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Analyzing the Performance of the Combined Cycle of Allam and Cooling System from the Point of View of Energy and Exergy

Emad Dokhaee [1], Mohsen Jabbari [2], Alireza Saraei [2]*
1- Department of Mechanical Engineering, Arak Branch, Islamic Azad University, Arak, Iran
2- Department of Mechanical Engineering, South Tehran Branch, Islamic Azad University, Tehran, Iran
* Corresponding Author: a_saraei@azad.ac.ir orcid.org/0000-0003-1476-1057

ABSTRACT

In the present study, the combined system including Allam cycle and absorption cycle has been investigated from the perspective of energy, exergy and exergy-economy. The use of the absorption cycle is to use the waste heat of the power cycle and increase energy efficiency. The simulation results show that the total exergy efficiency of the cogeneration cycle is 0.72. Turbine, compressor and absorption cycle are introduced as primary components that should be considered from the exergy-economic point of view because they account for the highest cost rate of exergy efficiency. Also, the results of parametric analysis indicate that increasing the compressor pressure ratio has a negative effect on the cycle performance, thus reducing the overall work and efficiency of the exergy as well as increasing the cost rate. Similarly, changing the compressor pressure ratio has the greatest impact on the performance of the combined cycle, so that changing the pressure ratio in the range of 2 to 10 resulted in reducing the exergy efficiency by 63%. The key assessment is that the performance of the system increases as the temperature of the cooled water in the evaporator rises. Exergy efficiency works in contrast to the system performance coefficient and the main reason for the return of imperfections in the absorption cooling system is the undesirable heat transfer in the system heat exchangers.

Keywords: Combined production cycle, Allam cycle, Absorption cooling cycle, Exergy-economic analysis

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1. INTRODUCTION

In recent years, the use of Allam generation cycle has received much attention. This cycle reduces the amount of carbon dioxide emissions to zero. Due to the operation of the Allam cycle at high temperatures, it is possible that by combining this cycle with the absorption cooling cycle, both the energy efficiency of the combined cycle is increased and the cooling produced in the required parts is used. Absorption cooling creates many opportunities to save energy; Because absorption cooling systems use low-level heat energy such as solar energy, geothermal energy and waste heat , steam and gas turbines instead of electricity to generate cold. On the other hand, these systems because they use environmentally friendly fluids; They also do not damage the ozone layer. Thermodynamic analysis according to the first law is used as a very common method for the analysis of heating systems. The first rule only deals with energy conservation and does not give us any other information such as the direction of the processes and the quality of their operation. In contrast, the second law is a more powerful tool in designing, optimizing and evaluating the performance of energy systems. Figure (1) shows a schematic of the Allam power generation system. The Allam generation cycle is a closed cycle that works with the carbon dioxide working fluid. This cycle operates at high temperatures and minimizes carbon dioxide emissions.

