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Thermodynamic Analysis of a Vapor Absorption System Using Modified Gouy-Stodola Equation

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Abstract**—**In this paper, the exergy analysis of vapor absorption refrigeration system using LiBr-H_2O as working fluid is carried out with the modified Gouy-Stodola approach rather than the classical Gouy-Stodola equation and effect of varying input parameters is also studied on the performance of the system. As the modified approach uses the concept of effective temperature, the mathematical expressions for effective temperature have been formulated and calculated for each component of the system. Various constraints and equations are used to develop program in EES to solve these equations. The main aim of this analysis is to determine the performance of the system and the components having major irreversible loss. Results show that exergy destruction rate is considerable in absorber and generator followed by evaporator and condenser. There is an increase in exergy destruction in generator, absorber and condenser and decrease in the evaporator by the modified approach as compared to the conventional approach. The value of exergy determined by the modified Gouy-Stodola equation deviates maximum i.e. 26% in the generator as compared to the exergy calculated by the classical Gouy-Stodola method.

Keywords**—**Exergy analysis, Gouy-Stodola, refrigeration, vapor absorption.

I. INTRODUCTION

RESEARCH and developments in refrigeration systems indicate growing interest in the vapor absorption cycles. The conventional refrigeration and air conditioning systems are being questioned not only because they consume high quality energy through the compressor but they also contribute to the ozone layer depletion and the greenhouse effect. Absorption systems can be driven by low grade thermal energy providing a means for converting waste heat into useful purposes, as well as help in reducing peak summer electric demands. It is quite similar to the vapor compression system with the only difference in the way of increasing the pressure of working substance. The process of evaporation and condensation of the refrigerant takes place at two different pressure levels to achieve refrigeration in both the cases but the method employed to create the two pressure levels in the system is different. In the absorption system the compressor of the vapor compression system is replaced by the combination of pump, absorber and generator. To conserve the energy, there is a need to optimize thermodynamic processes for minimum consumption of energy.

Many researchers had performed a number of analyses on vapor absorption refrigeration system. Extensive review of the literature reveals that LiBr-H_2O working fluid better suit for the cooling systems operating on more than 4ºC. Reference [1] studied the performance of solar assisted absorption refrigeration system. The study was carried out on the unit when there was enough solar energy i.e. around 4-5 h per day. The generator and evaporator temperature was varied during the test periods, and the performance of the unit was predicted as a function of temperature and available solar intensity. Some researchers have studied individual components mainly absorber and generators of the VARS rather than the complete system. Reference [2] carried out study on the absorber component of the system and the parameters that have significant effect on the overall efficiency of system. The effect of cooling water inlet temperature on absorber's performance was significant. It was observed as the inlet temperature of cooling water decreases from 32ºC to 30ºC, the heat flux of absorber increases by 17% and they also identified that using the strong solution as absorbent is advantageous to enhance the heat transfer and decrease the solution pump power. Reference [3] performed a detailed thermodynamic analysis of the water/lithium bromide absorption refrigeration and studied the influence of operating temperature and effectiveness of heat exchanger on the thermal loads of components. The thermal loads on the absorber and generator was decreased, as the generator and evaporator temperature was increased but the thermal load on the generator and absorber was increased as the condenser and an absorber temperature was increased. The reduction in the generator thermal load increased the COP of the system. The COP of the system decreased with the increase in generator thermal load especially when temperatures of the condenser and absorber were above 45ºC. The increase of the SHE effectiveness decreased the generator and absorber thermal loads hence the COP was increased from 0.57 to 0.82 with use of the SHE. In this case, the maximum increase in the COP was 44%. The studies are also carried out on the double effect absorption system as the COP of the double effect absorption system is high as compared to the single effect systems. Reference [4] applied the thermo-economic concept for the optimization of a double-effect H_2O/LiBr VARS. They aimed at minimizing its overall product cost. A simplified cost minimization methodology based on the thermo-economic concept is applied to calculate the economic costs of all the internal flows and products of the system by formulating thermo-economic cost balances. Once these costs are determined, the system is thermo-economically evaluated to identify the

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effects of the design variables on cost of the flows and products. This helps to suggest changes in the design variables that would make the overall system cost-effective. Reference [5] studied the energy and exergy analysis of single effect and series flow double effect water–lithium bromide absorption systems using computational model and used efficient property equations of water–lithium bromide solution. The analysis involved the determination of the effect of generator, absorber and evaporator temperatures on the energetic and exergetic performance of the system. Results indicated that COP of the single effect system lies in range of 0.6–0.75 and the corresponding value of COP for the series flow double effect system lies in the range of 1–1.28. The effect of parameters such as temperature difference between heat source & generator and evaporator & cold room were also investigated. The COP of the double effect system is nearly 60–70% greater than that of the single effect system. The exergetic efficiency was found to increase with the increase in generator temperature for a particular range but further increase in the generator temperature decreased the exergetic efficiency.

