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Energy and exergy analysis of a double-effect LiBr-H_2O absorption refrigeration system

Tuğba Kovacı, Arzu Şencan Şahin

Süleyman Demirel University, Technology Faculty, 32260, Isparta, Turkey.

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Abstract

An absorption refrigeration system is environmental friendly a technology with zero ozone depletion and global warming potential. The LiBr-H_2O solution in the generator is heated by any renewable source or industrial waste heat. In the present study the analysis of a parallel flow LiBr-H_2O double-effect absorption refrigeration system is performed to compute the optimum system conditions from the point of maximum exergetic efficiency and coefficient of performance (COP), minimum exergy destruction. This analysis is also provides to more develop efficiencies of an absorption driven chiller system by using avoidable exergy analysis. For this purpose of an avoidable and unavoidable exergy destruction analysis is also conducted for each of absorption chiller component. Effect of main temperature difference on the conductance (UA), COP, exergetic efficiency is lent assistance to recover absorption refrigerant system. This study also is showed that how the changing the temperature difference effects total thermal conductance, COP and exergetic efficiency.

Keywords: Absorption refrigeration; Double-effect; Performance; Exergy.

1. Introduction

By the increasing demand for cooling energy; the energy demand dispersion and the cooling systems using alternative energy sources has been more draw attention. While the conventional vapor compression refrigerating systems are used electric energy, the absorption refrigerating systems are used very little electric energy [1]. Absorption chillers present opportunities to utilize sustainable fuels in the production of chilled water [2]. Therefore absorption systems are becoming more popularize today because it is based heat driven system instead of conventional compressing chillers which are work driven [3].

The most of renewable mainstream refrigeration and air conditioning systems based on absorption refrigeration system are prevalent because they are reliable, relatively inexpensive [4]. The studies are concentrated on improve the COP value of absorption refrigeration system. A large number study (experimental and numerical) on this subject has been done. Kılıç and Ravul [5] compared energy and exergy analysis of LiBr-H_2O and LiCl-H_2O absorption refrigeration system is applied with single and double effect cycles. According to the results in this study, at low temperature work LiCl-H_2O system is more suitable and might be an alternative to LiBr-H_2O system. With increasing temperature, particularly in double effect system, LiBr-H_2O system has better exergetic efficiency and COP. Arora, *et al.* [6] developed a computational model for the parametric investigation of a double effect parallel flow LiBr-

H_2O absorption refrigeration system. In this study the maximum exergetic efficiency and COP values are obtained corresponding to same value of optimum solution distribution ratio. The maximum COP of parallel flow double effect system depends on the optimum distribution of solution, leaving the absorber, between high and low temperature generators. Energy, exergy and exergoeconomic analyses for single and double effect LiBr–H_2O absorption chillers systems to assess system performance and the effect of various operating parameters on investment cost is carried out by Avanessian and Ameri [7]. A comparative exergy analysis of a double effect parallel flow and single effect absorption cooling systems is presented by Karaali [8].

In this research the performance of a double effect parallel flow LiBr-H_2O absorption refrigeration system is investigated. This analysis is also provides to more develop efficiencies of an absorption driven chiller system by using avoidable exergy analysis. For this purpose of the unavoidable and avoidable exergy destruction in each component was determined. It is observed that the temperature changes of main system components is how effected on exergetic efficiency, COP and UA.

2. Materials and methods

2.1. LiBr-H_2O absorption cycle

Vapor absorption refrigeration systems are the most suitable alternate in vapor compression chiller. There are limited pairs available for these systems such as LiBr-H_2O and NH_3-H_2O. NH_3-H_2O absorption system is more complicated, while main problem for LiBr-H_2O system is the crystallization [3]. One of major disadvantage of NH_3-H_2O is its toxicity, high working pressure and corrosive reaction over copper, limiting its use of certain materials. In contrast, LiBr-H_2O cost of refrigerant is quite inexpensive. Moreover, boiling point temperature difference for LiBr and H_2O is higher so no need of rectifier and analyzer, and pump-work is less because of the lower pressure difference between generator and absorber [4].

The LiBr-H_2O solution in the generator can heated by industrial waste heat or any renewable source [4]. Most absorption cooling systems adopt the double-effect cycle for the purpose of increase the cooling performance of the system when the heat source available is at high temperature with LiBr-H_2O. As using series flow LiBr-H_2O double effect system the range of operation comes close to the crystallization line and the absorption ability becomes weak. When the parallel-flow type of double-effect cycle compared to the series-flow type; the operating conditions of the parallel-flow LiBr-H_2O double effect type is far away from crystallization line of the LiBr solution, but the flow rate control and the regulation of solutions are complicated [6].

As seen in Figure 1, main components of absorption refrigeration system are absorber (abs), condenser (con), evaporator (evap), high temperature heat exchanger (hthx), low temperature heat exchanger (lthx), high temperature regenerator (htrg), low temperature regenerator (ltrg), solution pump and expansion valve. This system is used water as refrigerant and LiBr solution as absorbent.

