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Energy and Exergy Analysis of Water-Lithium Bromide Absorption Refrigeration Systems

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Energy and Exergy Analysis of Water-Lithium Bromide Absorption Refrigeration Systems

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ABSTRACT

Energy and Exergy Analysis of Water-Lithium Bromide Absorption Refrigeration Systems

Energy and exergy analysis of single effect, double effect series, double effect parallel, and double effect reversed parallel flow water-lithium bromide absorption refrigeration systems presented in this study. We covered waste heat absorption cooling systems with a case study for a wood pencil factory having waste heat as wood chips located in Turkey.

The first and second law efficiencies were examined in terms of the variation of temperatures of evaporator and condenser. COP increase was observed when evaporator temperature was changed. However, an exergy efficiency decrease was observed at the same time due to increased irreversibility. Our analysis was performed in Engineering Equation Software (EES).

SYMBOLS

Nomenclature	
COP	coefficent of performance
h	specific enthalpy (kj/kg)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (kPa)
$\dot{Q}$	heat transfer rate (kW)
s	specific entropy (kJ/kg K)
T	temperature (K)
x	mass fraction of lithium bromide (%)
Ψ	specific flow exergy (kj/kg)
$\Delta\Psi$	specific flow exergy change (kj/kg)
E	exergy efficiency

ABBREVIATIONS

1-18	stations in the absorption refrigeration cycle
A	absorber
C	condenser
G	generator
E	evaporator, outlet
cm	cooling medium
ht	heat transfer
l	liquid phase
p	pump
o	ambient
she	solution heat exchanger
ss	strong solution
v	vapor phase
v1	refrigeration expansion valve
v2	solution expansion valve

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1. Introduction

The standard air conditioning system needs high-quality energy extracted from primary resources. However, despite CFC-free cooling liquids, energy consumption and air pollution levels have been dramatically rising over the past decade. Therefore, an assessment form the ecological point of view needs to be implemented as the greenhouse gases effect remains a threat to the environment [1]. Countries have signed some international agreements to reduce greenhouse gas use and prevent ozone depletion. The best known of these are the Kyoto and Montreal protocols. Kyoto Protocol signed by 192 countries in 1997[2]. Major decisions taken in the Kyoto Protocol are reducing the use of greenhouse gases, reducing greenhouse gas emissions of factories such as iron-steel and cement factories, heating with less energy, and using sustainable energy resources [2]. The Montreal protocol (1987) also includes regulations on refrigerants and restrictions against ozone-damaging gases. After these agreements signed, one of the problems to be solved in the industry was the utilization and reduction of waste heat. Waste heat is the wasted heat given to the surrounding atmosphere (in the form of thermal energy) by a heat engine in a thermodynamic phase in which it transforms heat into useful work. The waste heat is usually dissipated and is released into the atmosphere or the bodies of water including rivers, lakes and even the ocean. Since waste heat is a necessary by product of heat engines, power plants must burn more fuel to produce the energy they need. That raises the greenhouse effect, which raises global warming. There are environmentally friendly energy options, renewable resources, and lower-cost alternatives in heating and cooling applications that will avoid waste heat, the greenhouse effect, and ozone depletion. Geothermal, solar energy, biomass, hydronic heating, absorption, biodiesel, green coal and wind power are the most effective options for using renewable energy. In this study, we covered waste heat absorption cooling systems with a case study for a wood pencil factory having waste heat as wood chips located in Turkey.

2. General Description of Absorption Refrigeration System

As an alternative to high energy costs, absorption refrigeration becomes an appealing choice when there is a cheaper thermal energy source at 100 to 200°C [3]. Recent advances in cooling and heating technology indicate an increasing interest in absorption applications. The absorption cooling and heat pump systems have efficiency opportunities because they can use heat energy to cool instead of using electricity for cooling in vapour compression refrigeration systems. Therefore, absorption cooling systems suitable for Kyoto and Montreal protocols. Absorption refrigeration systems require low maintenance and are less noisy than conventional cooling systems. However, the low rate of the Coefficient of Performance(COP) is a problem with the absorption refrigeration system [4]. Absorption refrigeration systems are using environmentally friendly working fluids. The most common working fluids are water- ammonia and water-lithium bromide. Due to ammonia's toxicity, water-lithium bromide is the best working fluid for the absorption refrigeration system. There are four common types of absorption cooling systems: single effect, double effect in series flow, double effect in parallel flow and double effect reverse parallel flow. We will make the thermodynamic analysis of water-lithium bromide absorption refrigeration systems with a single effect, double effect in series flow, double effect in parallel flow and double effect in reverse parallel flow in our case study. The results are compared to the wood pencil factory's pre-existing chiller system in terms of energy and exergy efficiencies perspectives.

2.1 General Working Principle of Water Lithium Bromide Absorption Refrigeration System Explained in Single Effect

A single effect water-lithium bromide absorption refrigeration system's main components are generator, absorber, pump, evaporator, condenser, heat exchanger, and expansion valve. Two expansion valves installed points between 8-9 and 5-6, as shown in Figure 1. In this system, water as a refrigerant, lithium bromide is working fluid. The schematic of the single effect water-lithium bromide absorption refrigeration system shown in Figure 1.

Figure 1 shows that after water vapour is coming from the evaporator at Point 10, it is absorbed in a liquid at Point 1. Between Points 1 and 2, water pumped to higher pressure. Besides, the work done by the pump is negligible. At the generator, between Points 3 and 7, the refrigerant is boiled out with heat addition by our waste heat source. Our coolant goes to the condenser between Points 7 and 8 as a conventional refrigeration cycle. Finally, the water turns back to the evaporator as a saturated mixture [4].

In this cycle, water properties are used efficiently to minimize the amount of heat vaporizing water. The water's evaporation temperature is around 4 degrees Celsius in vacuum conditions.