Exergy analysis is also done by a number of researchers. Reference [6] used the approach of splitting the exergy destruction into unavoidable/avoidable parts and presented new development in the exergy analysis of energy conversion systems. This splitting improves the accuracy of exergy analysis, improves the understanding of the thermodynamic inefficiencies and facilitates the improvement of system. The advanced exergetic evaluation of absorption refrigeration system (ARS) supplies useful additional information that is not provided by exergy analysis without splitting the exergy destruction within the components of ARS. The avoidable exergy destruction identifies the potential for improving each system component. All these considerations become more powerful when they are used for the exergy-economic evaluation of the same system. In such a calculation, not only the exergy destruction, but also the investment cost for each system components is split into avoidable/unavoidable. As most of the studies were on the use of LiBr-H_2O because of its non toxic nature but we cannot achieve temperature below 0ºC so researchers also focused on the ammonia water solution to attain low temperature. Reference [7] carried out experimental investigation of the performance of commercially available vapor absorption refrigeration system using aqua-ammonia solution for the rated cooling capacity of 10 kW. The system initially had air-cooled condenser and absorber units but water-cooled absorber and condenser units were fitted to extend the VAR unit's range of operating conditions by varying the cooling water inlet temperature and flow rates to these units. Reference [8] experimented on a small air-cooled double-effect LiBr-H_2O absorption prototype, which has been designed to supply 7 kW. A new flat-sheet adiabatic absorber was used allowing it to operate at outdoor temperatures about 45ºC without any sign of crystallization. Since this absorption machine does not need cooling tower, there is neither water consumption nor pollution and also quite compacted unit.

The exergy analysis performed by the above researchers was based on simple Gouy-Stodola equation/availability function concept but this study makes use of modified Gouy-Stodola equation.

Reference [9] suggested the real power production and the maximum power production to be,

$$\dot{W}_{max} - \dot{W} = T_{eff}\dot{S}_{gen} \tag{1}$$

where $\dot{S}_{gen}$ is the rate of entropy generation and T_{eff} is the effective temperature for a process and is given by

$$T_{eff} = \frac{(h_2 - h_{2r})}{(s_2 - s_{2r})} \tag{2}$$

State 2 being the real final state where as Point 2r is the ideal isentropic final state [10] T_{2r} is the theoretical outlet temperature after a reversible process and T_2 the real outlet temperature and if the specific heat capacity and pressure are constant during the process, the change in entropy and enthalpy depends on the temperature alone and (2) may be written as,

$$T_{eff} = \frac{(T_2 - T_{2r})}{\ln\left(\frac{T_2}{T_{2r}}\right)} \tag{3}$$

This concept is used for the determination of irreversibility losses in different components of absorption system for refrigeration in the present work. The use of the modified Guoy-Stodola equation becomes important in view of the ever going quest of researchers to conduct more accurate analysis and the results of the present study shows a considerable variation in the exergy analysis compared to the classical method of determining the exergy destruction.

II. MODEL DESCRIPTION

A. System Description

The absorption system used in this study is based on LiBr-H_2O working pair as shown in the Fig. 1. The low pressure water (refrigerant) converts into low pressure vapor by absorbing heat in the evaporator. This low pressure cold vapor leaving evaporator is absorbed by hot LiBr-water solution in the absorber. The process is exothermic and hence absorber is cooled by external flow of fluid. The absorbent-refrigerant mixture, rich in water but weak in LiBr solution, is pumped from the absorber to the generator via heat exchanger to liberate the refrigerant (water vapor) from solution. The vapor refrigerant coming out from the generator flows into condenser.