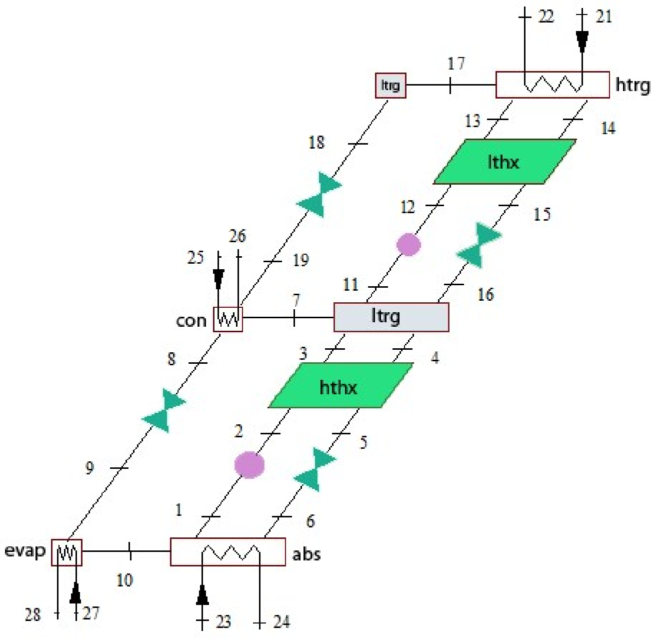

Figure 1. The schematic diagram of a parallel double-effect LiBr-H_2O vapor absorption cooling system.

2.2 Thermodynamic calculation and specification

The thermodynamic analysis primarily aimed at valuation the thermodynamic faultiness and suggested possible ways of improving these faultiness. The system is generally analyzed based on mass, energy and exergy balance. Each component of system can be assumed as control volume having inlet and outlet flow, work interactions and heat transfer [9].

To simplify the thermodynamic modeling of system, the following assumptions are made;

- The system is analyzed under steady state conditions, and the temperature, pressure, and solution concentration in each state are in equilibrium.
- Heat losses and pressure drop along pipes and elements are negligible.
- Refrigerant and solution expansion valves are in isentropic process.
- The refrigerant vapor is completely evaporates to a saturated vapor in evaporator.
- The refrigerant vapor is completely condenses to a saturated solution in the condenser.
- The refrigerant solution is saturated after it passes through the absorber and the generator.
- The kinetic and potential energy variations are negligible.

Yang, Lee, Chung and Kang [1] and Pandya, Patel and Mudgal [9] presented their studies related to absorption cycle, and the above assumptions were clearly stated and justified in the literature.

The mass, energy and heat transfer equations in each component are considered as following.

Mass balance:

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

Balance of the LiBr/H_2O concentrations:

$$\sum_{in} \dot{m}x_{weak} - \sum_{out} \dot{m}x_{strong} \tag{2}$$

Energy conservation:

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

Heat transfer equation:

$$\dot{Q} = UA\Delta\mathrm{T}_{\mathrm{LMTD}} \tag{4}$$

$$\Delta\mathrm{T}_{\mathrm{LMTD}} = \frac{(T_{H,in}-T_{C,out})-(T_{H,out}-T_{C,in})}{\ln((T_{H,in}-T_{C,out})/(T_{H,out}-T_{C,in}))} \tag{5}$$

Pump work:

$$W_p = m.V.\left(Pm - {Pl}/{100}\right) \tag{6}$$

The COP can alter substantially depending on the connection mode even with the same components in a absorption refrigeration cycle [1]. For double-effect absorption chillers, the COP is defined based on the heat transfers associated with the evaporator and the high temperature regenerator [2].

$$COP = \frac{Q_{evap}}{Q_{htrg}} \tag{7}$$

This paper analyzed a 16 kW parallel flow LiBr-H_2O double effect absorption chiller. To avoid LiBr crystallization, effectiveness of high and low temperature heat exchangers is taken at 0,5. Supply of cooling water for absorber and condenser, and supply of air to evaporator considered as 0,1 kg/s. The dead state conditions of the environment are considered as 20°C and atmospheric pressure.

The temperature from the building to the evaporator and to the building after the evaporator is assumed 12°C and 7°C, respectively, based on manufacturer design conditions [10].

In this study, the default input parameters are summarized in Table 1.

Table 1. The set of input data.

P_0 =101,3 kPa	ΔT_{abs} = 8K
T_0 = 293K	ΔT_{evap} = 8K
ε = 0,5	ΔT_{abs} = 8K
$\dot{m}_{21}$ = 1 kg/s	ΔT_{htrg} = 8K
$\dot{m}_{23}$ = 1 kg/s	ΔT_{ltrg} = 8K
$\dot{m}_{25}$ = 1 kg/s	T_{25} = 30°C
T_{21} = 150°C	T_{27} = 12°C
T_{23} = 30°C	T_{28} = 7°C

$$\Delta T_{abs}=T_1-T_{23} \tag{8}$$

$$\Delta T_{con}=T_8-T_{25} \tag{9}$$

$$\Delta T_{htrg}=T_{21}-T_{14} \tag{10}$$

$$\Delta T_{ltrg}=T_{18}-T_4 \tag{11}$$

$$\Delta T_{evap}=T_{28}-T_9 \tag{12}$$

The Engineering Equator Solver (EES) software program is frequently used for absorption chiller modeling because of their extensive libraries for LiBr-H_2O properties. Lake, Rezaie and Beyerlein [2] performed to quantify the exergy destruction rates of absorption chiller by using EES program. The mathematical model is created by used measurements of external processes and flows. Bellos, *et al.* [11] compared the working LiCl-H_2O couple with the LiBr-H_2O couple in solar cooling applications by using EES program, and have been indicated that the alternative working pair LiCl-H_2O is an alternative working pair to the conventional LiBr-H_2O. A Şentürk, *et al.* [12] analyzed thermodynamic properties of double effect absorption refrigerant system with both of LiCl-H_2O and LiBr-H_2O couple with using EES software. In this study, the system is analyzed by utilizing the commercial software EES.

