coming with ammonia flow in condenser and evaporator [2]. This is because of higher volatility of water and lower side boiling point difference of 180°C for ammonia-water pair. This pair exhibit relatively low COP. Comparative study has been done for the performance of ammonia-water with NH_3-$LiNO_3$ and NH_3-NaSCN in order to search for better pair [3].Ammonia-water absorption system can also be coupled with turbogenerator or engine in order to better exploit of primary energy sources and integrated production of utilities [4].

Especially in air-conditioning when required evaporating temperature is more than 0°C, LiBr-water working fluid pair found to be most suitable. Comparative study done for ammonia-water and LiBr-water working pair for same evaporative temperature and it is found that performance of system quite better if system using LiBr-water pair[5].Mostafavi and Agnew has investigated the

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effect of ambient temperature on the performance of LiBr-water absorption unit[6,7]. Crystallization of the LiBr-water solution becomes the main challenge for air-cooled system as absorber operates at a higher temperature and concentration level. Liao and Radermacher focuses on crystallization issues and control strategies in LiBr-H_2O air-cooled system [8].Thermodynamic analysis and comparison of water based refrigerant as a working fluid has been carried out by computer simulation. Variations of performance parameters of these aqueous solutions are compared with operating temperatures [9].Romero et al, have done the comparative performance study of LiBr-water absorption system with aqueous ternary hydroxide mixture for cooling and heating application [10,11]. Literature review on various types of LiBr-water absorption system has been done by Srikhirin et al [12]. Kaynakli and Kilic also presented theoretical study of system performance with various operating conditions [13].

Furthermore, parametric study of variation of COP and second law efficiency for single effect LiBr-water system has been presented by many researchers [14,15].Similar performance based comparative study has been carried out for single and double effect LiBr-water absorption system[16,17].

In this study, energy based parametric analysis of single effect LiBr-water absorption refrigeration system of 1 TR capacity is performed. Thermal load of heat exchangers, Circulation ratio (CR), Coefficient of performance (COP), Carnot COP and efficiency ratio has been compared with various heat exchanger temperatures. Effect of effectiveness of solution heat exchanger on performance of system is analysed. Apart from other studies, sensitivity analysis of system has been conducted out to study the effect of generator temperature on COP for different values of operating temperatures of condenser, evaporator and absorber.

II. Energy analysis of LiBr-water absorption system

A single stage LiBr-water absorption refrigeration system is shown schematically in **Fig 1**. The system consists of four major heat exchanger like generator, absorber, condenser, evaporator along with solution heat exchanger (SHE), pump and expansion valves. SHE preheats the weak solution pump out from absorber by exchanging heat from strong solution coming from generator. Thus for a given refrigerating effect thermal load of generator decreases. The thermodynamic analysis involves the application of principles of mass conservation (including species conservation) and first law of thermodynamics to individual components of the system. Each component of system can be assumed as control volume having inlet and outlet flow, heat transfer and work interaction.

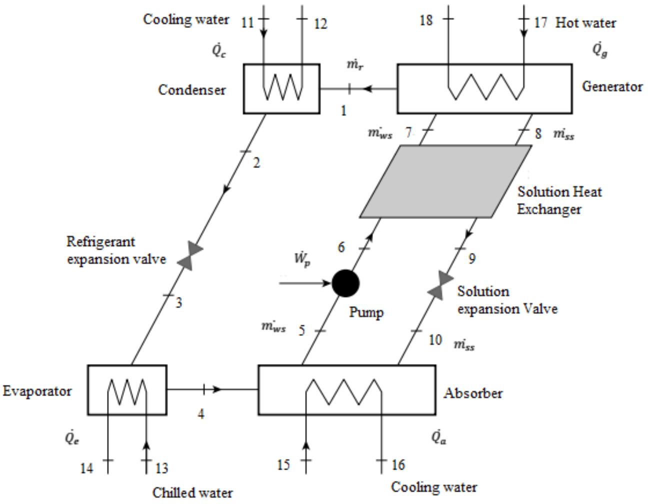

Fig 1: Schematic of LiBr-water single effect absorption system

Mass balance for the individual component can be considered as control volume,

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

and for mass of LiBr solution,

$$\sum(\dot{m}X)_{in} = \sum(\dot{m}X)_{out} \tag{2}$$

Energy balance for the individual component can be considered as control volume,

$$\sum \dot{Q} - \sum \dot{W} = \sum \dot{m}_{out} h_{out} - \sum \dot{m}_{in} h_{in} \tag{3}$$