The refrigerant change its phase at high pressure in the condenser by the external fluid arrangement and then it pass through the expansion valve lowering its pressure and temperature. This low pressure low temperature refrigerant flows into the evaporator and the cycle continues. The pump work is neglected as the specific volume of liquid is much smaller. The solution having some water (strong solution in terms of LiBr) is sent back to absorber via heat exchanger and pressure reducing valve. There is an arrangement of external fluids to provide heat source/sink for thermal energy exchange between components of VAS and environment.

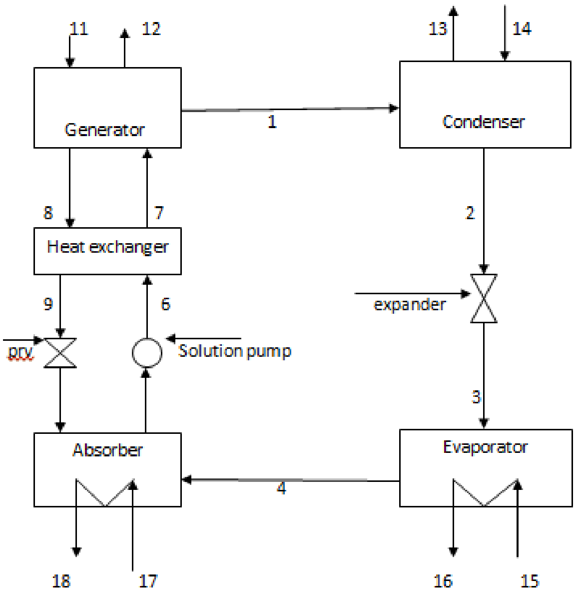

Fig. 1 Schematic Diagram of Single Effect Absorption Refrigeration System

B. Assumptions

Some assumptions are required to be taken into consideration before the analysis was performed and are quite acceptable for theoretical study. These are as follows:

1) The system is in steady state condition.
2) Isenthalpic process occurs in expander.
3) There are no pressure losses while the fluids are flowing.
4) There are negligible heat losses to the environment from the system.
5) The refrigerant is in saturated state when leaving the evaporator.
6) Effectiveness of heat exchanger is considered as constant.

C. General Equations

In this work exergy analysis has been performed by modified approach using the concept of effective temperature and the variation of exergy destruction with various input parameters is carried out at the design point of 200 kW refrigeration effect. Ambient conditions are assumed to be at temperature 25°C and 1.01325 bar.

Mass balance,

$$\sum \dot{m} = 0\,;\ \sum x\dot{m} = 0 \qquad (4)$$

Energy balance,

$$\sum \dot{Q} + \sum \dot{W} + \sum \dot{m}h = 0 \qquad (5)$$

Entropy generation,

$$\dot{s}_{gen} = \sum \dot{m}s_{out} - \sum \dot{m}s_{in} - \sum \frac{\dot{Q}}{T} \geq 0 \qquad (6)$$

Irreversibility,

$$\dot{I} = T_{eff}\dot{s}_{gen} \qquad (7)$$

III. VALIDATION OF THE MODEL

A computer program has been developed using Engineering Equation Solver (EES) for carrying out the energy and exergy analysis of the single effect absorption refrigeration system. Subroutines for calculating the properties of water–lithium bromide solution [11] are linked to the library file of the EES.

In order to validate the present model, the results of energy and exergy analysis of the present work have been compared with the available numerical data reported by [5] for the refrigeration effect of 2355 kW and its details are presented in Tables I and II.

TABLE I
VALIDATION OF RESULTS OF ENERGY ANALYSIS

Name of the component	Reference [5] (Heat rate in kW)	Present Work (Heat rate in kW)	% error
Generator	3095.7	3073.11	0.73
Absorber	2945.2	2922.39	0.77
Condenser	2505.9	2507.89	0.08
Evaporator	2355.45	2355.45	0.00
Heat exchanger	518.72	523.25	0.88

TABLE II
VALIDATION OF RESULTS OF EXERGY ANALYSIS

Name of the component	Reference [5] (Exergy destruction in kW)	Present Work (Exergy destruction in kW)	% error
Generator	55.57	56.23	1.19
Absorber	191.72	192.8	0.56
Condenser	109.76	107.8	1.78
Evaporator	86.28	84.71	1.82
Heat exchanger	25.08	25.44	1.44

Both Tables I and II clearly depict that the results obtained by the simulation are in good agreement with the existing work and the slight variation may be attributed to the difference in the properties of the working fluid pair evaluated by the software and that taken in the reference work.