2.3 Exergy analysis and efficiency

The thermodynamic analysis primarily aimed at valuation the thermodynamic faultiness and suggested possible ways of improving these faultiness. Exergy which a system ability to do useful work is a measure of the quality and class of energy, and can be destroyed in a thermal system, and always evaluated with respect to a dead state. It is derived from the combination of the first and second law of thermodynamics. Exergy is not just a thermodynamic property, but is a part of both a system and reference environment. The second law of thermodynamics is used for exergy balance and thermal system design for analysis [13]. The exergy balance of a system can be written as;

$$Exergyinput - Exergyoutput - Exergydestroyed = Exergyincrease \tag{13}$$

The exergy analysis of a thermodynamic system can be formulated based on equation (1) for a steady state system;

$$\sum \dot{Ex} = \sum_i (1-\frac{T_0}{T_i})\, \dot{Q}_i + \sum \dot{Ex}_{in} - \sum \dot{Ex}_{out} - \dot{W} \tag{14}$$

The specific exergy of pure substance values for each flow state are calculated using the first law energy balance from the characteristics of the working environment. The mathematical formula used for this purpose is given by [14];

$$\dot{Ex} = \dot{m}_{kh}[(h-h_o) - T_o(s-s_o)] \tag{15}$$

The exergy efficiency can be expressed as [7];

$$\eta_{Ex} = \frac{Ex_{useful\ gained\ energy}}{Ex_{total\ input\ energy}} \tag{16}$$

2.5 Avoidable exergy destruction

The reducing exergy destruction can improve system efficiency. When the present technological limitations considering, it does not seem possible to recover whole exergy destruction. In the same temperature conditions, the exergy destruction of each component can be split into unavoidable/avoidable parts (un/av). The unavoidable exergy destruction is not recoverable. The avoidable exergy destruction (the remaining part) is recoverable. To improve system efficiency, engineers should be focused on this exergy destruction [15, 16].

Gong and Goni Boulama [16] identified the endogenous, exogenous, avoidable and unavoidable fractions of the exergy destruction for absorption refrigerant system with LiBr-H_2O. According to this study, as the difference between the absorption and condensation temperatures are raise, both the first and second law efficiencies are degrade. Janghorban Esfahani, Lee and Yoo [15] evaluated conventional and exergy and exergoeconomic analyses for a multi-effect evaporation–absorption heat pump desalination system. It was identified that the best optimal operation conditions can be achieved by minimization of overall avoidable cost rates, thus and so can be decrease the total product cost rates by 33,33% and can be increase the exergy efficiency by 4,75%.

$$Ex = Ex_{un} + Ex_{av} \tag{17}$$

To approach this ideal, the temperature difference was assumed about ten times less. For all of the system components, the temperature difference is specified as 0,8 K, except for the evaporator. For the evaporator, the temperature difference is specified as 0,3 K. The expansion valves were neglected.

The settings for the real and ideal cycles in Table 2 are given.

Table 2. Real and ideal cycle settings.

	ΔT for real cycle (K)	ΔT for ideal cycle (K)
ΔT_{abs}	8	0,2
ΔT_{con}	8	0,2
ΔT_{htrg}	8	0,2
ΔT_{ltrg}	8	0,2
ΔT_{evap}	3	0,1

2.6 Model validation

For the purpose of validate the present model of LiBr-H_2O, the results from this model have been compared with data available from literatures of Iranmanesh and Mehrabian [17]. The comparison results are quite satisfactory. The results are presented in Table 3, 4 and 5.

Table 3. Comparison of present model with model of literature data corresponding to input data.

	Present study	Ref. [17]	Error (%)
COP	1,308	1,325	0,017
η	0,4889	0,457	0,0319
T_{max}	150	150	0
T_{min}	4,35	5,13	0,78
P_{max}	64,311	64,286	0,025
P_{min}	0,834	0,881	0,047
x_{max}	61,954	62,926	0,972
x_{min}	53,262	52,753	0,509
W_{ptotal}	0,025	0	0,025

Table 4. Heat duty corresponding to input data.

	evap	abs	htrg	ltrg	con	hthx	lthx
Heat duty, kW (Present study)	354,336	439,794	270,91	193,512	185,541	40,715	39,715
Heat duty, kW [17]	354,336	436,179	267,492	192,776	185,702	38,387	37,116
Error (%)	0	3,615	3,418	0,736	0,161	1,328	2,599

Table 5. Comparison of design specification data.

	evap	abs	htrg	ltrg	con	hthx	lthx
UA, kW/K (Present study)	67,365	86,606	26,142	65,146	10,223	1,531	0,845
UA, kW/K [17]	80,0138	81,405	25,007	65,096	10	1,4252	0,7839
Error (%)	12,6488	5,201	1,135	0,05	0,223	0,1058	0,0611

3. Results and discussion

In this study, to increase the system efficiency, a detailed exergy analysis is performed for the parallel flow LiBr-H_2O double-effect absorption refrigeration system which includes pumping exergy loss. The obtained results are valid for these conditions. Also, it can be seen that the obtained theoretical results are in harmony within acceptable limits of difference with other works.