Mass balanced equation applied to the Absorber, which yields

$$\dot{m}_{ws} = \dot{m}_r + \dot{m}_{ss} \qquad (4)$$

$$X_{ss}\dot{m}_{ss} = X_{ws}\dot{m}_{ws} \qquad (5)$$

From equations (4) and (5), mass flow rates of strong and weak solution can be estimated,

$$\dot{m}_{ss} = \frac{X_{ws}}{X_{ss}-X_{ws}}\dot{m}_r \qquad (6)$$

$$\dot{m}_{ws} = \frac{X_{ss}}{X_{ss}-X_{ws}}\dot{m}_r \qquad (7)$$

The Circulation Ratio (CR) can be defined as the mass flow rate of the strong solution required to evaporate unit mass flow rate of refrigerant from evaporator

$$CR = \frac{\dot{m}_{ss}}{\dot{m}_r} = \frac{X_{ws}}{X_{ss}-X_{ws}} \qquad (8)$$

Above equation yields,

$$\dot{m}_{ss} = CR * \dot{m}_r \text{ and } \dot{m}_{ws} = (1 + CR)\dot{m}_r \qquad (9)$$

Thermal load of heat exchangers,

$$\dot{Q}_a = \dot{m}_r[(h_4 - h_5) + CR(h_{10} - h_5)] = \dot{m}_{cwa}(h_{16} - h_{15}) \qquad (10)$$

$$\dot{Q}_g = \dot{m}_r[(h_1 - h_7) + CR(h_8 - h_7)] = \dot{m}_{hw}(h_{17} - h_{18}) \qquad (11)$$

$$\dot{Q}_c = \dot{m}_r(h_1 - h_2) = \dot{m}_{cwc}(h_{12} - h_{11}) \qquad (12)$$

$$\dot{Q}_e = \dot{m}_r(h_4 - h_3) = \dot{m}_{ch}(h_{13} - h_{14}) \qquad (13)$$

Solution pump work required;

$$\dot{W}_p = \dot{m}_{ws}\frac{(P_k - P_o)}{\rho_{ws} * \eta} \qquad (14)$$

Heat transfer across the SHE,

$$\dot{Q}_{she} = \dot{m}_{ss}(h_8 - h_9) = \dot{m}_{ws}(h_7 - h_6) \qquad (15)$$

The COP of the absorption system,

$$COP = \frac{\dot{Q}_e}{\dot{Q}_g + \dot{W}_p} \qquad (16)$$

COP_{carnot} and efficiency ratio (η),

$$COP_{carnot} = \frac{(T_g - T_a)}{T_a}\frac{T_e}{(T_c - T_e)} \qquad (17)$$

$$\eta = \frac{COP}{COP_{carnot}} \qquad (18)$$

III. Thermodynamic simulation model

Computer program coding is developed in Engineering Equation Solver (EES) to investigate the energy analysis of the system. The computer program is developed based on heat transfer equations and the state point equations for the thermodynamic properties of lithium bromide-water. Subroutines for calculating the properties of lithium bromide-water solution (taken from Pa´tek and Klomfar 2006) are linked to the library file of the EES. The initial conditions read into the program include the temperature of heat exchangers, S.H.E effectiveness, pump efficiency, cooling and chilled water inlet-outlet temperature. By feeding appropriate parameter, the program calculates at all state points of the cycle like the values of temperature, pressure, enthalpy, mass flow rate, CR, thermal load of heat exchangers and COP of the system. Developed model is simulated by assuming following conditions:

- Thermodynamically consistent temperature and pressure values are assumed in analysis.
- Saturated vapour refrigerant leaves the evaporator whereas saturated liquid coming out from condenser.
- Superheated vapour refrigerant at the temperature of generator enters the condenser.
- Outlet temperature of strong solution from generator and weak solution from absorber are at the temperature of generator and absorber respectively.
- Simulation is under steady state condition with constant capacity of 1 TR.
- Efficiency of Solution pump is assumed 95% and effectiveness of SHE is 75%
- Cooling water inlet temperature to condenser and absorber is T_c-7 whereas outlet cooling water temperature is T_c-3 and T_c-2 respectively.
- Hot water supplied to generator is pressurised and inlet-outlet temperature of hot water is T_g+20 and T_g+10 respectively.
- Chilled water supplied to evaporator is T_e+10 whereas outlet temperature is T_e+5

IV. Result and Discussion

4.1 Effect of operating temperature on thermal load

Change in thermal load of major heat exchanger of absorption system with generator temperature is shown in **Fig 2**. It is found that absorber and generator thermal loads (Q_a and Q_g) decrease when generator temperature increases. As the generator temperature increases, the concentration of the solution leaving the generator increases, and hence, the Circulation ratio (CR) decreases. Moreover, the weak solution temperature is increased by the strong solution in SHE. The generator thermal load is decreased both by decreasing the CR and increasing temperature of weak solution. Condenser thermal load (Q_C) continuously rises from 3.683 KW to 3.767 KW because of increase of temperature of superheated water vapor leaving the generator. The evaporator thermal load remains unchanged with generator temperature and remains as a constant value of 3.517 KW. Absorber load decreases because of decreasing mass flow rate of strong solution, which is directly proportional to CR.

The effect of evaporator temperature on the thermal load on components of the system is shown in **Fig 3**. The concentration of the weak solution decreases if the evaporator temperature rises. This is because of more absorption of water vapour and hence CR decrease. They cause a decrease in the absorber and generator thermal load. A small decrease in condenser load is noticed with almost constant evaporator load

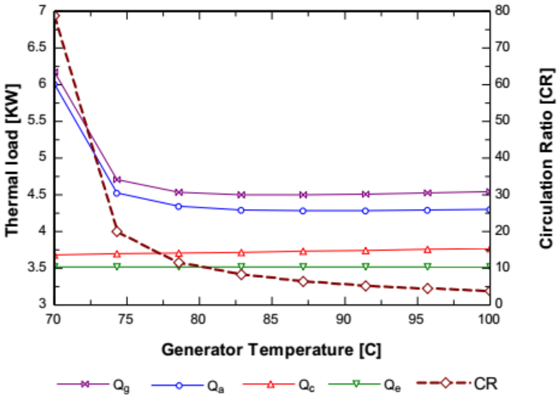

Fig 2: Change in thermal load with Generator temperature ($T_e=10^{\circ}C, T_c=35^{\circ}C, T_a=40^{\circ}C$)

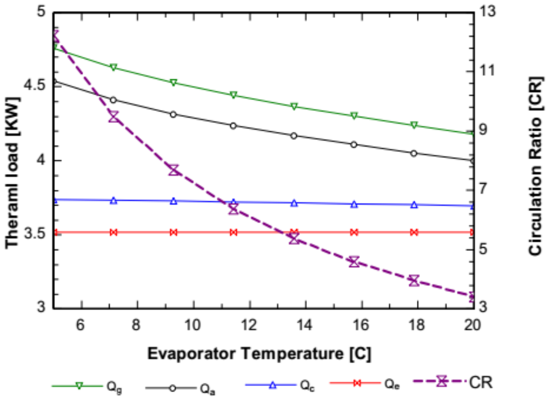

Fig 3: Change in Thermal load with Evaporator temperature ($T_g=85^{\circ}C, T_c=35^{\circ}C, T_a=40^{\circ}C$)

Change in thermal load with condenser temperature is shown in **Fig 4**.The concentration of the strong solution found to decreases when the condenser temperature increases because system pressure increases. With decreasing strong solution concentration, the CR increases, that leads to increase of thermal loads of both the absorber and generator.

