Parametric Study of a Double Effect Absorption Refrigeration System

[1]Abbas Alpaslan KOCER, [2]Murat OZTURK
[1]Uluborlu Selahattin Karasoy Vocational School, Suleyman Demirel University,
32260, Isparta Turkey, alpaslankocer@sdu.edu.tr
[*2]Department of Mechatronics Engineering, Faculty of Technology, Suleyman Demirel University, 32260, Isparta Turkey, muratozturk@sdu.edu.tr

Abstract:

Recovering the waste heat would contribute greatly not only to reduce the total energy consumption but also to protect the environment. Absorption refrigeration systems are an alternative to use of waste heat for cooling of volume or refrigeration applications. In this paper, parametric study of a double effect lithium bromide/water absorption refrigeration system has been developed to study and compare the effects of the operating parameters on improvement potential of the system. In order to obtain this purpose, a schematic model of the double effect absorption system is established, and the second-law efficiencies and exergy destruction rates associated with the overall system and its components are determined and the effect of different configurations and operating conditions are analyzed.

Key words: Double effect absorption, parametric study, energy, exergy, efficiency.

1. Introduction

As the world energy consumption has increased enormously, the global environmental problems such as global warming have been caused. According to the long term estimation of the world energy consumption in 2025, it will be 1.5 times larger than the present figure. The system design to develop the optimum system is carried out. The purposes of these efforts are the effective and efficient operation of the system and the integration of the systems and components by coordinating specifications and operating conditions in order to meet various useful outputs.

A greater part of the energy requirements for heating and cooling applications is supplied by fossil fuels i.e. coal, natural gas and petroleum. Natural gas is an important imported product and its increased use has a negative effect on the balance of payments of energy importing countries. Additionally, use of fossil fuels has negative effects on the environment and on health of human beings [1]. In order to decrease fossil fuel consumption, waste heat assisted absorption refrigeration systems are coming into commercial use in domestic space heating and cooling. Nowadays, energy production and consumption systems for generating electricity, heating, cooling, etc., are modeled using thermodynamic assessment viewpoint. Energy analysis based on the first law of thermodynamics had been considered to evaluate the energy efficiency and performance of the system. But in the past three decades, it has been proposed that the second law of thermodynamics, which is related directly to the term of exergy, can confirm the quality of energy in the system analysis. Thereafter, the fundamental concept of exergy has been widely applied [2]. Processes using mainly thermal energy for producing of the useful products are good targets for exergy analysis. This is especially true for thermodynamic evaluation of an absorption refrigeration system.

*Corresponding author: Address: Department of Mechatronics Engineering, Faculty of Technology, Suleyman Demirel University, 32260, Isparta, Turkey. E-mail address: muratozturk@sdu.edu.tr, Phone: +902462111473 Fax: +902462111984

P. Colonna and S. Gabrielli [3] have studied modern multi-generation system using NH_3-H_2O vapor absorption refrigeration sub-system. They have mentioned that, in many modern places, there is a simultaneous requirement for electricity and refrigeration application at lower temperatures. They figured out that, the increase in the fossil energy costs and the environmental impacts present an impulse to integrated energy systems should be considered when planning a modern energy production or consumption system.

Gomri [4] has used the thermodynamic assessment method to investigate the efficiency of a theoretical study between single effect and double effect absorption heat transformer systems used for seawater desalination. The balance equations for mass, energy, entropy and exergy are given for the system analysis. Also, in this paper, lithium bromide and water are chosen as working fluid mixture.

Horus et al. [5] have analyzed the single effect absorption cooling system using the cooling working mixture as water-lithium bromide. The fundamental characteristics of the single effect absorption cooling system are described, the operating sequences are investigated, and thermodynamic cooling process is given for detailed system analysis. The practical ways of the absorption cooling system to an industrial facility are given. A computer program is given to investigate the impacts of different operating parameters on the cooling system, and investigating outputs of the parametric studies are presented in figures.

Zhao [6] has investigated a new type double effect absorption cooling system based on the energy and exergy analysis. Also, balance equations of the mass, energy and exergy are given for the whole system and its components.