3.1 Energy and exergy analysis of double-effect LiBr-H_2O absorption refrigerant cycle

This study is lent assistance to identify the major sources of exergy destruction within the chiller. It is observed that the exergy destruction in htrg of the cycle is as 49,99% and, in absorber is as 19,58%, and in evaporator is as 10,78, and in ltrg is as 6,31, and in condenser is as 5,7, in hthx and lthx are as 5,8, and in all valves are as 2,2. It is determined that the htrg, absorber and evaporator are the largest contribution to the exergy destruction. In this study the exergetic efficiency is found to be 49,46% with a COP of 1,06. Thermodynamics properties at each state point of the cycles are given in Table 6.

Table 6. Thermodynamic properties of absorption chiller state points corresponding to input data.

Point	h kJ/kg	m kg/s	P kPa	T °C	x %	s kJ/kgK
1	101,1	0,105	0,814	38	57,867	0,2179
2	101,1	0,105	6,63	38	57,867	0,218
3	143,2	0,105	6,63	59,16	57,867	0,3471
4	212,6	0,098	6,63	85,99	61,881	0,4725
5	167,6	0,098	6,63	62	61,881	0,3427
6	167,6	0,098	0,814	47,22	61,881	0,3442
7	2643,8	0,003	6,63	77,03	0	8,517
8	159,1	0,007	6,63	38	0	0,5455
9	159,1	0,007	0,814	4	0	0,5746
10	2507,9	0,007	0,814	4	0	9,049
11	178,8	0,06	6,63	77,03	57,867	0,4515
12	178,9	0,06	81,448	77,06	57,867	0,4517
13	244,7	0,06	81,448	110,07	57,867	0,6344
14	336,5	0,056	81,448	152	61,881	0,7989
15	266,1	0,056	81,448	114,53	61,881	0,6187
16	266,1	0,056	6,63	88,63	61,881	0,6178
17	2760,5	0,004	81,448	141,42	0	7,67
18	393,7	0,004	81,448	93,99	0	1,239
19	393,7	0,004	6,63	38	0	1,299
21	675,7	1	617,663	160		1,943
22	660,6	1	617,663	156,53		1,908
23	125,8	1	101,3	30		0,4365
24	148,7	1	101,3	35,48		0,5115
25	125,8	1	101,3	30		0,4365
26	133,9	1	101,3	31,94		0,4632
27	50,5	0,764	101,3	12		0,1804
28	29,5	0,764	101,3	7		0,1063

3.2 Exergetic efficiency, COP and UA improvement depending on the temperature changes

The variation of exergy destruction, COP, UA and exergetic efficiency in whole system with operating temperature is specified. It is observed that generally with temperature increasing, COP and exergetic efficiency showed a decrease, and total exergy destruction also increase.

Figure 2 illustrates the variation of COP, exergetic efficiency and total exergy destruction in various components with htrg temperature. It is found that exergy destruction of system increases, the COP and exergetic efficiency decreases with the htrg temperature under given operating condition. Besides, it is seen that the obtained result for the specified conditions have a good agreement with Modi, Mudgal and Patel [4], Ayou*, et al.* [18] and Noman Yousuf*, et al.* [19].

As Figure 3 seen that it is found that exergetic efficiency of the system first decrease and then start increasing after condenser temperature reach up to 40°C. It is seen that the obtained result for the specified conditions have a good agreement with Patel, Pandya and Mudgal [3].

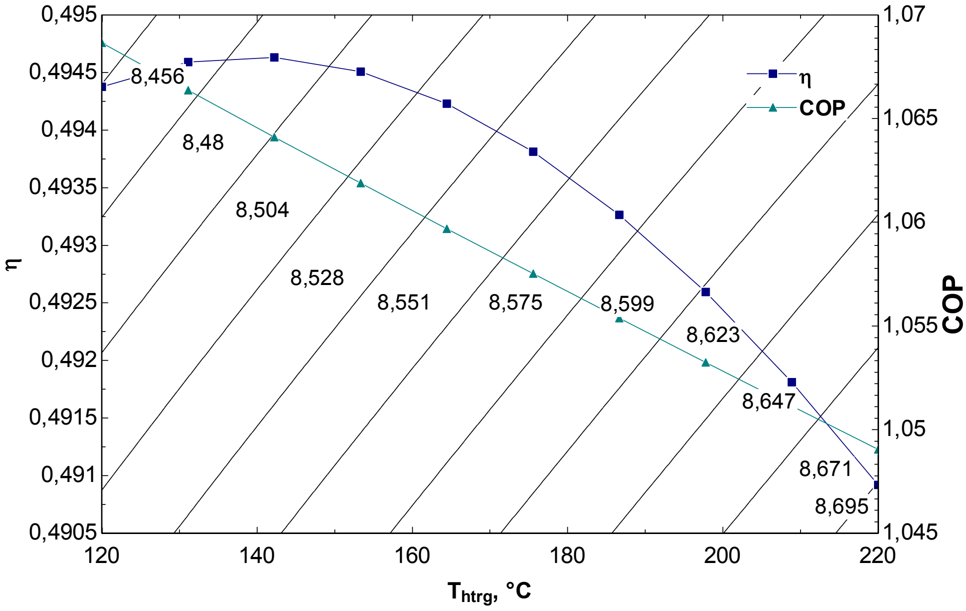

Figure 2. The exergetic efficiency, COP and exergy destruction improvement depending on the htrg temperature changes (T_{con} ,T_{abs}=35°C, T_{evap}=4°C, Q_{evap}=16 kW).