IV. CONDITIONS AT DESIGN POINT

Water is used as an external fluid to receive or reject the heat from different components and the specifications of the water loop circuit in different components are given in Table III.

The various operating conditions and the thermodynamic properties at different state points as shown in Table IV are computed numerically and then the heat transfer rate, and exergy destruction is calculated.

TABLE III
WATER LOOP SPECIFICATIONS-EXTERNAL FLUID ARRANGEMENT

Name of the component	Water temperature (°C) IN	Water temperature (°C) OUT	Water flow (kg/s)
Absorber	303	307.2	15
Generator	380	374	11
Condenser	303	307	13
Evaporator	293	286.2	7

V. VARIATION OF RESULTS BETWEEN BOTH APPROACHES

The exergy destruction or irreversibility of every component is determined using both the approaches, the Gouy-Stodola and modified Gouy-Stodola equation and a comparison is drawn in graphical form to differentiate the outputs of the two methods. It is evident that the latter results are more accurate considering the real/practical conditions of system operation and provides the actual losses in terms of irreversibility. Exergy analysis using conventional and modified Gouy-Stodola equation produced the irreversibility values of all the components and of the overall system as shown in Table V. It is observed that the values of exergy destruction increases in the case of modified Gouy-Stodola application as compared to the usual case. This is due to the fact that the real heat exchange temperature at the outlet of the external fluid is considered in this approach.

TABLE IV
PROPERTIES AT VARIOUS STATE POINTS

Point	T (ºC)	P (KPa)	X_m (mass-fraction) LiBr	h (KJ/kg)	S (KJ/kg.K)
1	100	9.59	0	2676	8.466
2	45	9.59	0	188.4	.6385
3	8	1.073	0	188.4	.6719
4	8	1.073	0	2515	8.498
5	45	1.073	0.5856	119.5	.2582
6	45	9.59	0.5856	119.5	.2582
7	77.7	9.59	0.5856	183.7	.4502
8	100	9.59	0.6394	252.9	.5301
9	61.5	9.59	0.6394	182.9	.3318
10	61.5	1.073	0.6394	182.9	.3318

The increase in total exergy destruction by the modified analysis is 7.3%. Results show that exergy destruction rate is dominant in absorber & generator followed by evaporator & condenser. Maximum difference in conventional and modified approach of exergy determination is in generator and is about 26%. There is an increase in exergy destruction in generator, absorber and condenser by the modified approach but little decrease in exergy destruction in the evaporator by the modified approach as compared to the conventional approach.

VI. EFFECT OF VARIATION IN DIFFERENT PARAMETERS

The effect of the variation of various parameters as temperature of individual component and effectiveness of heat exchanger is studied and all other parameters were kept constant while varying the temperature of individual component or effectiveness of heat exchanger the value of heat, Q changes which is referred as the heat load and depending upon the variations it decreases or increases for components other than evaporator as we designed for fixed cooling effect only and the effect on the system performance and exergy destruction are as follows.

TABLE V
COMPARISON OF THE RESULTS OBTAINED WITH AND WITHOUT MODIFIED GOUY-STODOLA EQUATION

Name of the component	Exergy destruction using Gouy-Stodola equation	Exergy destruction using modified Gouy-Stodola equation	% change in irreversibility
Absorber	14.6	15.2	4.2
Generator	8.1	10.2	26
Condenser	7.4	7.7	4
Evaporator	7.2	6.8	-5.6
Heat exchanger	2.8	3.1	10.7
Total	40.1	43	7.3

A. Effect of Absorber Temperature

In this section, the performance of the system is studied by varying the temperature of absorber from 42ºC to 45ºC and due to which the heat load on the component varies while all other parameters as external mass flow rate, inlet temperature are kept constant for the different components in this study.

This increase in the temperature of absorber causes the exergy destruction to increase by 12.2% and heat load by 3% in the absorber. Rate of irreversibility increases by 12.35% in the heat exchanger i.e. the increase in absorber temperature significantly affect the exergy destruction in the generator and the heat exchanger. Exergy destruction in generator is decreased by 10.5%.

The increase in heat rejection in absorber and increase of heat input to generator is due to an increase of about 30% in the circulation ratio with an increase of absorber temperature from 42ºC to 45ºC. So the circulation ratio should be kept as minimum as possible for the efficient working of the system. The overall effect of this variation is that there is an increase of exergy destruction by 2.4%.