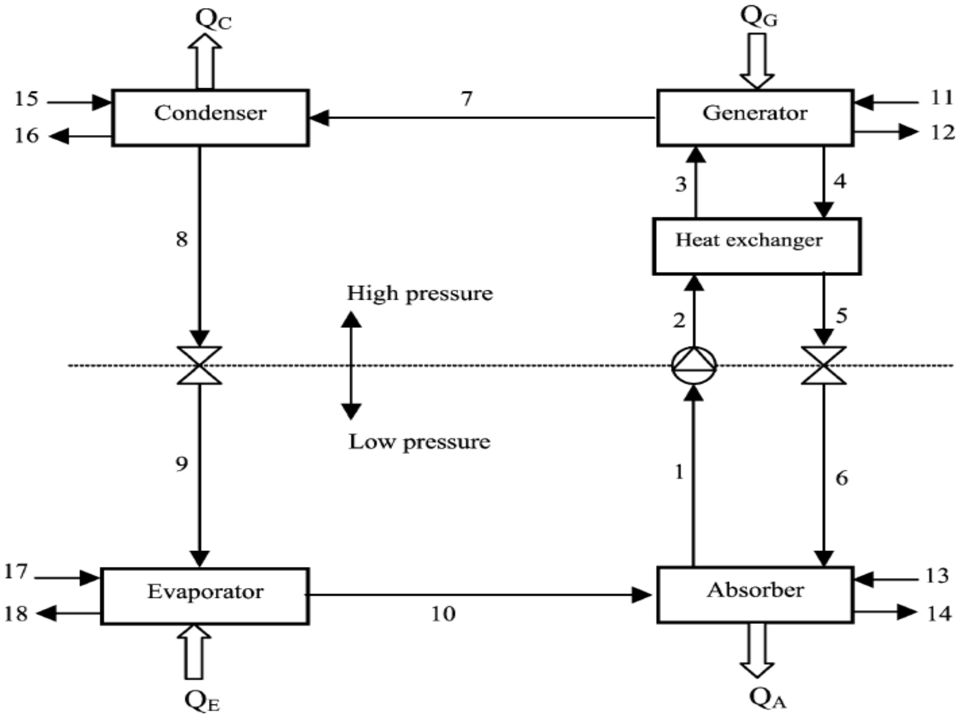

Figure 1. Schematic of Single Effect Water-Lithium Bromide Absorption Refrigeration System [4].

2.2 Double Effect Series Flow Water Lithium Bromide Absorption Refrigeration System

The double effect series flow absorption refrigeration system includes two generators, 1 of which is the high pressure and the other low pressure, as shown in Figure 2. The system also involves one additional heat exchanger and two additional valves, and the other configuration parts are the same as a single effect system. The system consists of five temperature levels: temperature in the high-pressure generator, the temperature in the low-pressure generator, evaporator, condenser and absorber temperatures. The system also involves three pressure levels. They are low, medium and high-pressure levels. Evaporator and absorber work at the low-pressure level. Low-pressure generator and condenser work at medium pressure level. The high-pressure generator works at the high-pressure level. The heat exchanger II has a higher temperature than heat exchanger I. In the cycle process, the high refrigerant concentrated solution (weak solution) is pumped from the absorber to the high-pressure generator (HPG) by passing through solution heat exchangers (Processes point between 4 and 11). Waste heat is utilized in a high-pressure generator to produce water vapour from the high refrigerant concentration solution. The high lithium bromide concentrated solution, the strong solution, will go from the high-pressure generator to the low-pressure generator (LPG) by passing through an expansion valve placed in points between 10 and 9. The high-pressure generator's vapour condensed in the low-pressure generator due to the high lithium bromide solution's low temperature. At the low-pressure generator's outlet, secondary vapours generated, and together with the condensed water of the primary vapour, flow to the condenser, where the heat rejection process occurs. Water continues to flow to the evaporator from the condenser to evaporate at a low-pressure level, removing the medium's heat to be cooled. The high lithium bromide concentrated solution, which flows from point 15, became more concentrated after leaving from the low-pressure generator. It reaches to absorber by passing through heat exchanger I and valve between points 16 and 17. Then it rejects its heat in the absorber [5-6].

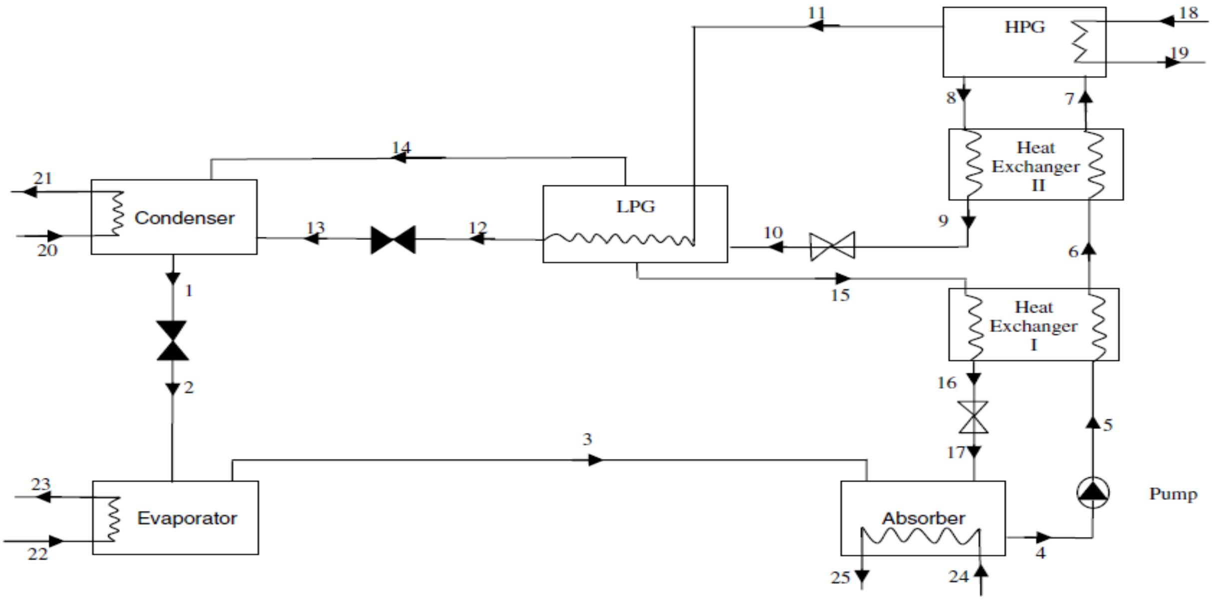

Figure 2. Schematic of double effect series flow absorption refrigeration system [5].

2.3. Double Effect Parallel Flow Water Lithium Bromide Absorption Refrigeration System

In this configuration, three pressure levels still exist, similar to the series flow configuration. Heat exchanger II has a higher temperature than heat exchanger I. The schematic of the parallel flow system shown in Figure 3. The high refrigerant concentrated solution exits from the absorber at 4 then goes to a low-temperature heat exchanger by the pump. After exiting heat exchanger I, flow is divided into two flow streams; one of them flows to the high-pressure generator passing through heat exchanger II, the other flows to the low-pressure generator passing through an expansion valve. The vapour refrigerant, which comes from the high-pressure generator, is condensed, and its heat used to obtain water vapour from the weak solution in the low-pressure generator. The waste heat source used to supply heat to the high-pressure generator for vaporizing water from the weak solution, then our solution has a stronger concentration. Stronger solution goes to the low-pressure generator from the high-pressure generator and mixing with other strong solution. The combined strong solution goes to the absorber by passing through mixing point 10a, heat exchanger I, and expansion valve [6-7].