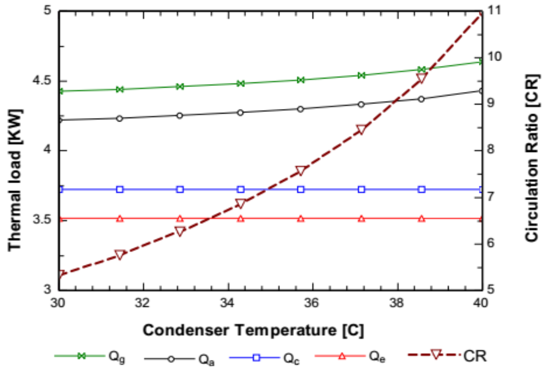

Fig 4: Change in Thermal load with Condenser temperature ($T_e=10^{\circ}C, T_g=85^{\circ}C, T_a=40^{\circ}C$)

The effect of absorber temperature on thermal load is shown in **Fig 5**.The concentration of the weak solution increases by increasing the absorber temperature. This is because of decrease of water vapor absorption capacity of weak solution and concentration of weak solution approaches the concentration of the strong solution. Thus the CR increases, that leads to increases thermal load of the absorber generator and. However, the thermal loads of the condenser and evaporator (3.725 KW and 3.517 KW, respectively) are seen almost constant thorough out the increase of the absorber temperature.

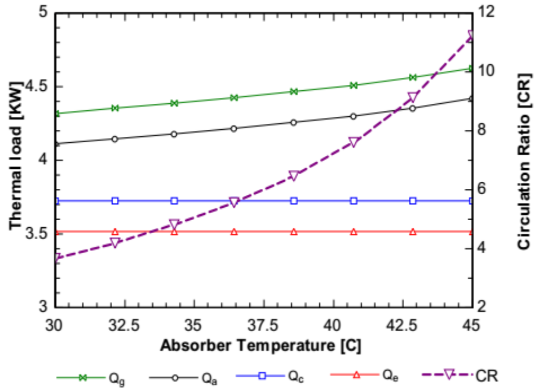

Fig 5: Change in Thermal load with Absorber temperature (T_e=10°C,T_g=85°C,T_c=35°C)

4.2 Effect of operating temperature on COP of system

Fig 6 shows the COP of system increases up to optimum value of generator temperature, 85.3°C. At optimum generator temperature, COP of system 0.7825 and then start decreasing with negligible variation. The initial rise in COP with increase in generator temperature is observed due to decrease in solution Circulation ratio (CR), which leads to decrease in thermal load of generator and absorber. But at higher generator temperatures (i.e, after optimum generator temperature) the rate of reduction in CR drops but the temperature difference between the generator and weak solution entering the generator increases, causing a slight increase in the thermal load of generator. Thus positive effect of decrease in CR is balanced by a negative effect of increase in difference of temperature of generator and weak solution entering generator. Therefore, marginal increase of generator thermal load leads to flattens or even decrease in COP at higher generator temperature. COP$_{carnot}$ increases continuously with generator temperature. Since the increase in COP$_{carnot}$ is faster than that in COP, the Efficiency ratio (η %) value gradually decreases after 74°C generator temperature.

It is shown in **Fig 7**, the higher value of COP$_{carnot}$ and COP values are obtained at high evaporator temperatures because of reduction in thermal load of generator. The performance of the Carnot cycle gets better with increasing evaporator temperatures. Since the increase in COP$_{carnot}$ is faster than that in COP, the η % value gradually decreases.