B. Effect of Generator Temperature

While keeping all other input parameters fixed except the temperature of generator which is varied from 99ºC to 102ºC the exergy destruction in the generator decreases by 10.3% and decrease of irreversibility by 12.88% in the heat exchanger and the increase of irreversibility by 4.7% in the absorber took place.

The heat load on the generator and absorber get decreased by 1.5% each i.e. the increase in temperature of the generator is beneficial for both absorber and generator in the energy point of view.

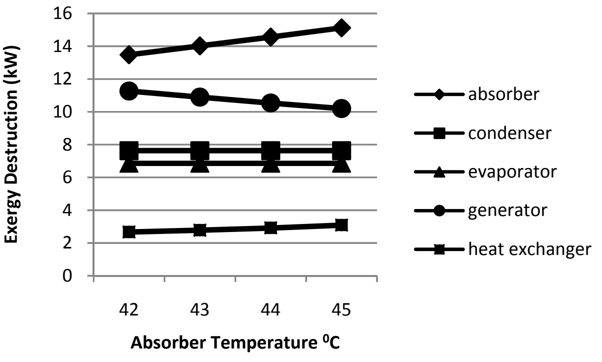

Fig. 2 Effect of Absorber Temperature

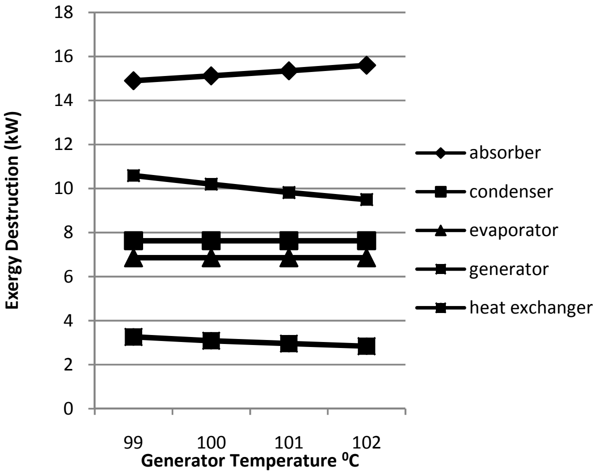

Fig. 3 Effect of Generator Temperature

Due to lower heat requirement in generator, the performance of the system increases and the effect of increasing temperature of generator by 4ºC causes a decrease in the exergy destruction by 2% i.e. this also shows that the increase of temperature of the generator by 3ºC is beneficial for the system as the exergy destruction is reduced in generator, heat exchanger and overall system.

Moreover, this variation also causes the circulation ratio to decrease by 14.85 % which is beneficial for the system performance.

C. Effect of Condenser Temperature

As the temperature of the condenser is increased by 3ºC there is an increase of heat load on the generator and absorber by 2.5% and 2.9% respectively. The increase of temperature causes the total irreversibility to increase by 2% of total exergy. Hence increase in the temperature of the condenser causes the degradation of the system performance. The rise in the temperature of condenser causes a drop in exergy destruction by 4.4 % and 9.8% in the absorber and generator respectively. Increase the irreversibility in the condenser and heat exchanger by 33.3% and 30.4% respectively. This increase of condenser temperature for 42ºC to 45ºC causes an increase of the circulation ratio by 28.8% which implies that the system performance is going to decrease because increase in circulation work increase the pump work and heat load on the generator. The variation clearly tells that for the best performance of the system the condenser temperature should be maintained as minimum possible. The effect on the exergy destruction by this variation is linear in nature for all individual components as well for the system.

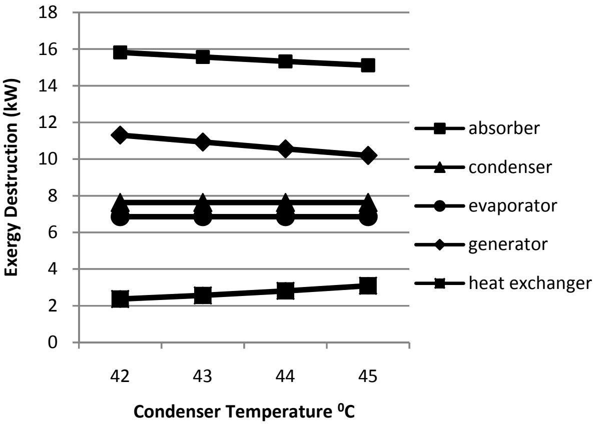

Fig. 4 Effect of Condenser Temperature

D. Effect of Evaporator Temperature

As the temperature of evaporator is increased by 3ºC the exergy destruction in the absorber and generator get increased by 4% and 9.8% respectively. But there is a higher percentage of decrease in the exergy destruction in the evaporator and heat exchanger as 31.3% in evaporator and 27% in the heat exchanger and the total exergy destruction decreases by increasing the temperature of the evaporator.