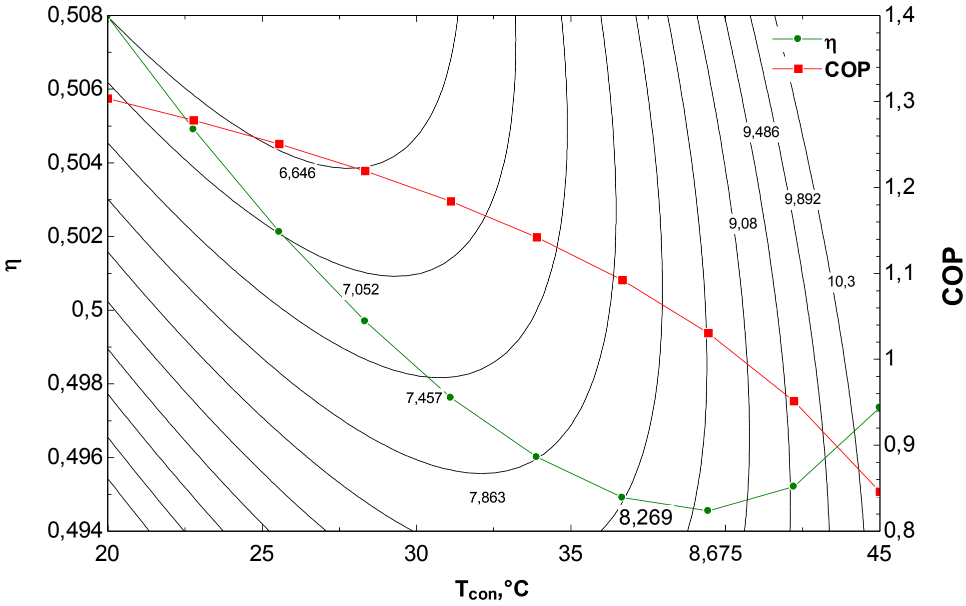

Figure 3. The exergetic efficiency, COP and exergy destruction improvement depending on the condenser temperature changes (T_{abs}=38°C, T_{evap}=4°C, T_{htrg}=141°C, Q_{evap}=16 kW).

From Figure 4 it is found that with increasing absorber temperature, the exergetic efficiency of system decreases as parabolic; when absorber temperature reach up to 35°C, the exergetic efficiency is observed to increases. It is seen that the obtained result for the specified conditions have a good agreement with Arora and Kaushik [20].

Figure 5 illustrated that the COP of the system increases with the temperature of heating resource, while total exergy destruction in various components decreases with the temperature of heating resource.

Figure 6 illustrated that the COP of condenser and evaporator is increase with the conductance increasing. It is observed that the COP in absorber, htrg, ltrg, hthx and lthx is decline with the conductance increasing. It is seen that the obtained result for the specified conditions have a good agreement with Zadeh [21] and Oberweis and Al-Shemmeri [22].

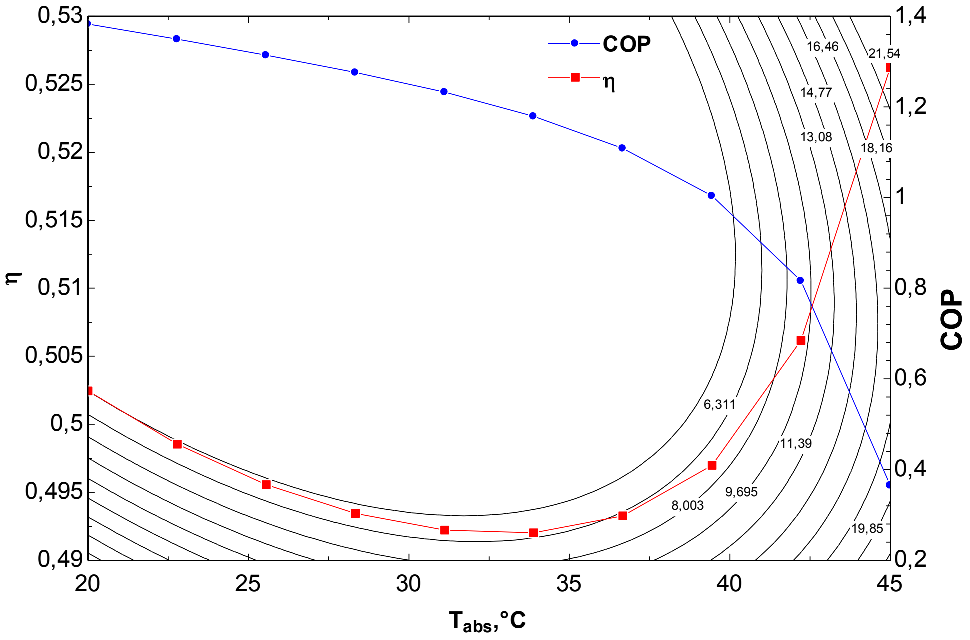

Figure 4. Contour plot of the total exergy destruction, COP and exergy efficiency corresponding to absorber temperature (T_{con}=38°C, T_{evap}=4°C, T_{htrg}=141°C, Q_{evap}=16 kW).