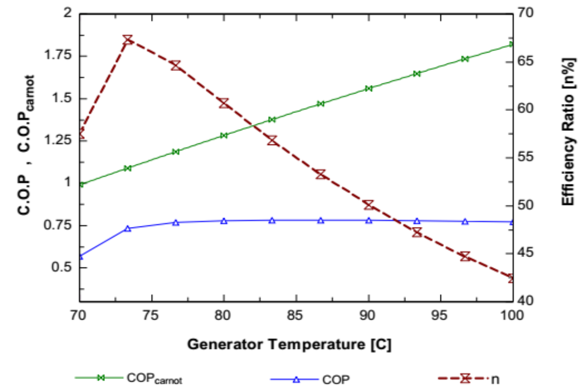

Fig 6: Change in C.O.P. ,C.O.P$_{carnot}$ and Efficiency Ratio with Generator Temperature (T_e=10°C,T_c=35°C,T_a=40°C)

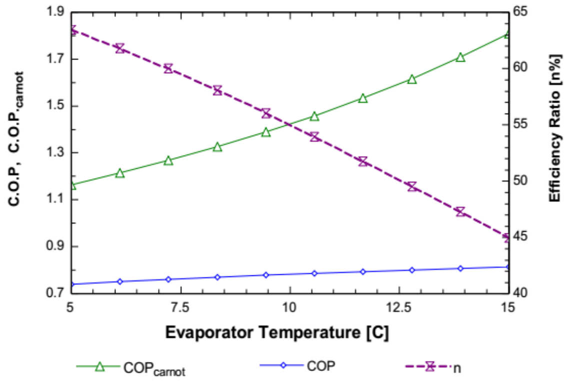

Fig 7: Change in C.O.P. ,C.O.P$_{carnot}$ and Efficiency Ratio with Evaporator Temperature (T_g=85°C,T_c=35°C,T_a=40°C)

It is seen from **Fig 8 and 9** that the COP$_{carnot}$ and COP values decrease with increasing condenser and absorber temperatures. When the temperatures of the condenser and absorber increase, refrigerating capacity decreases for given thermal load in generator. While the Efficiency ratio (η) value increases due to rapid decrease of COP$_{carnot}$ compared to COP of system.

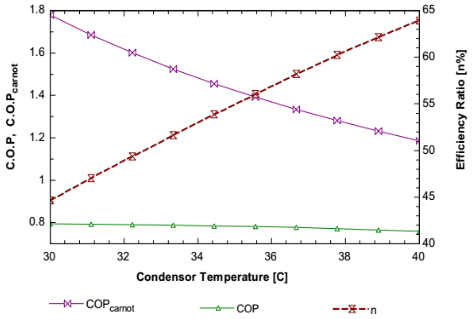

Fig 8: Change in C.O.P. ,C.O.P$_{carnot}$ and Efficiency Ratio with Condenser Temperature (T_e=10°C,T_g=85°C,T_a=40°C)

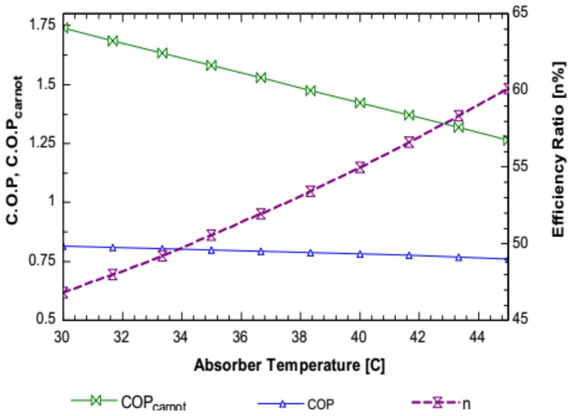

Fig 9: Change in C.O.P. ,C.O.P$_{carnot}$ and Efficiency Ratio with Absorber Temperature (T_e=10°C,T_g=85°C,T_c=35°C)