In this paper, the energy and exergy analyses of the double effect absorption cooling system using the working mixture as water-lithium bromide are investigated. Also, the thermodynamic and design analyses are given for the purpose of optimal integrated system design based on the exergy analysis. In addition, the parametric investigation is given in order to investigate the effect of the operating condition, such as environment temperature on the exergy efficiency and exergy destruction rate of the system components.

2. System Description

In double effect absorption refrigeration systems, a secondary fluid (absorbent) should be chosen to circulate and to absorb the primary fluid (refrigerant). The performance of the system relies on the selection of a suitable combination of absorbent and refrigerant. The most widespread absorbent and refrigerant combinations in absorption refrigeration systems are LiBr-H_2O and ammonia-water [7]. The LiBr-H_2O pair is the most suitable for air-conditioning and chilling applications. Ammonia-water is utilized for cooling and low-temperature freezing applications.

Figure 1 shows a simplified flow diagram of a double effect absorption refrigeration system, which uses water as the absorbent and Li/Br as the refrigerant. The system mainly consists of a generator, a condenser, an evaporator and an absorber. In vapor absorption cooling systems, the compressor is replaced by an absorber-generator pump assembly in which the refrigerant is absorbed into water as heat is removed. The liquid refrigerant-water solution is pumped and heated to drive off the refrigerant vapor and is then sent back into the refrigeration system [8]. There are two solutions in the absorption cycle as strong solution, which refers to a solution with high refrigerant content, and weak solution, which means a solution with a low content of refrigerant.

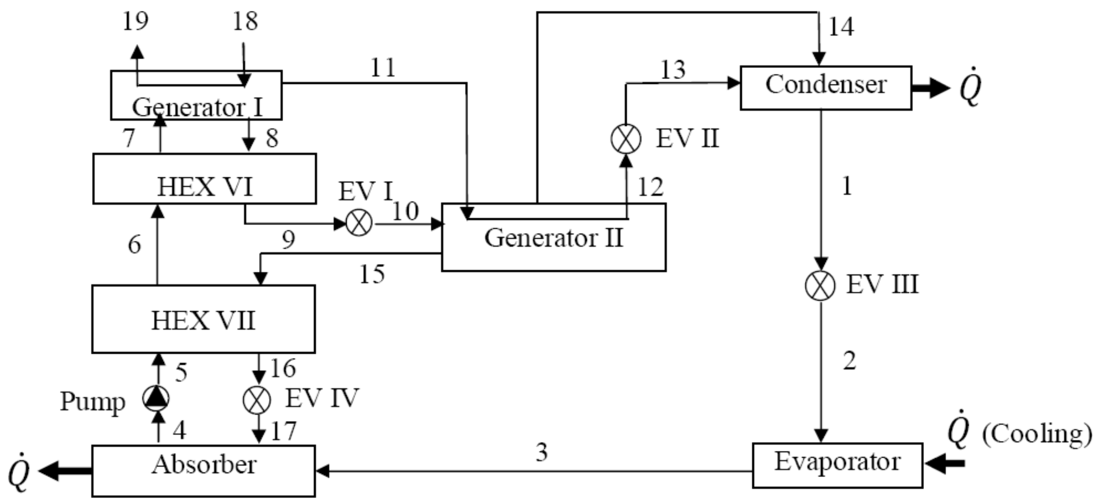

Figure 1. A schematic diagram of a double effect absorption cooling system

To decrease the water amount in the refrigerant flow, a heat exchanger as a distillation column is commonly used. The saturated liquid solution leaving the absorber (4), is send to the heat exchanger II (HEX II), using the solution pump. In order to increase the heat input (18) of high level energy as water vapor, the saturated weak solution leaves from the generator I (8), and exchanges heat with the saturated liquid solution coming from the HEX II.

The sub-cooled weak solution (9) exiting from the HEX I is throated to the generator II pressure. The strong solution leaving the generator II (15) exchanges heat with solution coming from the absorber (5). The sub-cooled strong solution (16) exiting from the HEX II is throated to the absorber pressure (low pressure), and two phase solution is brought into contact with the refrigerant vapor in the absorber (3). The heat produced in the absorption cycle ($\dot{Q}_a$) is rejected from the absorber to the working fluid for cooling of the medium. Unused heat energy should be later used for the space heating. After that, the saturated liquid strong solution in the refrigerant (4), leaves the absorber and starts again the solution circuit.