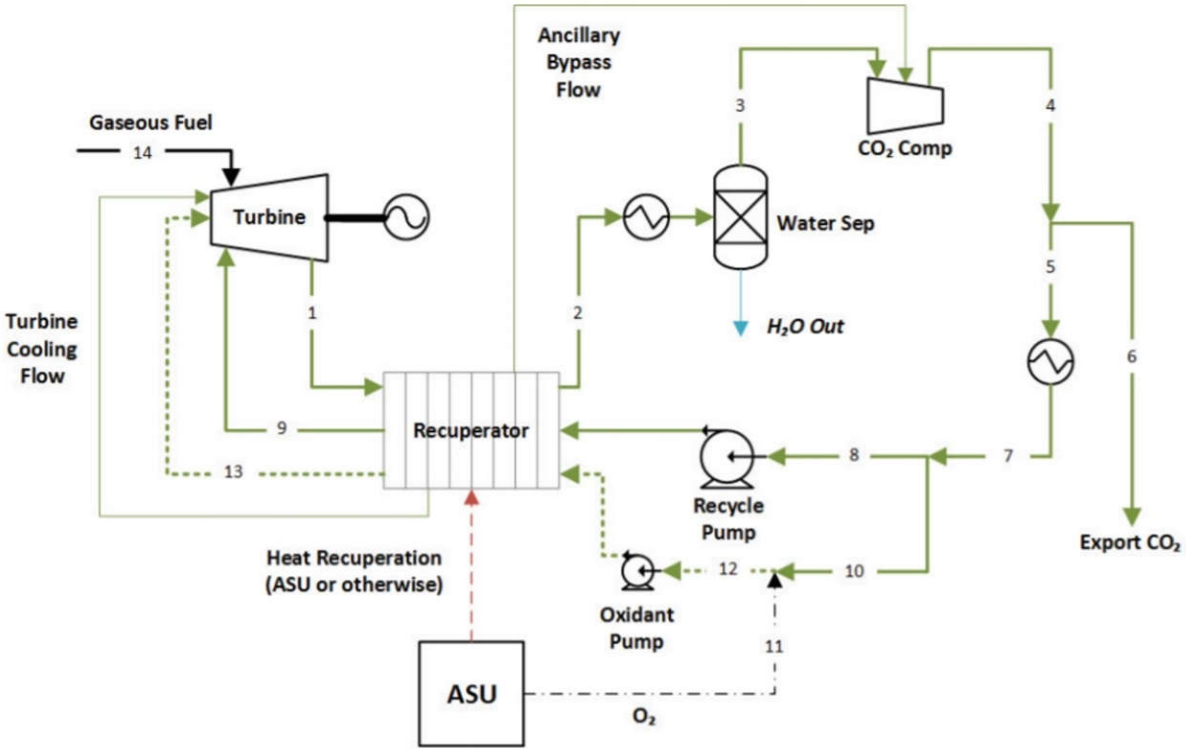

Figure 1- Schematic of the Allam cycle [1]

Numerous combined cycles have been introduced in numerous studies. In the following, a number of combined cycles are introduced.

In 2012, Magalhães integrated a solar hot water system and an air conditioning system. Based on local climate data, building elements, load profile and storage, the net results of the system were calculated using a simple supply and demand approach [2]. In 2014 and 2015, Abbaspour et al. Proposed a model for optimizing the CCHP system based on minimum energy consumption and initial investment costs. It should be noted that the selected variables were gas turbine size, absorption chiller capacity and other system components. The optimal values of design parameters and objective functions were found and compared with the initial values. The results showed significant improvements in system COP, exergy efficiency and total cost. [3], [4] In 2016, Klimenko et al. Showed in a study that in the Russian electricity industry, facilities have been used in which the technology of simultaneous production, ie the simultaneous production of electricity and heat, is implemented. Such facilities can use different power plants, namely gas and steam turbine power plants and other power plants. The main advantage of gas turbine-based power plants to other power plants is the increase in efficiency due to the use of waste gas heat not only in winter but also in summer [5]. Also in 2018, Kialashaki et al. Presented a linear programming optimization model for the optimal planning and size of CCHP systems. The purpose of this model was to design the CCHP system by considering both electric chiller and absorption chiller economically [6]. In 2018, LUO et al. Presented a comprehensive study on CCHP. The results of the case study showed that the optimal decision can be achieved by adjusting different levels of budget and considering the control of the model [7]. In 2019, Yang et al. In a study examined the summer refrigeration scenario and the comparison of two microgrids, of two types of buildings, with or without virtual energy storage. This paper concludes that compared to traditional optimization methods, the method of distribution of cooling, heating and power optimization improves every aspect in terms of economy, environment and energy [8]. In CCHP systems, energy storage is one of the most important issues. In 2019, Iranfar et al. Conducted a numerical study of nano-encapsulated phase change materials in a double-tube heat exchanger. In their research, in terms of energy, a fluid numerical study based on NPCM was performed in a heat exchanger. Numerical simulation results were validated using experimental heat transfer data. Reynolds and Nusselt numbers were evaluated using thermal conductivity and viscosity under the same conditions as the numerical model. The results showed a standard improvement compared to the base fluid [9]. In 2019, Hong et al., In a study, investigated the problem of heat pump evaporator freezing and poor low temperature performance in cold regions. In this study, an important reference for the combined and efficient application of CCHP systems and heat pump units was presented [10].