4.3 Effect of effectiveness of Solution Heat Exchanger on thermal load and COP of the system

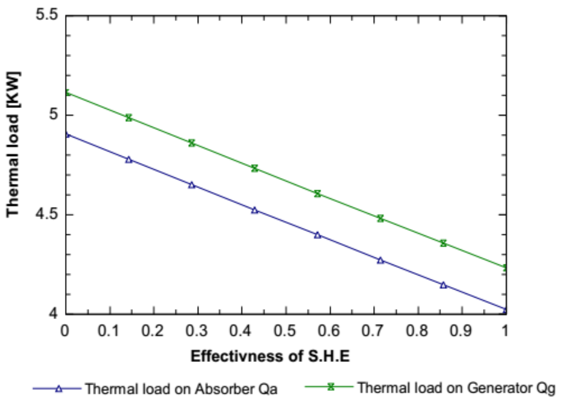

Fig 10: Effect of Effectiveness of S.H.E. on Thermal load (T_e=10°C,T_g=85°C,T_c=35°C,T_a=40°C)

Fig 10 shows the effect of effectiveness of S.H.E on the thermal load. If the effectiveness of Solution Heat Exchanger (S.H.E) increases, the heat exchange between the weak and strong solutions increases, and as a result of this, the temperature of the strong solution T[9] entering the absorber decreases and that of the weak solution T[7] entering the generator increases. With an increase in the weak solution temperature T[7] , the thermal load of the generator decreases. Similarly, with a decrease in the strong solution temperature T[9] entering the absorber, the heat rejected from the absorber to cooling water also decreases.

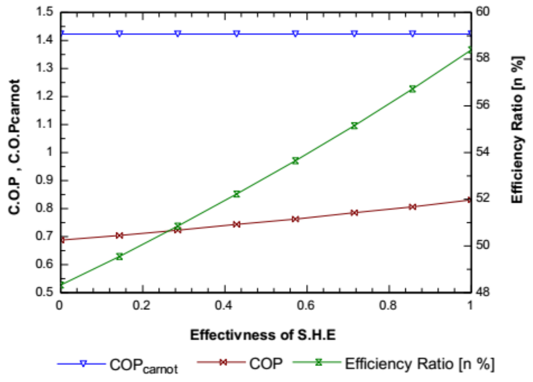

Fig 11: Effect of Effectiveness of S.H.E. on COP, COP$_{carnot}$ and Efficiency ratio [η %] (T_e=10°C,T_g=85°C,T_a=40°C)

Fig 11 shows the effects of effectiveness of S.H.E on the system performance. If the effectiveness of the S.H.E is zero (ε_{SHE} = 0), the COP system is 0.6875. The performance of the system gets better with an increase in the effectiveness. For ideal condition in which effectiveness of S.H.E equal 1, then strong solution outlet temperature T[9] equals to the weak solution outlet temperature T[7] , the COP value found to be 0.8309.There is rise in COP is about 20.86%. The COP$_{carnot}$ value does not change with the effectiveness and remains at 1.423. The COP$_{carnot}$ remains unchanged whereas the COP increases. As a result of this, the Efficiency ratio (η %) value increases with rise in effectiveness of solution heat exchanger (S.H.E)

V. SENSITIVITY ANALYSIS

Sensitivity of COP to generator temperature for different operating temperatures has been carried out. It is observed from **Fig 12** that decreasing condenser temperatures from 40°C to 30°C (in steps of 5°C) causes the raise in maximum value of COP. It has also to be noticed that the optimum generator temperature corresponding to maximum values shift on lower side when condenser temperature decreases. This is because of reduction in heat duty of the generator and irreversibility associated with absorber, generator and condenser due to reduction in their average temperatures. From **Fig 13** , decreasing evaporator temperatures 15°C to 5°C (in steps of 5°C) causes reduction in maximum value of COP with higher value of optimum generator temperature. Decrease of absorber temperature from 45°C to 35°C (in steps of 5°C) causes increase in COP with lower value of optimum generator temperature value which is obtained in **Fig 14**.