The vapour leaving from the generator I (high pressure generator) (11) enters the generator II (low pressure generator), and exchange heat with saturated weak solution coming from the HEX-I. At the exiting of the generator II, secondary vapour enters the condenser where the steam is condensed by rejecting heat to a medium temperature sink (cooling water). Evaporator III expand the saturated liquid refrigerant leaving the condenser (1), and this refrigerant fluid enters the evaporator (2). The evaporation of refrigerant takes place at low pressure using the heat released by the water to be chilled. The refrigerant flows to the absorber (3) to dilute the weak solution.

3. Thermodynamic Analysis

The substantial exergy of a stream of matter can be divided into thermal exergy, is resulting from the temperature difference between the material and the dead state, mechanical exergy, is resulting from pressure difference between the material and the dead state, and chemical exergy, is resulting from the composition difference between the material and the dead state [9]. Determination of the exergy of the whole system and its components represents the more complex procedure [10]. The mass, energy and exergy balance equations should be given for thermodynamic assessment of the double effect absorption refrigeration system. The mass balance equation for steady flow conditions can be approximated as [11];

$$\sum \dot{m}_i = \sum \dot{m}_e \tag{1}$$

where $\dot{m}$ is the mass flow rate, subscripts i and e shows the inlet and outlet streams, respectively. The energy and exergy balance equations for any control volume at steady state with negligible kinetic and potential energy changes should be gives as, respectively,

$$\sum \dot{m}_i h_i + \dot{Q} = \sum \dot{m}_e h_e + \dot{W} \tag{2}$$

$$\sum \dot{m}_i ex_i + \dot{E}x^Q = \sum \dot{m}_e ex_e + \dot{W} + \dot{E}x^D \tag{3}$$

The heat exergy can be given as follows;

$$\dot{E}x^Q = \sum \left(1 - \frac{T_o}{T}\right) \dot{Q} \tag{4}$$

where T_o and T are the reference and component temperature, respectively. The specific flow exergy and the rate of total exergy are written as, respectively.

$$ex = (h - h_o) - T_o(s - s_o) \tag{5}$$

$$\dot{E}x = \dot{m}ex \tag{6}$$

where h is the specific enthalpy and s is the entropy enthalpy.

3.1 Energy and Exergy Efficiency

There are very various definitions and names of thermodynamic efficiencies that can be used in literature to evaluate the performance of the double effect absorption refrigeration system. A thermodynamic efficiency can be defined based only on the first law of thermodynamic as the energy efficiency or consider both laws of thermodynamic as the exergy efficiency. The exergy efficiency of the process is the maximum theoretical useful work obtainable as the process, and plays a prominent role for thermodynamic system analysis [12]. The definitions for energy efficiency (η) and exergy efficiency (ψ) for a given process should be written as, respectively;

η = (total energy in products/total energy input) (7)

ψ = (total exergy in products/total exergy input) (8)

Exergy destruction rate and exergy efficiency equations for the double effect absorption cooling system are given in Table 1.