In 2020, Chen et al. Simulated a new CCHP system with advanced adiabatic compressed air energy storage technology (AA-CAES) as a link between wind energy production and internal combustion engine (ICE). Water and electricity capital costs, energy costs and environmental protection costs were examined as indicators of system performance. They showed that, on a typical summer day, simultaneous strategy is the best solution [11]. Also, in two studies in 2020, Alimohammadi et al. Performed an energy and economic analysis of a combined CCHP-GSHP system. Heat and cold were studied. Each of these systems can be used alone as a supplier of heat and refrigeration demand, but their combination can provide higher capabilities in heat supply and refrigeration and is more cost-effective. A study conducted on a hospital found that using a combination of systems to generate electricity, heat and cold and a geothermal heat pump at the same time would provide more energy-efficient results [12], [13]. In 2020, Marques et al. Performed energy, exergy, and economic evaluations for a natural gas-fired production unit, including an internal combustion engine (ICE) and an absorption refrigeration system. The energy system was designed to meet the electricity and cooling needs of a university building. Analysis of energy and exergy parameters (first and second laws of thermodynamics) was performed [14]. In 2021, Wang et al. Showed in a study that thermal energy storage (TES) can improve the energy efficiency of CCHP systems. The results showed that when the nominal capacity of TES is more than a certain value, the cost of optimal performance does not change significantly [15]. In 2021, Song et al. In an article summarized the classification, development history, and status of shallow GSHP use in China. Also, several typical engineering cases of GSHP technology were identified and analyzed. Finally, promising development trends and some advanced technologies were demonstrated [16]. In 2021, Kumar et al. Showed in a review study that the gas turbine (GT), the organic Rankine cycle, and the Kalina cycle are the basis of major heat recovery technologies. An important step in improving the efficiency of a renewable energy source. It is done by integrating cooling, heating and power cycle with the reproduction cycle [17]. Also in the same year, Golchoobian et al. Conducted an economic evaluation of a new system for generating electricity, refrigeration, and fresh water using energy recovery at natural gas pressure reduction stations. The results showed that the period of return to electricity prices is very sensitive. [18]

In 2021, Sanaye et al. In a study proposed a combined cooling, heating and power system suitable for a residential complex, with two new cycles in the hot and cold seasons. With a comprehensive modeling method (in four aspects of energy, exergy, economy and environment), the system was optimized for variable electrical loads, heating and cooling during one year [19]. Also, when the excess heat of an energy system is very low, waste heat can be used by combining this system with a small desalination system. In 2021, Yanbolagh et al. Conducted an experimental study on the performance of a small desalination system with different heat sources. This study was conducted from the perspectives of energy, exergy and economic analysis [20].

One of the systems that has a high potential in combination with other systems is the Allam cycle. In 2021, Dokhaee et al. Simulated the Allam cycle with carbon dioxide working fluid and compared it to the Brayton cycle [21]. The Allam cycle is a new approach to reducing CO2 emissions. In this cycle, combustion of oxy fuel and carbon dioxide (CO2) is used. Also in the same year, in two studies, Nazarzadehfard et al. And Ahmadi et al. Performed thermal and economic analysis of the MED combined desalination system and the Allam power generation system. In conventional desalination plants, a boiler is used to supply steam to the desalination system, but in their research, the excess heat of the Allam system has been used. Ideally, the price of fresh water using steam generated by the boiler would be $ 1,131 per cubic meter, and the steam generated by the power generation system would be $ 1,087 per cubic meter [22], [23]. Also in 2021, Riyahi et al. Proposed a system that, in addition to generating electricity on Kish Island, also produces fresh water. In newer systems, in addition to generating electricity, cooling, and heating, fresh water production is also a very important product [24].