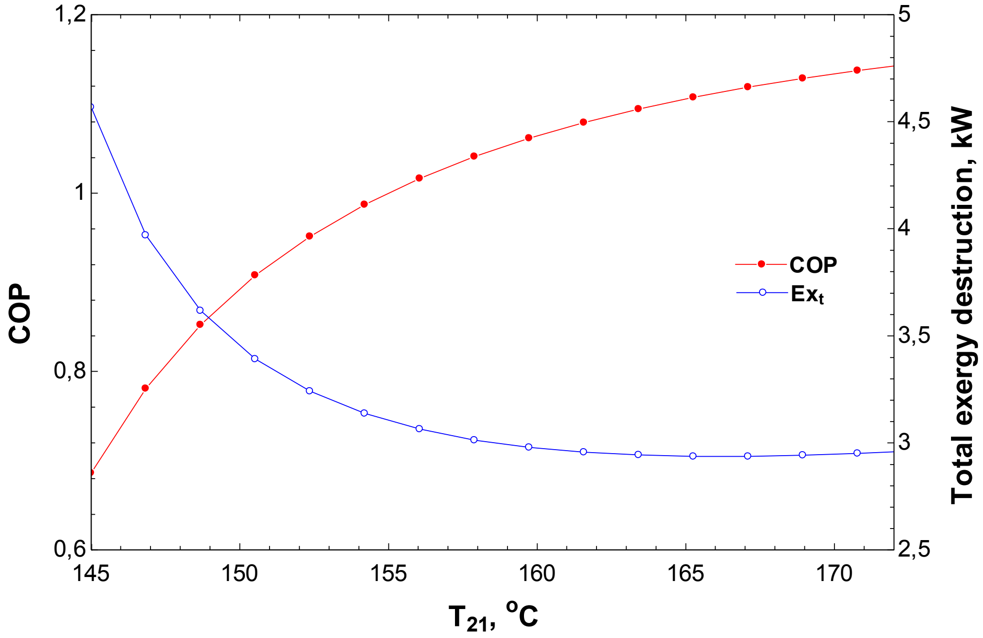

Figure 5. Contour plot of the COP and total exergy destruction corresponding to temperature of heating resource (T_{con}-T_{abs}=38°C, T_{evap}=4°C, T_{htrg}=141°C, Q_{evap}=16 kW).

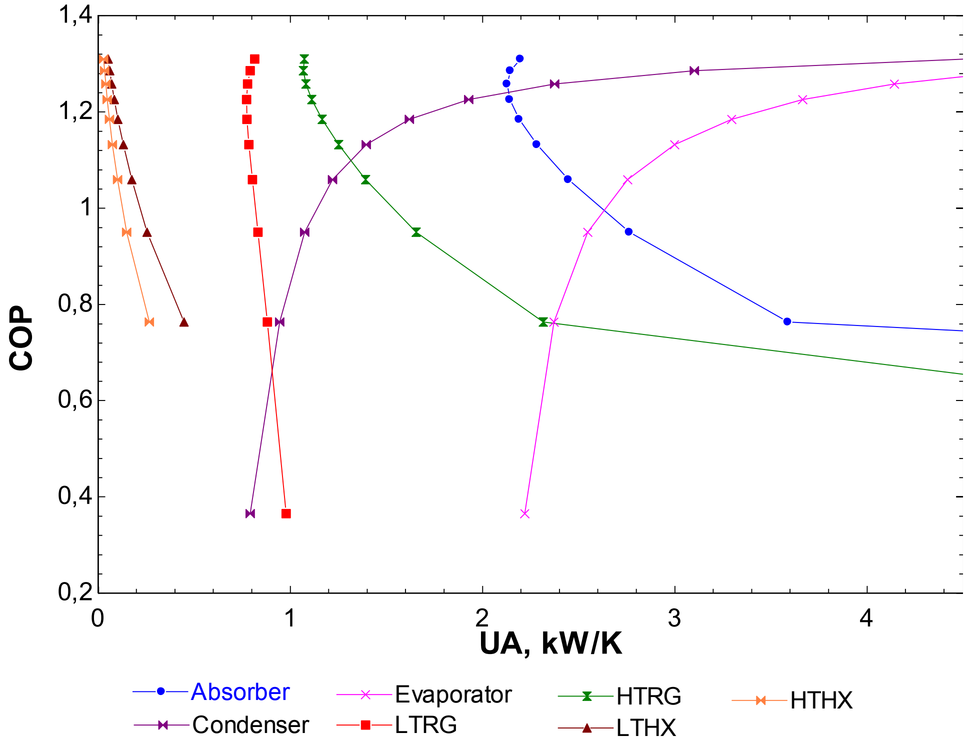

Figure 6. Effects of UA differences on COP.

The study also is showed that the increase in difference temperature change is led to a decline of the condenser and evaporator conductance, is increase of the others (Figure 7).
Figure 8 gives the effects of main temperature differences on the COP and exergetic efficiency. It is obvious that the increasing the evaporator temperature difference is caused decrease of the COP. Exergy efficiency of evaporator is showed a slow increase until reach to the temperature difference of 4°C, and then the quantity of increase is fast. With the increasing the temperature differences excluding evaporator, the exergetic efficiency is increases, while the COP is reduces.