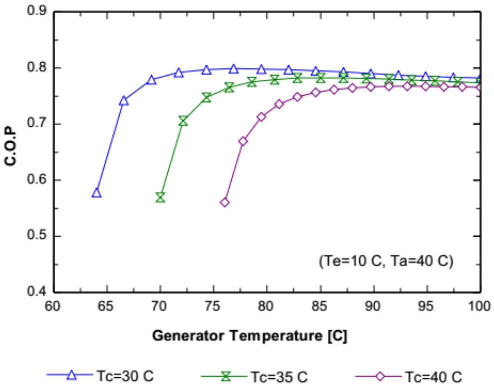

Fig 12: Sensitivity of C.O.P to generator temperature for different condenser temperature

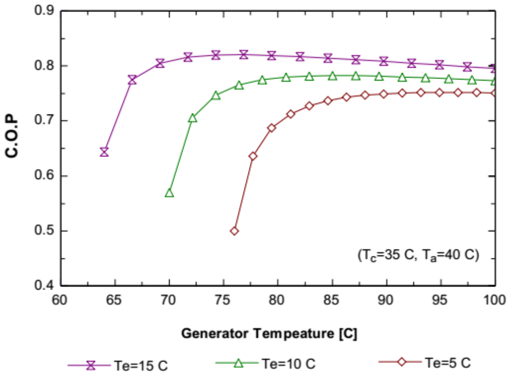

Fig 13: Sensitivity of C.O.P to generator temperature for different evaporator temperature

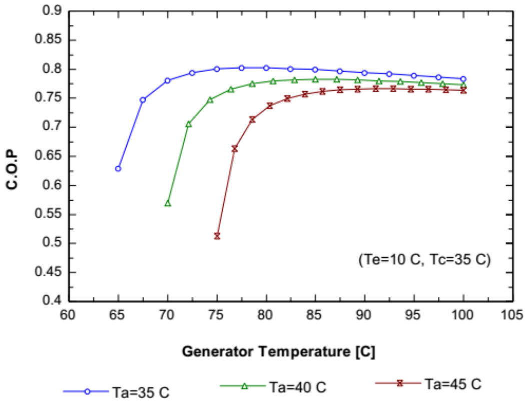

Fig 14: Sensitivity of C.O.P to generator temperature for different absorber temperature

VI. CONCLUSION

In this study, energy analysis of single effect absorption system of lower capacity of 1 TR has been conducted Change in thermal load of different heat exchangers, Circulation ratio (CR),COP and efficient ratio has been studied for different operating temperatures of the system. Study also includes sensitivity analysis in order to understand the effect of generator temperature on COP for different values of operating temperatures of condenser, evaporator and absorber. The following results can be drawn:

- Thermal load of generator and absorber is greatly affected with circulation ratio (CR) of the system. Thermal load of both varies directly proportional to CR.
- Thermal load of generator, absorber decreases with increase of generator and evaporator temperature. Condenser thermal load varies negligibly while evaporator thermal load remains almost constant with increasing of generator and evaporator temperature.
- Generator and absorber thermal load of the system increases with rise of condenser and absorber temperature. Very small decrease of condenser and evaporator thermal load with increase of condenser temperature, whereas both load remains unaffected with increase of absorber temperature.
- COP of the system increases up to maximum value with increase of generator temperature and then it level off or even decreases with further rise of generator temperature. Maximum attainable value of the COP is 0.7825 (Te=10°C, Tc=35°C, Ta=40°C) with generator temperature of 85.3°C. COP of the system continuously increases with rise of evaporator temperature.
- COP of the system decrease with increase of condenser and absorber temperature.
- Increase of effectiveness of SHE decreases of thermal load of generator and absorber. Hence COP of the system increases with increase of effectiveness of SHE.

- Decrease of condenser and absorber temperatures increases maximum value of COP with lower value of generator temperature.

T_e (°C)	**T_c (°C)**	**T_a (°C)**	**Maximum COP**	**Optimum temp in °C at which maximum COP occurs**
10	30	40	0.7987	77.51
10	35	40	0.7825	85.33
10	40	40	0.7674	93.09
5	35	40	0.7516	95.42
10	35	40	0.7825	85.33
15	35	40	0.8204	76.13
10	35	35	0.8023	78.73
10	35	40	0.7825	85.33
10	35	45	0.7664	92.07

- Increase of evaporator temperature increases maximum value of COP with lower generator temperature.

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