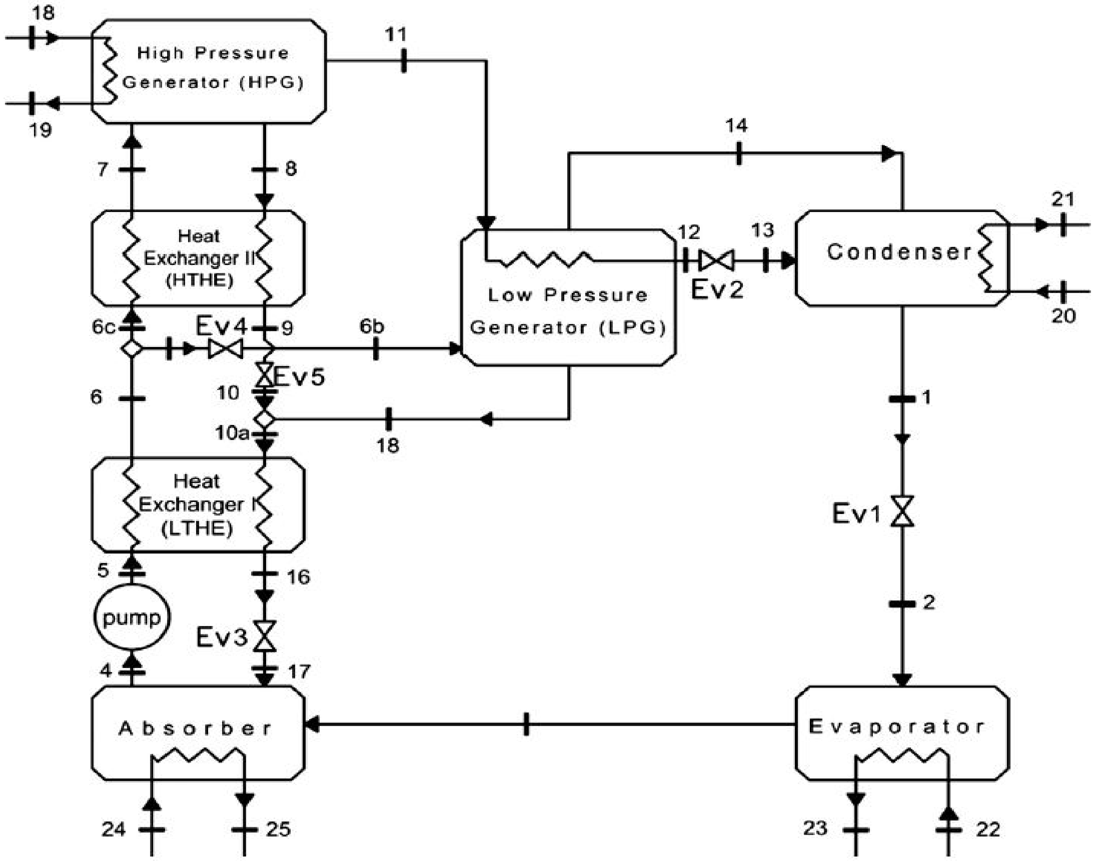

Figure 3. Schematic of double effect parallel flow absorption refrigeration system [7].

2.4 Double Effect Reversed Parallel Flow Water Lithium Bromide Absorption Refrigeration System

The schematic of the system is shown in Figure 4. The weak solution leaves from the absorber at point 4 flows to the low-temperature heat exchanger using the pump. In P1, the strong solution divides two flow streams after exiting the low-pressure generator. One of the divided streams is going high-pressure generator by pump passing through the high-temperature heat exchanger. The other one flows to P2, then mixing with a strong solution exits from the high-pressure generator. The mixed solution enters the absorber by passing through the low-temperature heat exchanger and expansion valve 3, which located between points 16 and 17. The external low-grade heat source that can be used is the low-pressure generator. If external heat source not used in low-pressure generator $\dot{Q}_{LTG} = 0$ [6].

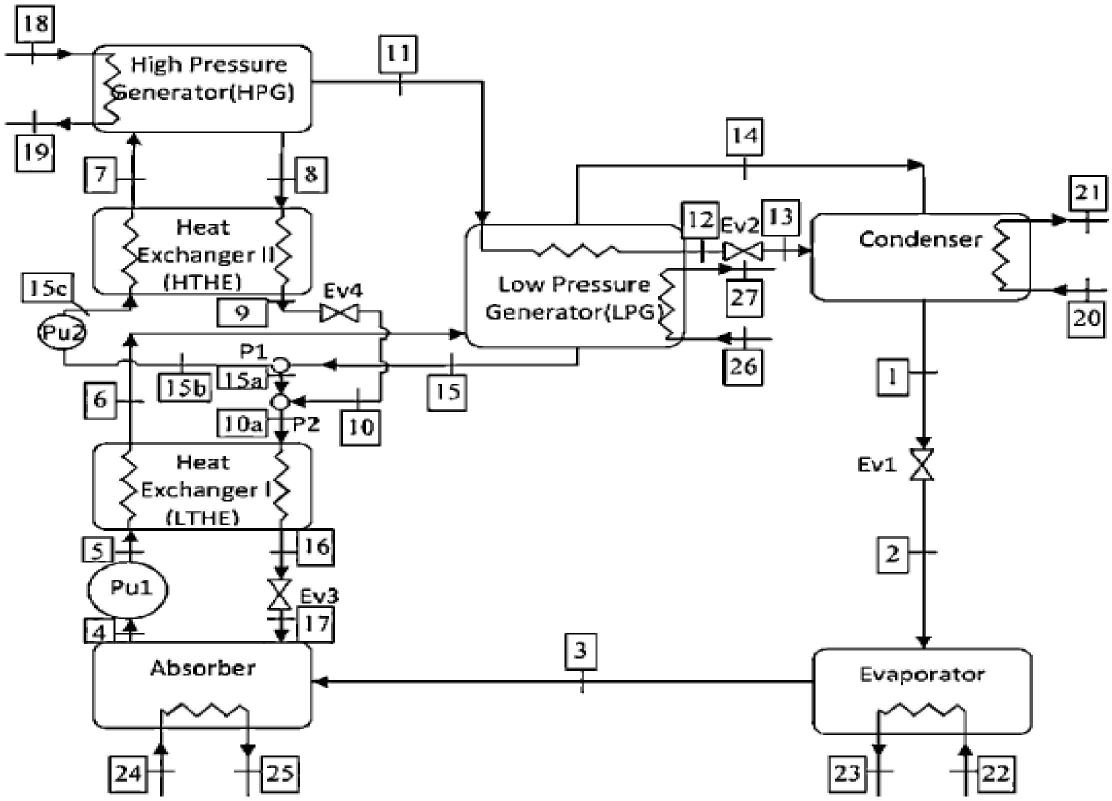

Figure 4. Double effect reversed parallel flow absorption refrigeration system[6].