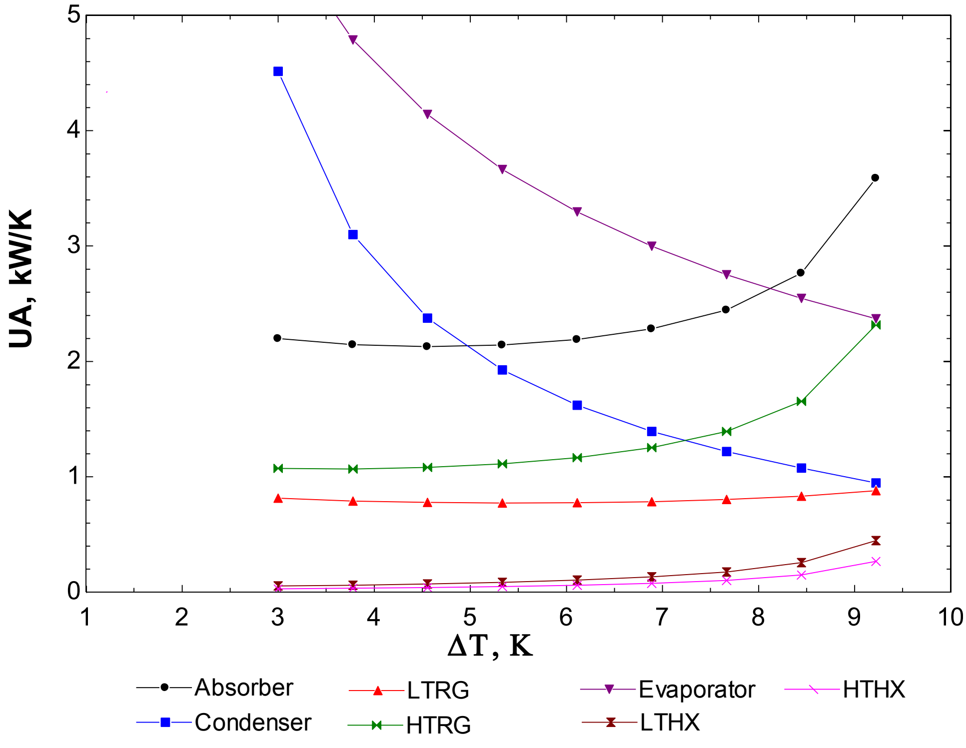

Figure 7. Effects of main temperature differences on UA.

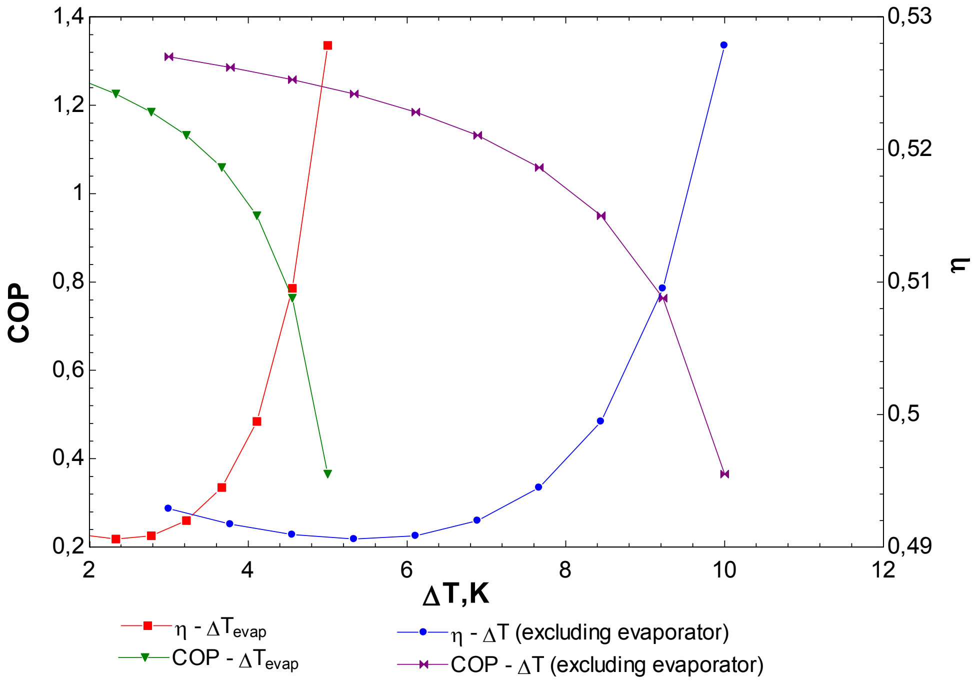

Figure 8. Effects of main temperature differences on COP.

3.3 Unavoidable/avoidable exergy destruction

The avoidable exergy destruction based on the minimum heat transfer temperature difference could be recovered. The avoidable contribution to the exergy destruction can be obtained by subtracting the unavoidable exergy destruction from the overall exergy destruction. In this system, when the given the same amount of exergy provided for cooling, 75,91% of exergy destruction is unavoidable and 24,08% of exergy destruction is avoidable. Graphical presentation of avoidable/unavoidable exergy destruction in each component for absorption chiller is shown in Figure 9.