Table 1. Exergy destruction rate equations of the system components

System Components	Exergy Destruction rate equations	Exergy efficiency equations
Generator-I	$\dot{E}x_{D,Gen-I} = \dot{E}x_{18} + \dot{E}x_7 - \dot{E}x_{19} - \dot{E}x_8 - \dot{E}x_{11}$	$\Psi_{Gen-I} = \frac{\dot{E}x_8 + \dot{E}x_{11} - \dot{E}x_7}{\dot{E}x_{18} - \dot{E}x_{19}}$
HEX-I	$\dot{E}x_{D,HEX-I} = \dot{E}x_6 + \dot{E}x_8 - \dot{E}x_7 - \dot{E}x_9$	$\Psi_{HEX-I} = \frac{\dot{E}x_7 - \dot{E}x_6}{\dot{E}x_8 - \dot{E}x_9}$
Expansion Valve-I	$\dot{E}x_{D,EV-I} = \dot{E}x_9 - \dot{E}x_{10}$	$\Psi_{EV-I} = \frac{\dot{E}x_{10}}{\dot{E}x_9}$
Generator-II	$\dot{E}x_{D,Gen-II} = \dot{E}x_{12} + \dot{E}x_{14} + \dot{E}x_{15} - \dot{E}x_{10} - \dot{E}x_{11}$	$\Psi_{Gen-II} = \frac{\dot{E}x_{11} - \dot{E}x_{12}}{\dot{E}x_{14} + \dot{E}x_{15} - \dot{E}x_{10}}$
Expansion Valve-II	$\dot{E}x_{D,EV-II} = \dot{E}x_{12} - \dot{E}x_{13}$	$\Psi_{EV-II} = \frac{\dot{E}x_{13}}{\dot{E}x_{12}}$
Condenser	$\dot{E}x_{D,Con} = \dot{E}x_{13} - \dot{E}x_{14} - \dot{E}x_1 - \dot{E}x^Q_{Con}$	$\Psi_{Con} = \frac{\dot{E}x^Q_{Con}}{\dot{E}x_{13} + \dot{E}x_{14} - \dot{E}x_1}$
Expansion Valve-III	$\dot{E}x_{D,EV-III} = \dot{E}x_1 - \dot{E}x_2$	$\Psi_{EV-III} = \frac{\dot{E}x_2}{\dot{E}x_1}$
Evaporator	$\dot{E}x_{D,Eva} = \dot{E}x_2 - \dot{E}x_3 + \dot{E}x^Q_{Eva}$	$\Psi_{Eva} = \frac{\dot{E}x^Q_{Col}}{\dot{E}x_3 - \dot{E}x_2}$
Absorber	$\dot{E}x_{D,Ab} = \dot{E}x_3 + \dot{E}x_{17} - \dot{E}x_4 - \dot{E}x^Q_{Ab}$	$\Psi_{Ab} = \frac{\dot{E}x^Q_{Ab}}{\dot{E}x_3 + \dot{E}x_{17} - \dot{E}x_4}$
Pump	$\dot{E}x_{D,pump} = \dot{E}x_4 - \dot{E}x_5 + \dot{W}_P$	$\Psi_{Pump} = \frac{\dot{E}x_5 - \dot{E}x_4}{\dot{W}_{Pump}}$
Expansion Valve-IV	$\dot{E}x_{D,EV-IV} = \dot{E}x_{16} - \dot{E}x_{17}$	$\Psi_{EV-IV} = \frac{\dot{E}x_{17}}{\dot{E}x_{16}}$
HEX-II	$\dot{E}x_{D,HEX-II} = \dot{E}x_5 + \dot{E}x_{15} - \dot{E}x_6 - \dot{E}x_{16}$	$\Psi_{HEX-II} = \frac{\dot{E}x_6 - \dot{E}x_5}{\dot{E}x_{15} - \dot{E}x_{16}}$

4. Results and Discussion

Absorption refrigeration systems have ability to utilize low grade heat gaining from solar thermal systems and geothermal energy. The other benefits of absorption refrigeration systems are that they do not cause ozone layer retrenchment, they make use of natural refrigerants possibly having less CO_2 emissions and they are independent of electric grids. Nevertheless, absorption refrigeration systems suffer from having a limitation on the temperature of heat source used. Also the other disadvantage of refrigeration systems is their low efficiencies. These two points have reasoned the improvement of advanced absorption systems. Because of the disadvantages mentioned above, these absorption systems are being improved. In order to succeed this, in this paper, the double effect absorption cooling system is theoretically investigated in detailed using with the energy and exergy analysis.

The values of mass flow rate (kg/s), pressure (kPa), temperature (℃), enthalpy (kJ/kg), entropy (kJ/kgC), LiBr solution percent (%), energy rate (kW), specific exergy (kJ/kg) and exergy rate (kW) for the components of the double effect absorption cooling system are given in the Table 2. In this paper, reference temperature and pressure are taken as 25℃ and 100 kPa, respectively. The thermodynamic properties of the working fluids are calculated via the Engineering Equation Solver (EES) software [13].