3. Thermodynamic Analysis

For the energy and exergy analysis of the absorption refrigeration systems, each component is defined as control volume with their inlet and outlet flow streams and energy transfers. The principles of conservation of mass, first and the second law of thermodynamics, are applied to each control volume in all absorption refrigeration system configurations. The overall mass conservation equations under the steady-state condition which applied in every control volume in below:

$$\sum \dot{m}_i - \sum \dot{m}_o = 0 \tag{1}$$

$$\sum (\dot{m}x)_i - \sum (\dot{m}x)_o = 0 \tag{2}$$

where x represents the mass concentration of lithium bromide in the water-lithium bromide solution. $\dot{m}$ stands for the mass flow rate of the flow stream.

In applying the first law of thermodynamics, basically conversation of energy principles is used. The general first law of thermodynamics equation under steady-state conditions in absorption refrigeration systems written below:

$$\sum (\dot{m}h)_i - \sum (\dot{m}h)_o + [\sum Q_i - \sum Q_o] + W = 0 \tag{3}$$

The first law efficiency of the absorption refrigeration systems measured with cooling coefficient of performance equation. The overall coefficient of performance equation of the absorption refrigeration systems as follows:

$$COP_{cooling} = \frac{\dot{Q}_E}{\dot{Q}_G + \dot{W}_p} \cong \frac{\dot{Q}_E}{\dot{Q}_G} \tag{4}$$

where $\dot{W}_p$ represents the work rate of the pump. In our analysis, pump work neglected.

The overall exergy equation of flow stream in unit mass basis expressed as

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

where kinetic and potential energies of the system neglected.

The rate form of the overall exergy equation of a control volume in steady-state process calculated by

$$\Delta\Psi = \sum(\dot{m}\Psi)_i - (\dot{m}\Psi)_o - \left[\sum \dot{Q}(1 - \tfrac{T_o}{T})_i - \sum \dot{Q}(1 - \tfrac{T_o}{T})_o\right] + \sum W \tag{6}$$

Our analysis revealed the effects of temperature changes in evaporator and condenser to COP and exergy efficiency in single effect, double effect in series, double effect in parallel, and double effect reverse-parallel absorption refrigeration systems. The schematic of the single-effect absorption refrigeration system shown in Figure 5. According to the enumeration of the schematic, the cooling exergy efficiency equation is

$$E_{cooling} = \frac{\dot{m}_{17}(\Psi_{17} - \Psi_{18})}{\dot{m}_{11}(\Psi_{11} - \Psi_{12})} \tag{7}$$

The cooling coefficient of performance equation of single-effect absorption refrigeration system according to the numeration of the schematic in Figure 5 can be written as

$$\mathrm{COP_{cooling}} = \frac{\dot{Q}_E}{\dot{Q}_G + \dot{W}_p} \cong \frac{\dot{Q}_E}{\dot{Q}_G} = \frac{\dot{m}_{10}h_{10} - \dot{m}_9 h_9}{(\dot{m}_7 h_7 + \dot{m}_4 h_4 - \dot{m}_3 h_3)} \tag{8}$$

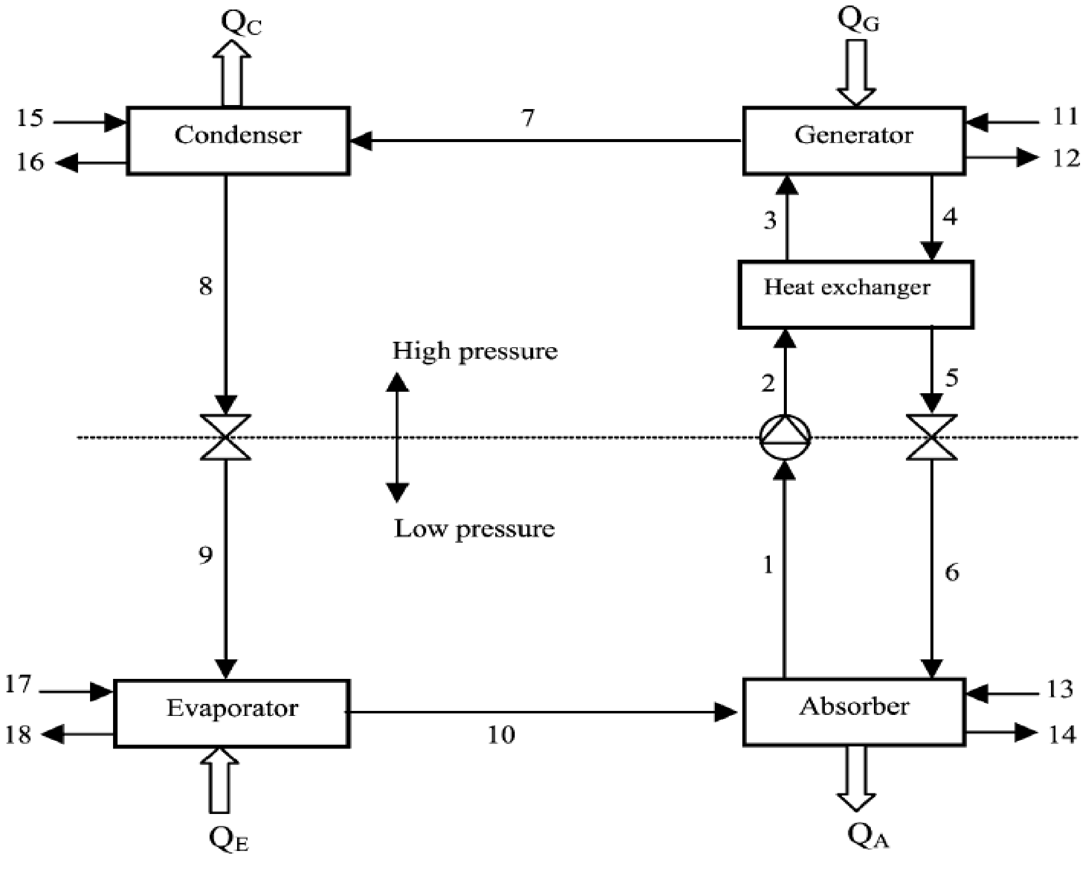

Figure 5. Schematic of single-effect absorption refrigeration system [4].

For the double effect series flow absorption refrigeration system, the cooling coefficient of performance and cooling exergy efficiency according to the numerations of the schematic in Figure 6 as follows:

$$\mathrm{COP_{cooling}} = \frac{\dot{Q}_E}{\dot{Q}_{HPG}+\dot{Q}_{LPG}+\dot{W}_p} \cong \frac{\dot{Q}_E}{\dot{Q}_{HPG}+\dot{Q}_{LPG}} = \frac{\dot{m}_3 h_3-\dot{m}_2 h_2}{(\dot{m}_8 h_8+\dot{m}_{11} h_{11}-\dot{m}_7 h_7)} \tag{9}$$

$$\mathrm{E_{cooling}} = \frac{\dot{m}_{22}(\Psi_{22}-\Psi_{23})}{\dot{m}_{18}(\Psi_{18}-\Psi_{19})} \tag{10}$$

if there is no additional external heat in low-pressure generator $\dot{Q}_{LPG} = 0$. We neglected pump work because pump work is compared to too small with the rate of heat in the high-pressure generator.