The avoidable exergy analysis can help to much better identify than unavoidable exergy analysis. Rather than focusing on the total exergy destruction, engineers could focus on the correct components (the quantities of the avoidable exergy destruction), thus could increase the efficiency all of the system. In this study, given the same amount of exergy provided for absorption system, the system exergetic efficiency can be improved by 24%.

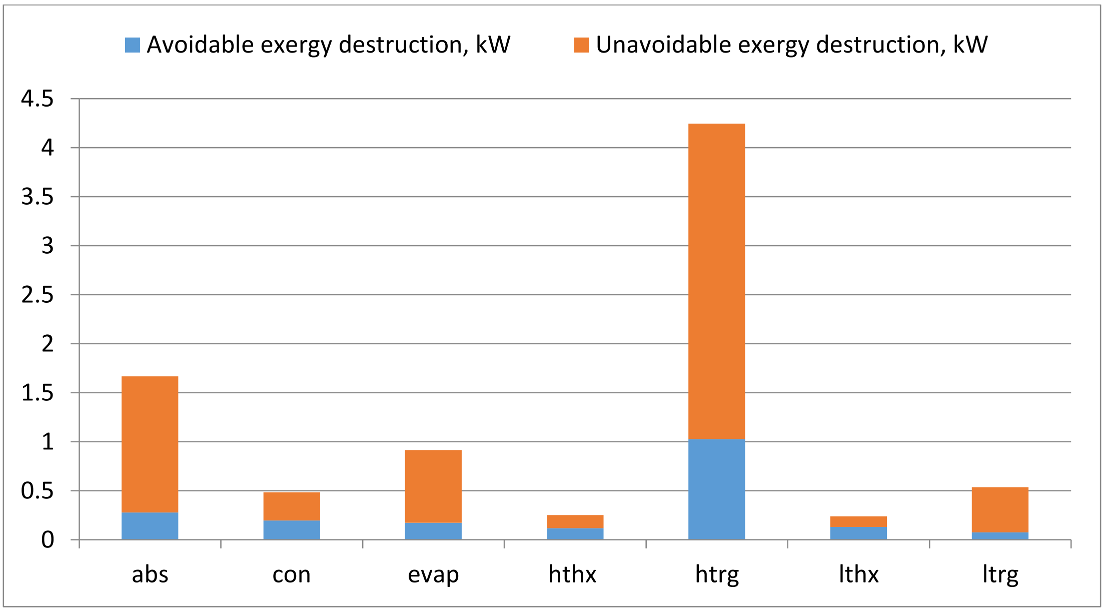

Figure 9. Exergy destruction into avoidable and unavoidable parts for absorption chiller.

4. Conclusion

In this study, the performance of double-effect parallel flow LiBr-H_2O absorption refrigeration system is performed to compute the optimum system conditions. It is observed that the largest contribution to exergy destruction is by htrg, absorber and evaporator, respectively. As the given the same amount of exergy provided for cooling, 75,91% of exergy destruction is unavoidable and 24,08% of exergy destruction is avoidable. This study also is showed that how the changing the temperature difference effects total thermal conductance, COP and exergetic efficiency. It does not seem possible to recover whole exergy destruction, because of technological and economic limitations. These results would lend assistance to more improve double-effect absorption system efficiency.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

COP	Coefficient of performance	p	Pump
EES	Engineering equation solver	v	Volume, m^3
Ex	Exergy destruction	W	Work, kW
L	Exergy lost		
LiBr	Lithium Bromide	***Subscripts***	
LiCl	Lithium Chloride	0	Ambient condition
LMTD	Log mean temperature difference	abs	Absorber
T	Temperature, °C	av	Avoidable part of exergy destruction
P	Pressure, kPa	con	Condenser
ε	Heat exchanger effectiveness	evap	Evaporator
η	Exergetic efficiency	hthx	High temperature heat exchanger
cp	Working fluid specific heat at constant pressure, kJ/kgK	htrg	High temperature regenerator
h	Specific enthalpy	lthx	Low temperature heat exchanger
$\dot{m}$	Mass flow rate	ltrg	Low temperature regenerator
$\dot{Q}$	Heat transfer rate, kW	t	Total
x	Concentration of LiBr in LiBr-H_2O solution	un	Unavoidable part of exergy destruction
e	Exergy per unit mass, kJ/kg	max	Maximum
s	Entropy per unit mass, kJ/kgK	min	Minimum
UA	Thermal conductance, kW/K	in	Inlet
V	Expansion valve	out	Outlet

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Tuğba Kovacı received her all degree (BS, 2002; MS, 2006) in faculty of agriculture from Akdeniz University, Turkey, and is continues to receive her PhD in energy systems engineering from Süleyman Demirel University, Turkey. Her work covers topics in engineering thermodynamics, heat transfer and drying technology.
E-mail address: tugbakovaci@gmail.com, Fax:+90246 2111984, Tel: +90246 2111568.

Arzu Şencan Şahin received all her degrees (BS, 1996; MS, 1999; PhD, 2004) in Mechanical engineering from the Süleyman Demirel University, Turkey. Her work covers topics in engineering thermodynamics, heat transfer and cooling. Professor Şahin is the author or co-author of over 120 peer-refereed articles.
E-mail address: arzusencan@sdu.edu.tr, Fax:+90246 2111984, Tel: +90246 2111399.