Table 2. Mass flow rates, steam properties and exergy rates of the system

No	Fluid	Mass flow rate $\dot{m}$ (kg/s)	Pressure, P (kPa)	Temperature T (°C)	Enthalpy h (kJ/kg)	Entropy s (kJ/kgC)	x LiBr %	Energy rate $\dot{E}$ (kW)	Specific exergy ex (kJ/kg)	Exergy rate $\dot{E}_x$ (kW)
0	H_2O		100	25	104.8	0.3669	-	-	-	-
1	H_2O	0.127	2.547	35	146.6	0.5051	-	5.308	0.07445	0.5862
2	H_2O	0.127	1.069	4	131.4	0.4746	-	16.69	0.7025	5.532
3	H_2O	0.127	1.069	4	2508	9.051	-	305.2	23.58	185.6
4	H_2O/LiBr	1.737	2.547	35	87.63	0.2081	0.5588	64	48.03	27.65
5	H_2O/LiBr	1.737	5.616	35.2	88.03	0.2094	0.5588	64.7	48.05	27.66
6	H_2O/LiBr	1.737	5.616	62.5	143.2	0.381	0.5588	160.4	54.94	31.63
7	H_2O/LiBr	1.737	5.616	107	235.9	0.6394	0.5587	321.6	82.23	47.34
8	H_2O/LiBr	1.671	5.616	130	288.6	0.7365	0.5806	397.3	118.7	71.04
9	H_2O/LiBr	1.671	5.616	83.09	192.5	0.4844	0.5806	236.8	83.75	50.12
10	H_2O/LiBr	1.671	2.547	82.09	190.5	0.4788	0.5806	233.4	83.2	49.79
11	H_2O	0.066	5.616	130	2745	8.862	-	174.2	7.064	107
12	H_2O	0.066	5.616	82.45	345.2	1.104	-	15.86	1.354	20.52
13	H_2O	0.066	2.547	77	322.3	1.04	-	14.36	1.12	16.96
14	H_2O	0.061	2.547	51.79	2597	8.819	-	152	7.478	122.6
15	H_2O/LiBr	1.61	2.547	80.92	197.7	0.4557	0.6029	236.5	102.8	63.84
16	H_2O/LiBr	1.61	2.547	48.67	136	0.273	0.6029	137.2	91.24	56.67
17	H_2O/LiBr	1.61	1.069	47.67	134.1	0.2671	0.6029	134.1	91.02	56.54
18	H_2O	7.326	1000	160	675.9	1.942	-	4183	742	101.3
19	H_2O	7.326	1000	152	641.3	1.862	-	3930	664.6	90.72

The values for exergy destruction rate (kW), exergy destruction ratio (%), exergy efficiency (%) and the power or heat transfer rate (kW) of the double effect absorption cooling system are calculated using the data in Table 2, and given in Table 3, respectively. As seen this table, although exergy efficiency of the generator-I is 56.27%, exergy destruction rate and exergy loss ratio of the generator-I is higher than the other system components. According to exergy loss ratios and exergy destruction rates, it is significant to supply development applications on this generator type. Therefore, minimization of exergy destruction rate in the generator-I is vital to flourish the performance of the absorption cooling system, which in turn diminishes the cost and emissions and thus assists in lessening the associated environmental impact. Also, Table 3 demonstrates that exergy efficiency of expansion valves have high exergy efficiency values as 82.34-99.77%. The expansion valves are a highly effective device because the refrigerant pressure is diminished without any energy exit from the system.

Table 3. Thermodynamic analysis results for the double effect absorption cooling system

Devices	Exergy destruction rate (kW)	Exergy destruction ratio (%)	Exergy efficiency (%)	Power or heat transfer rate (kW)
Generator-I	33.85	0.85	56.27	253.5
Generator-II	21.36	0.53	23.09	158.4
HEX-I	7.676	0.19	78.05	161.1
HEX-II	4.658	0.11	59.68	95.75
Pump	12.08	0.30	60.12	55.36
Condenser	8.523	0.21	72.68	161.1
Expansion valve-I	0.553	0.013	99.34	3.366
Expansion valve-II	0.2346	0.005	82.68	1.509
Expansion valve-III	0.6281	0.015	84.77	1.932
Expansion valve-IV	0.2144	0.005	99.77	3.039
Evaporator	27.44	0.68	45.46	301.9
Absorber	8.264	0.20	22.64	49.57

As another part of the thermodynamic assessment analysis, some variable major design parameters are examined the effects on the exergy efficiency and exergy destruction rate. The variation of exergy destruction rate and exergy efficiency by changing in the reference temperature from 0 ^{o}C to 30 ^{o}C for the absorption cooling system is shown in Figure 2. When Figure 2 is examined, it can be seen that, exergy destruction rate in the absorption refrigeration system increases with the increasing reference temperature. Thus, exergy efficiency dwindles with increasing the reference temperature, thanks to the increasing temperature difference between the refrigeration system and ambient.