The aim of the present study is to analyze the exergy and economics of the combined Allam cycle and the absorption cooling cycle. In the following, after introducing the power generation cycle and the cooling cycle, modeling and analyzing the results are presented.

2. MODELING

A schematic of an absorption cooling system is shown in Figure (2). When vapor leaves the evaporator, it is absorbed in lithium bromide. The pressure of this solution is increased by the pump and the water is boiled and separated from the solution by the excess heat received from the heat source in the generator, then the water goes to the condenser like a normal cooling system. Finally, the liquid, which contains a very small amount of water, returns to the absorber. The useful output energy for the absorption cooling system is the heat taken from the evaporator, While the energy entering the system is the heat entering the generator.

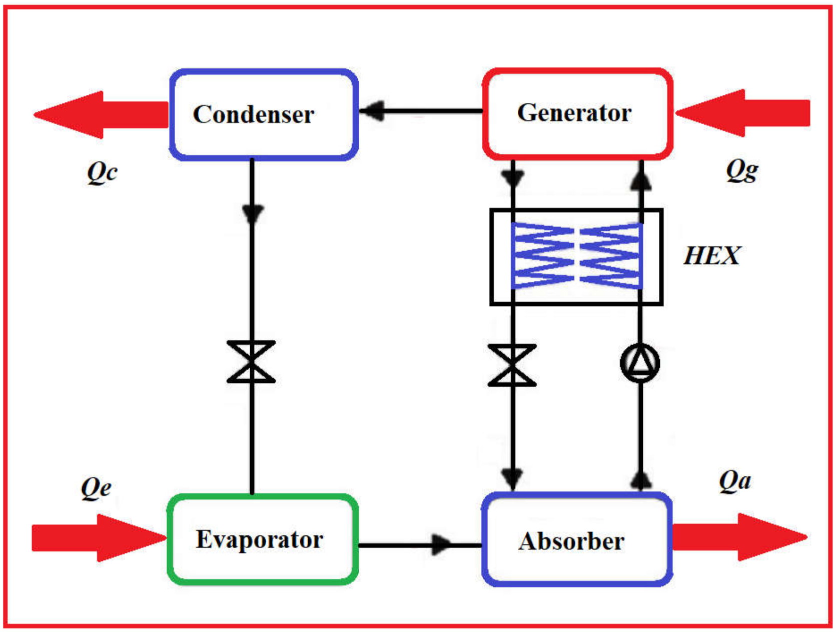

Figure 2- Schematic of the absorption cooling cycle

Figure (3) shows the combined cycle of Allam and absorption cooling. As can be seen, the waste heat of generation cycle can be used to start the cooling system.