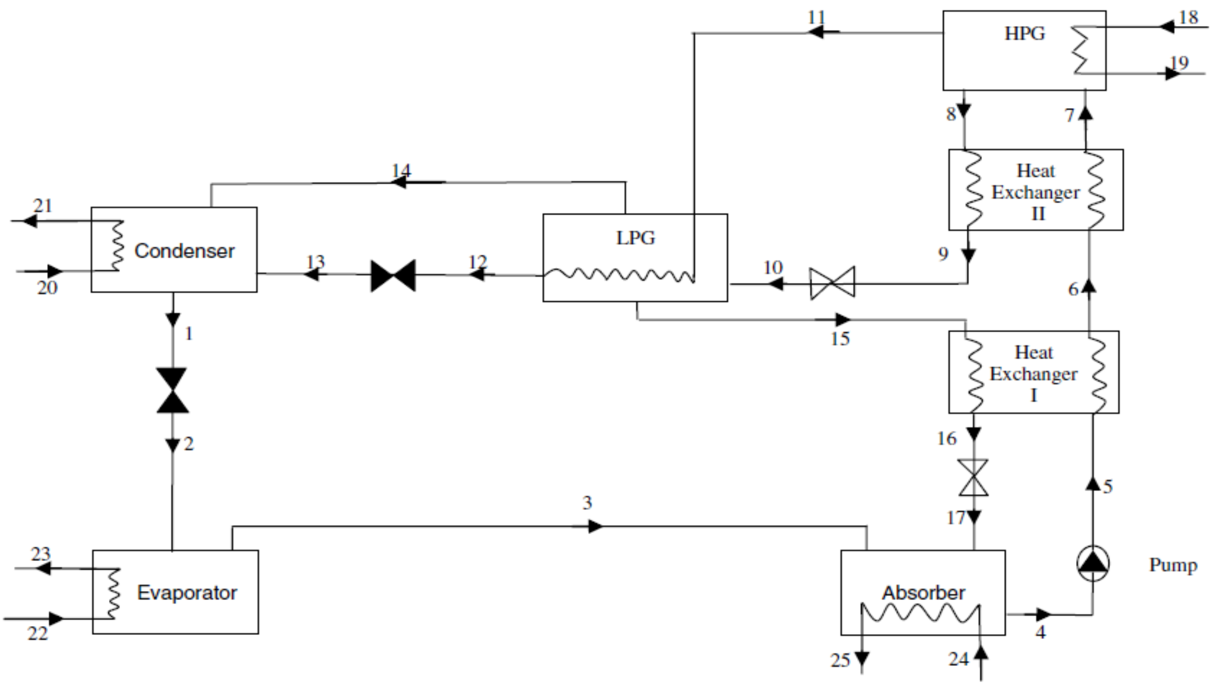

Figure 6. Schematic of double effect series flow absorption refrigeration system [5].

For the double effect parallel flow absorption refrigeration system, the cooling coefficient of performance and cooling exergy efficiency according to the numerations of the schematic in Figure 7 as follows:

$$\mathrm{COP_{cooling}} = \frac{\dot{Q}_E}{\dot{Q}_{HPG}+\dot{Q}_{LPG}+\dot{W}_p} \cong \frac{\dot{Q}_E}{\dot{Q}_{HPG}+\dot{Q}_{LPG}} = \frac{\dot{m}_3 h_3-\dot{m}_2 h_2}{(\dot{m}_8 h_8+\dot{m}_{11} h_{11}-\dot{m}_7 h_7)} \tag{11}$$

$$\mathrm{E_{cooling}} = \frac{\dot{m}_{22}(\Psi_{22}-\Psi_{23})}{\dot{m}_{18}(\Psi_{18}-\Psi_{19})} \tag{12}$$

As in the double effect series flow configuration, the heat rate in the low-pressure generator and the pump's work rate are neglected.

For the double effect reversed parallel flow configurated system, the cooling coefficient of performance and cooling exergy efficiency according to numerations of the schematic in Figure 8 can be written as:

$$\mathrm{COP_{cooling}} = \frac{\dot{Q}_E}{\dot{Q}_{HPG}+\dot{Q}_{LPG}+\dot{W}_p} \cong \frac{\dot{Q}_E}{\dot{Q}_{HPG}+\dot{Q}_{LPG}} = \frac{\dot{m}_3 h_3-\dot{m}_2 h_2}{(\dot{m}_8 h_8+\dot{m}_{11} h_{11}-\dot{m}_7 h_7)} \tag{13}$$

$$E_{cooling} = \frac{\dot{m}_{22}(\Psi_{22}-\Psi_{23})}{\dot{m}_{18}(\Psi_{18}-\Psi_{19})} \tag{14}$$