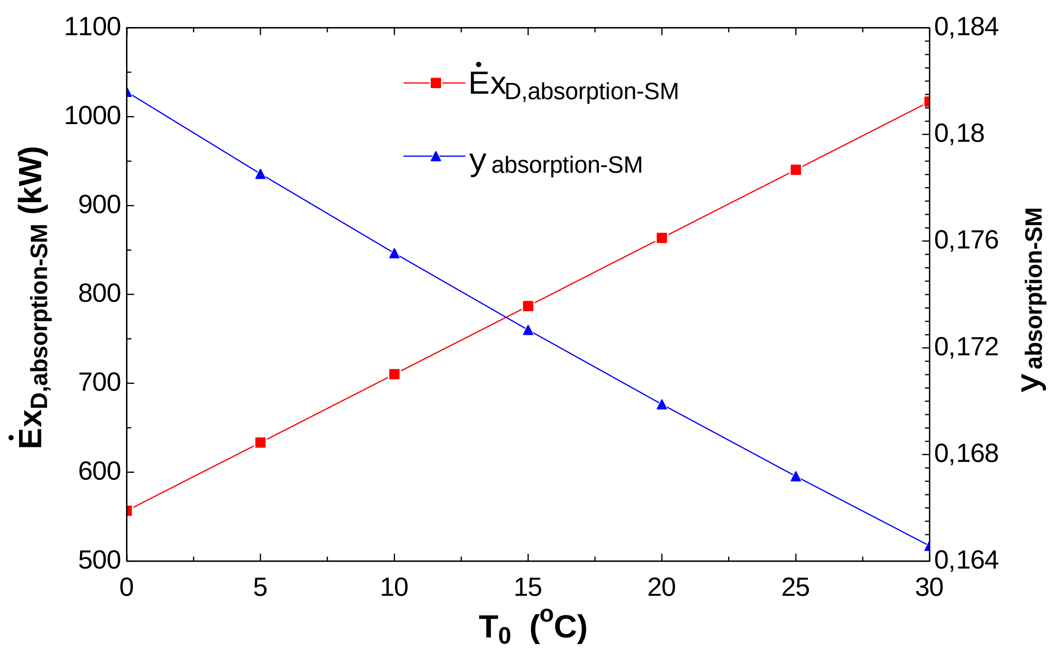

Figure 2. Exergy destruction rates and exergy efficiencies of the double effect absorption system depending on the reference temperature changes

5. Conclusions

For the double effect absorption refrigeration system, it is important to rate the performance and energy savings potential, estimate the system efficiency, power to heat ratio, emissions performance and temperature compatibility. In the present study, a thermodynamic analysis of the double effect absorption cooling system is investigated so as to better determine the true magnitude of losses and the true efficiencies by determining the exergy efficiency and exergy destruction rate for the system components. The parametric study is performed so as to examine the effects of varying operating conditions such as ambient temperature on the system performance. Moreover, the following concluding remarks can be drawn from the thermodynamic analyses.

- The maximum value of the COP of the system is about 0.612, this value is decreases with increasing the generators and condenser temperature.
- The expansion valves have the maximum exergy efficiency, but the absorber has the minimum exergy efficiency. The absorber is the most important system component, and it has an important role on the efficiency of the cooling system, and should be considered as a system component requires development.
- The parametric studies are given to analyze the effect of the reference temperature on the exergy efficiency and exergy destruction rate of the sub-system in general.
- The exergy destruction rates of the system increase with increasing ambient temperature from 0 ^oC to 30 ^oC, but exergy efficiency of the system decreases with increasing ambient temperature.

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