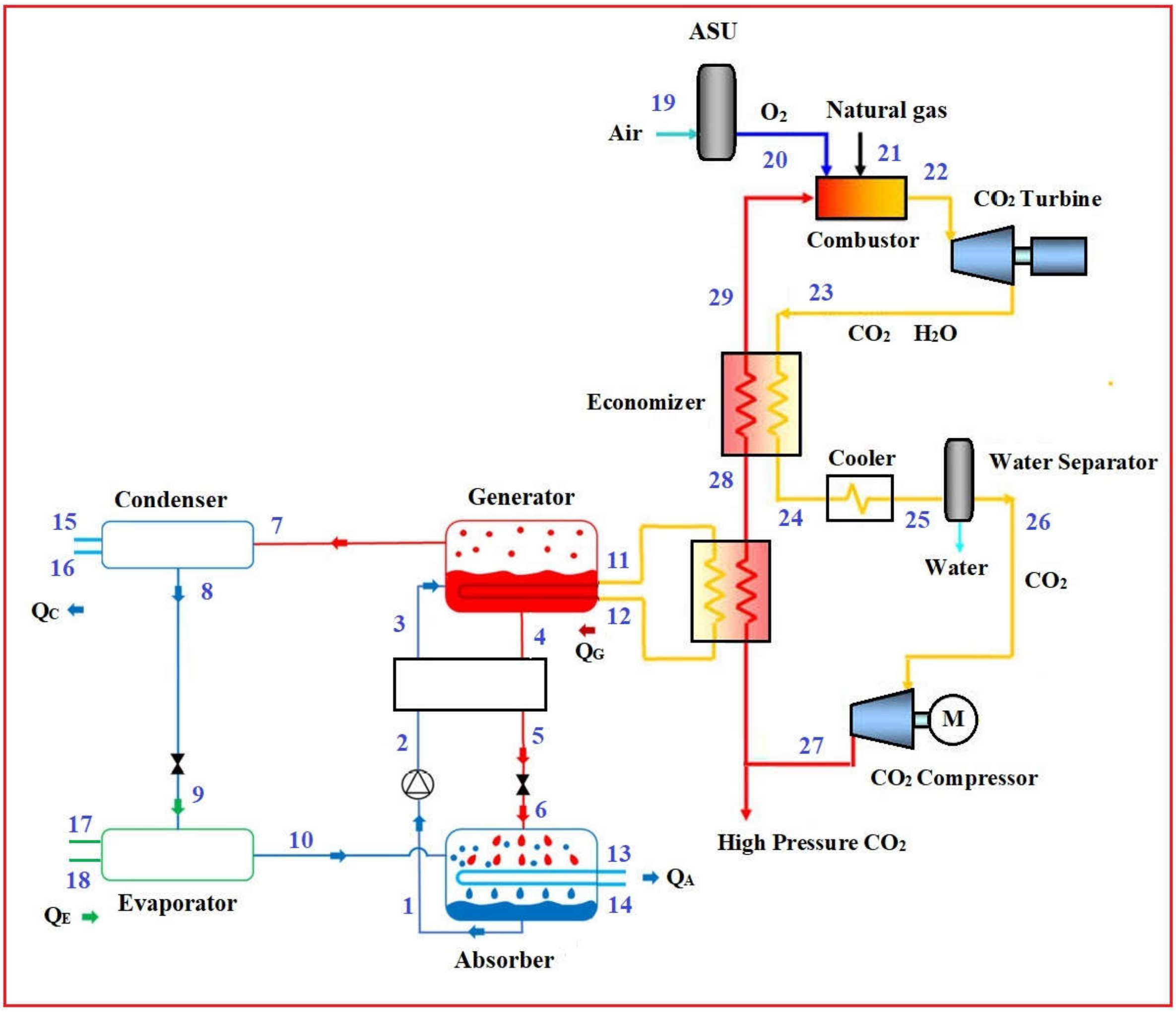

Figure 3- Schematic of the combined cycle of Allam and absorption cooling system

Thermodynamic, exergetic and economic analysis

For thermodynamic analysis, the law of mass conservation and the first and second laws of thermodynamics are expressed for each component of the system. Each component is considered a control volume that has input and output currents and work-heat exchanges. Equations 1 and 2 show the mass conservation in steady state and steady flow (SSSF). The first law of thermodynamics is actually the energy balance for each component and is written as Equation 3, and the COP of the absorption cooling system is defined as the ratio of the heat load of the evaporator to the heat load of the generator, which is expressed in Equation 4.

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

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

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

$$COP_{cooling} = \frac{Q_E}{Q_G} = \frac{\dot{m}_{10} h_{10} - \dot{m}_9 h_9}{\dot{m}_4 h_4 + \dot{m}_7 h_7 - \dot{m}_3 h_3} = \frac{\dot{m}_{17}(h_{17} - h_{18})}{\dot{m}_{11}(h_{11} - h_{12})} \tag{4}$$

By ignoring the term related to chemical exergy, the specific exergy of a stream is defined by Equation 5. It is also obtained by ignoring the terms related to kinetic exergy and the potential of Equation 6. The second law efficiency or exergetic efficiency is defined as the ratio of product exergy to fuel exergy of a system. For example, for an absorption cooling system, equation 7 is calculated. In an absorption cooling system, the product is the cooling load of the evaporator and the fuel is the heat load given to the generator from a heat source. Also, the exergy balance is calculated from Equation 8 and the irreversibility is calculated from Equation 9. From an economic point of view, the relationship between Total Investment Cost Rate and Total Cost Rate is also expressed in Equation 10.