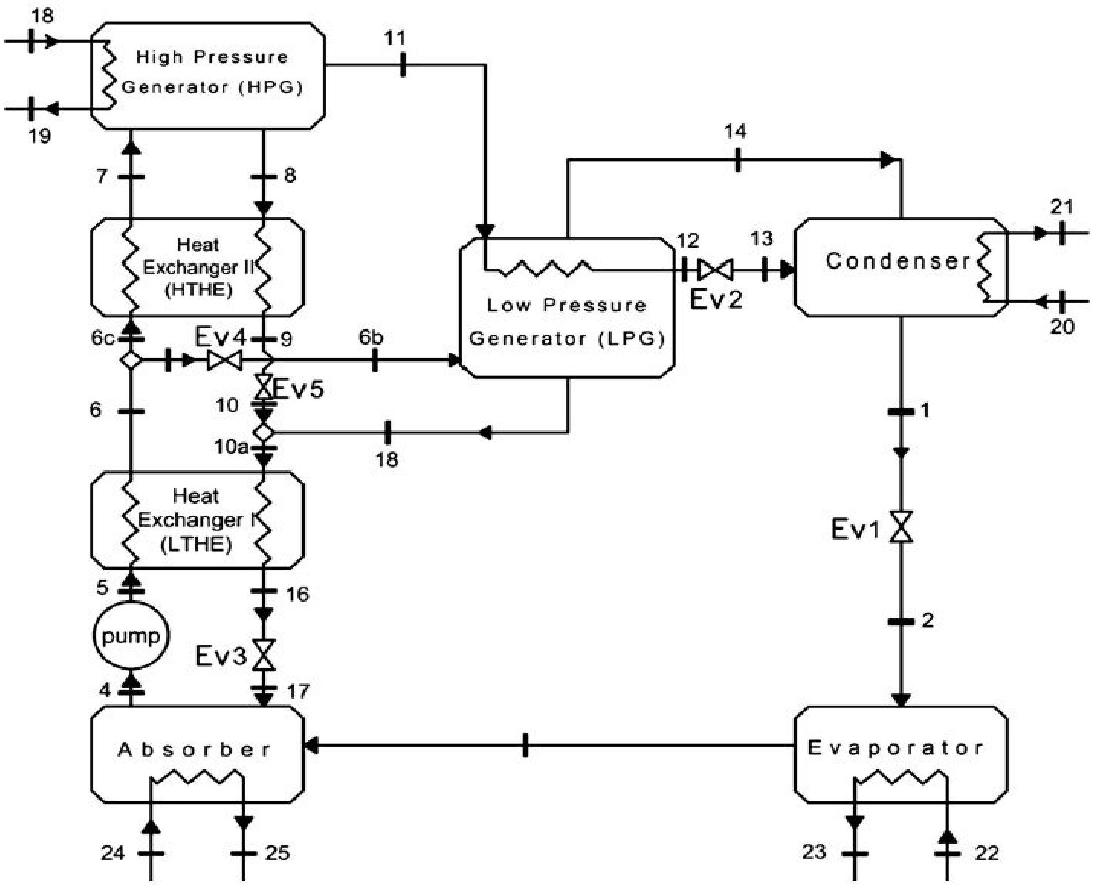

Figure 7. Double effect reversed parallel flow absorption refrigeration system [6].

Which cooling system to choose in absorption refrigeration system may differ depending on generator temperature. In Gomri's studies published in 2010, we can see that single effect absorption refrigeration systems are more efficient in below 100 degrees of Celsius generator temperature in terms of exergy efficiency [5]. In Farshi's studies published in 2010, we can observe that double effect absorption refrigeration systems operate efficiently in terms of exergy efficiency at higher temperatures than 120 degrees Celsius [6]. Double effect systems offer higher COP values than single effect absorption refrigeration systems. COP range of single effect systems is 0.7-0.8, in double effect systems, this range are 1.3-1.45 [5,6].

3.1. Assumptions

During the analysis, the following assumptions were considered for simplify the mathematical modelling of the system:

- All configurations of absorption refrigeration systems operate at steady-state conditions.
- Pump work is neglected.
- Water is considered as a saturated liquid at condenser exit.
- Water is considered as saturated vapour at the evaporator exit.

- The rate of heat amount in low-pressure generators is zero.
- Pressure drops are neglected.
- The ambient temperature and pressure for water 26 ^{o}C and 1 bar, respectively.
- Heat transfer between systems and surrounding are negligible.
- Chemical exergy changes are negligible.
- Effectiveness of solution heat exchangers 95%.

4. Results and Discussion

We made a parametric study to analyze the effects of evaporator and condenser temperature in COP and $E_{cooling}$ values. Our evaporator temperature range is 4-10 degrees of Celsius, and the condenser temperature range is 28-33 degrees of Celsius during our parametric study. We conducted our parametric study in Engineering Equation Solver (EES) software. We kept generator temperature as a fixed parameter. The high-pressure generator's temperature and pressure in single effect absorption refrigeration system were 143 degrees of Celsius and 300kPa, respectively. For double effect systems, temperature and pressure values are 143 degrees of Celsius and 4 bar, respectively. Evaporator inlet and outlet temperatures 4 and 10 degrees of Celsius are fixed parameters when condenser temperature increases. Condenser inlet and outlet temperatures 28 and 33 degrees of Celsius which are fixed parameters when evaporator temperature increases. Figure 8 shows how COP changes when condenser temperature increases in our all absorption refrigeration system configurations, which we studied. In this parametric study, evaporator inlet and outlet temperature 7 and 12 degrees of Celsius, respectively.

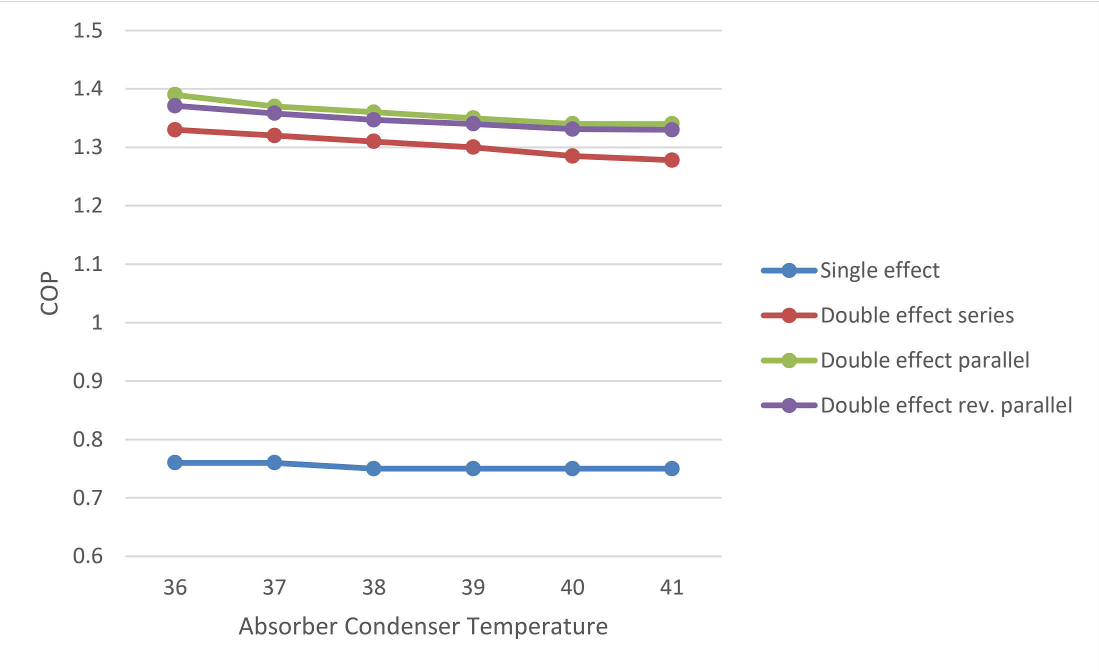

Figure 8. COP comparison of four configurations of absorption refrigeration systems when absorber condenser temperature changes.

As shown in Figure 8, the COP value of the single effect system varies between 0.76-0.75. COP ranges of double effect series, parallel, and reversed parallel are 1.33-1.28, 1.39-1.34, 1.371-1.330, respectively. Table 2 shows COP values of double effect configurations when absorber condenser temperature changes. Table 1 shown below:

Temperature (^oC)	Series	Parallel	Reversed-parallel
36	1,33	1,39	1,371
37	1,32	1,37	1,358
38	1,31	1,36	1,347
39	1,30	1,35	1,340
40	1,29	1,34	1,331
41	1,28	1,34	1,330

Table 1. COP values of double effect configurations of absorption refrigeration systems when condenser temperature changes.