As per the above variation of temperature of evaporator there is decrease in heat load of the generator by 3.6% and 3.5% in the absorber.

The effect of increasing the evaporator temperature is sudden in the evaporator component as compared to the other component of the system. So increasing temperature of the evaporator is beneficial as this decreases the exergy destruction of the system i.e. system performance increases by this variation.

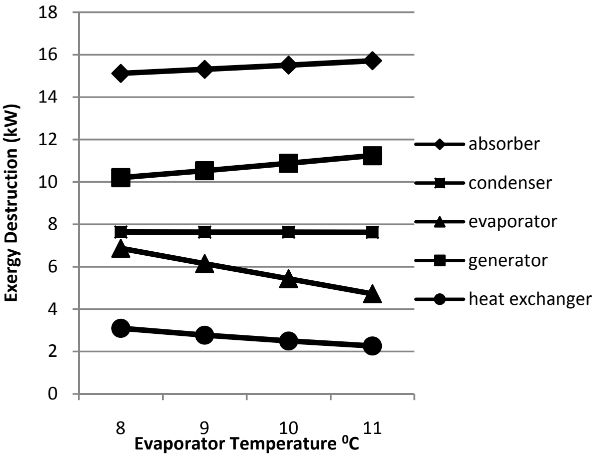

Fig. 5 Effect of Evaporator Temperature

E. Effect of Effectiveness of Heat Exchanger

As the effectiveness of the heat exchanger is increased from 0.6 to 0.75 the exergy destruction in the components mainly absorber, generator, heat exchanger get decreased by 7%, 9.2% and 19.4% respectively.

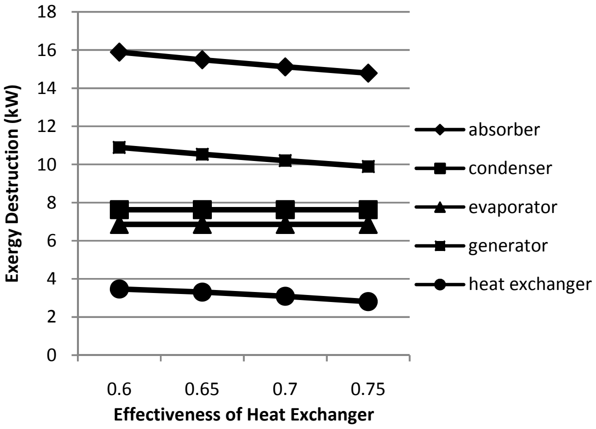

Fig. 6 Effect of Effectiveness of Heat Exchanger

This shows that increasing the effectiveness has a dominant effect on the heat exchanger followed by generator and absorber. So for least destruction of exergy in the system the effectiveness of heat exchanger should be as maximum as possible.

This much amount of increases of effectiveness of heat exchanger causes a decrease in the heat load on the absorber and generator by 5.3% and 4.8%. This increase of effectiveness causes a decrease of 7.8% of total exergy destruction of the system.

VII. CONCLUSION

The modified approach is more realistic approach of the exergy analysis and following conclusions are drawn from this study:

1) Generator is most sensitive part of the system when results of conventional and modified approach are compared for each component as the variation in the environmental temperature and effective temperature is maximum for generator.
2) When modified approach is applied the exergy destruction of the evaporator decreases as compared to conventional approach because the effective temperature of evaporator decreases.
3) An increase in the evaporator temperature and generator temperature improves the overall performance of the system.
4) An increase in the temperature of absorber and condenser degrade the performance of the system. Thus both of these should be maintained at low temperature.
5) As the effectiveness of the heat exchanger increases the exergy destruction in the heat exchanger decreases at faster rate followed by generator and absorber.

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