We can see from Figure 9 that the highest COP values obtained in double effect parallel configuration. Maximum COP values obtained at 28 degrees of Celsius. The maximum COP value of parallel configuration is 1.45 % higher than reversed parallel configuration,4.51% higher than series configuration, and 82.89% higher than single effect system. Figure 9 shows COP comparison of four configurations of absorption refrigeration systems when evaporator temperature changes. Figure 9 shown below:

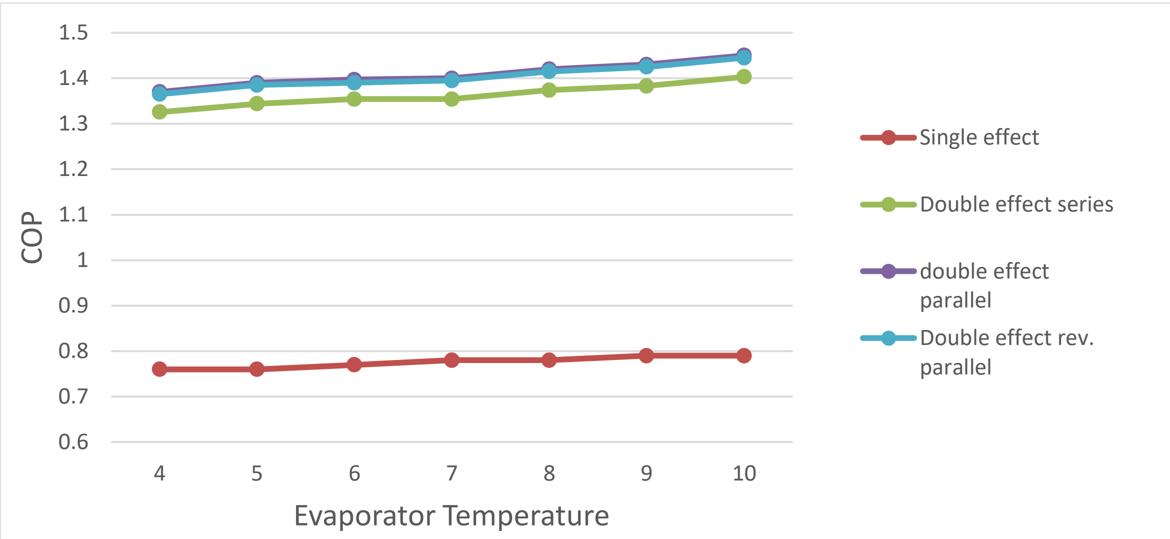

Figure 9. COP comparison of four configurations of absorption refrigeration systems when evaporator temperature changes.

Figure 9 shows COP ranges of the single effect, double effect series, double effect parallel, and double effect reversed-parallel flow systems 0.76-0.79 1.3255-1.403,1.37-1.45 and 1.365-1.445, respectively. Maximum values higher than condenser temperature variation study because COP directly related to $\dot{Q}_E$ in Eqn. (4). In this study, condenser inlet and outlet temperatures are 29 and 34 degrees Celsius. Table 2 shows COP values of double effect configurations when evaporator temperature changes. Table 2 shown below:

Temperature (^oC)	Series	Parallel	Reversed-parallel
4	1,3255	1,37	1,365
5	1,344	1,39	1,385
6	1,354	1,397	1,390
7	1,354	1,4	1,395
8	1,374	1,42	1,415
9	1,383	1,43	1,425
10	1,403	1,45	1,445

Table 2. COP values of double effect configurations of absorption refrigeration systems when evaporator temperature changes.

At high evaporator and low generator and condenser temperatures, high COP values are obtained, as we see in our figures above. We performed the second law analysis to see how exergy efficiency changes when evaporator and condenser temperature changes. The most efficient system is the double effect parallel configuration. The second is double effect reversed parallel then double effect series and last single effect system. Single effect systems more efficient in below 100 degrees of Celsius [4,8]. Our reason for selecting generator temperature of 143 degrees of Celsius in single effect is to make a reasonable comparison between the single effect and double effect configurations. As shown in Figure 10 below, the single effect system's exergy efficiency range is 0.186-0.1960 when evaporator regime 7-12 degrees of Celsius as fixed-parameter and condenser temperature varies between 28-33 degrees of Celsius. Exergy efficiency range of double effect series, parallel reversed parallel are 0.4208-0.4034, 0.4387-0.4206, and 0.4341-0.4160, respectively. Table 3 shows the exergy efficiency values of double effect configurations when condenser temperature changes. Table 3 shown below:

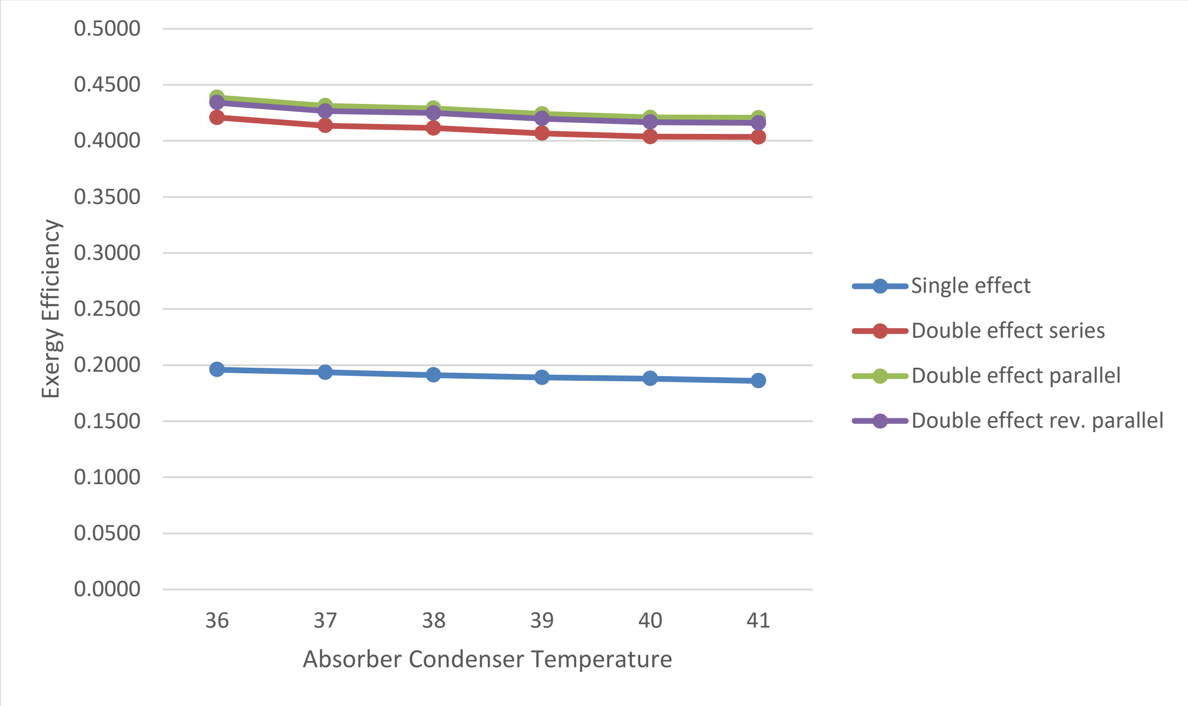

Figure 10. Exergy efficiency comparison of single and double effect configurations of absorption refrigeration systems when condenser temperature changes.

Temperature (^{o}C)	Series	Parallel	Reversed-parallel
36	0,4208	0,4387	0,4341
37	0,4136	0,4312	0,4266
38	0,4115	0,4290	0,4248
39	0,4067	0,4240	0,4198
40	0,4037	0,4209	0,4167
41	0,4034	0,4206	0,4160

Table 3. Exergy efficiency values double effect absorption refrigeration systems when condenser temperature changes.

Figure 11 shows how evaporator temperature variation affects exergy efficiency in absorption refrigeration systems. Increasing evaporator temperature increased COP but decreased exergy efficiency. This is explained by the fact that chilled water has a greater ability at a lower temperature to produce a cooling effect at the same flow rate. This compensates for the decrease related to the first law in the cooling load. According to the second law of thermodynamics, the higher temperature, the higher irreversibility. It decreases exergy and exergy efficiency. Highest exergy efficiency values obtained at 4 degrees of Celsius. According to our second law analysis, the most efficient system is the double effect parallel system. The range of exergy efficiency in the double effect parallel system is 0,4387-0,4206, as shown in Figure 11. The range of exergy efficiency in the double effect reversed-parallel system is 0,4341-0,4160. The double effect parallel system's maximum exergy efficiency is 1.04% higher than reversed parallel configuration at its maximum value. According to our second law analysis, double effect series configuration is the least efficient system in double effect configurations.

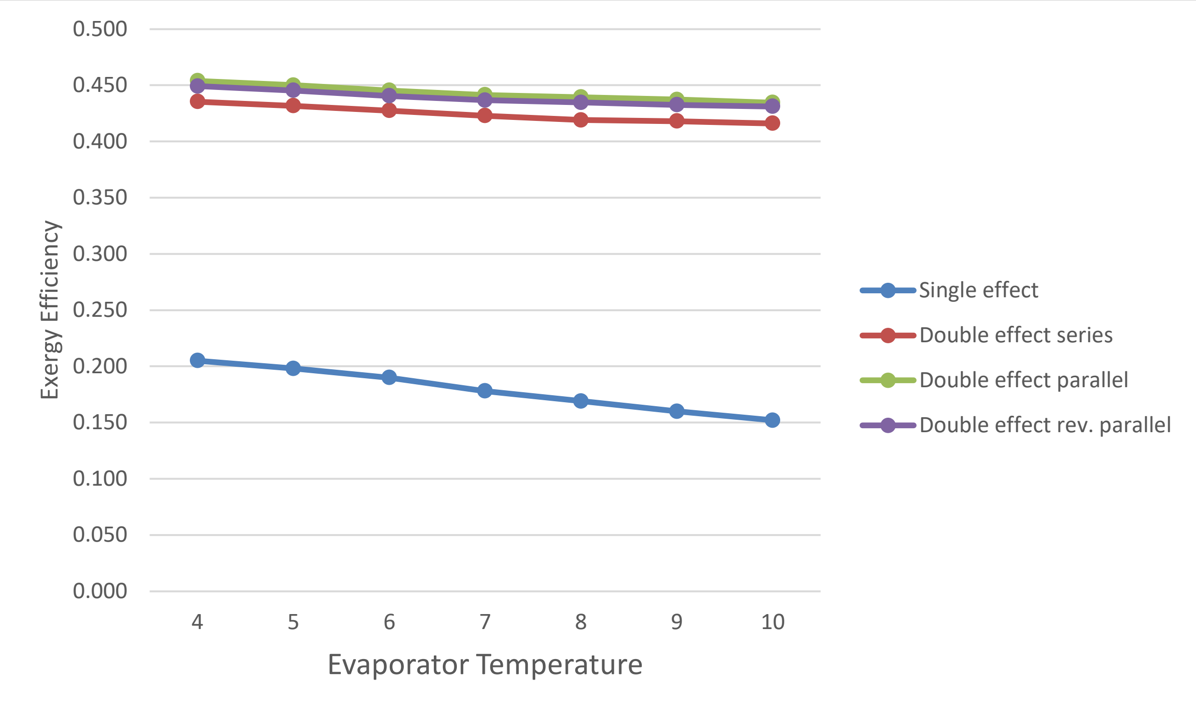

Figure 11. Exergy efficiency comparison of double effect configurations of absorption refrigeration systems when evaporator temperature changes.

Temperature	Series	Parallel	Reversed-parallel
4	0,4354	0,4539	0,4492
5	0,4317	0,4501	0,4454
6	0,4275	0,4453	0,4406
7	0,4229	0,4414	0,4367
8	0,4191	0,4394	0,4347
9	0,418	0,4373	0,4326
10	0,416	0,4346	0,4311

Table 4. Exergy efficiency values of double effect absorption refrigeration systems when evaporator temperature changes.

5. Conclusion

Absorption refrigeration systems are becoming more popular and important due to global warming and international protocols. They are environmentally friendly systems, sustainable and cost-effective. In this study, we described how single effect, double effect series, double effect parallel, and double effect reversed parallel absorption refrigeration systems. We covered waste heat absorption cooling systems with a case study for a wood pencil factory having waste heat as wood chips located in Turkey. We made the first law and second law of thermodynamic analysis on evaporator and condenser components of systems. Our results are first law and second law efficiencies in the variation of temperature of our selected components. According to our first and second law of thermodynamic analysis, double effect parallel configuration is the most efficient system. There is a significant difference between single and any double effect systems regarding first and second law efficiencies. Maximum COP and exergy efficiency values of single-effect absorption refrigeration systems are 0.79 and 0.205, respectively. Even though increasing evaporator temperature increase COP, exergy efficiency decreases. According to the second law of thermodynamics, higher temperatures have higher irreversibility, and due to that, exergy decreases. Absorption refrigeration systems offer sustainable, environmentally friendly, cost-effective cooling in low-grade energy sources. Absorption refrigeration systems are designed under Kyoto and Montreal Protocols.

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