$$\varepsilon = (h - T_0 s) + \frac{1}{2}V^2 + gz - (h_0 - T_0 s_0) \tag{5}$$

$$\varepsilon = (h - T_0 s) - (h_0 - T_0 s_0) \tag{6}$$

$$\psi = \frac{\dot{E}_P}{\dot{E}_F} = \frac{\dot{E}_E}{\dot{E}_G} = \frac{\dot{m}_{17}\left[(h_{17} - h_{18}) - T_0(s_{17} - s_{18})\right]}{\dot{m}_{11}\left[(h_{11} - h_{12}) - T_0(s_{11} - s_{12})\right]} \tag{7}$$

$$\dot{E}_W = \sum \dot{E}_Q + \sum (\dot{m}\varepsilon)_i - \sum (\dot{m}\varepsilon)_o + T_0 S_{gen} \tag{8}$$

$$I = T_0 S_{gen} \tag{9}$$

$$\dot{C}_{P,tot} = \dot{C}_{F,tot} + \dot{Z}^{CI}_{total} + \dot{Z}^{OM}_{total} \tag{10}$$

3. RESULTS AND DISCUSSION

All equations of mass and energy conservation and irreversibility relationships as well as relationships related to economic exergy analysis are arranged in different components of the combined cycle, respectively.

Figure (4) shows the effect of the pressure ratio on the exergy efficiency, as shown by the increase in the pressure ratio of the exergy efficiency decreases.

This is because by increasing the pressure ratio, the pressure difference created increases the exergy destruction and in this case the exergy efficiency decreases.

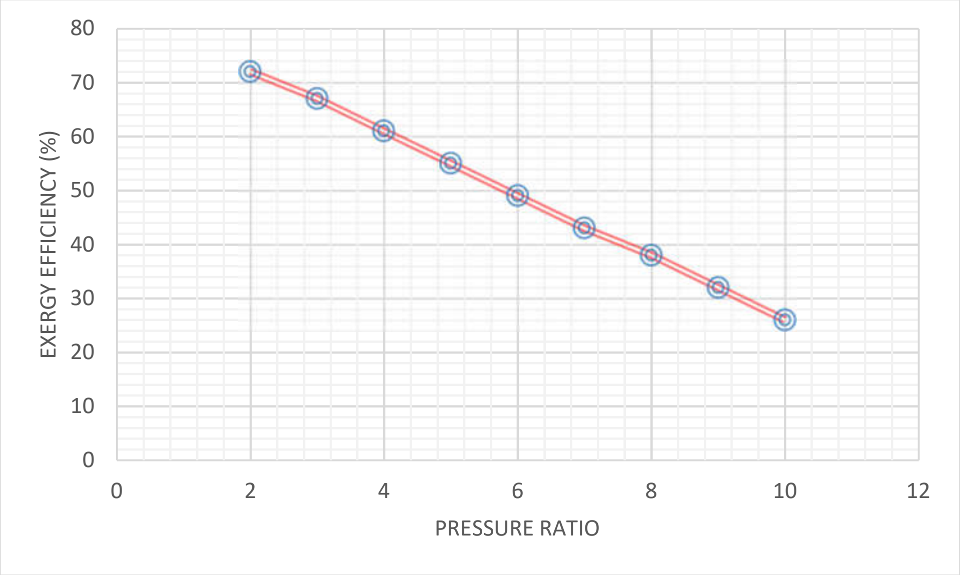

Figure 4- Exergy efficiency in terms of pressure ratio

Figure (5) shows the Total Investment Cost Rate in terms of Pressure Ratio. As can be seen, as the pressure ratio increases, the Total Investment Cost Rate increases, while as the pressure ratio increases from 2 to 10, the Total Investment Cost Rate increases from $ 1.4 per second to $ 1.48 per second.

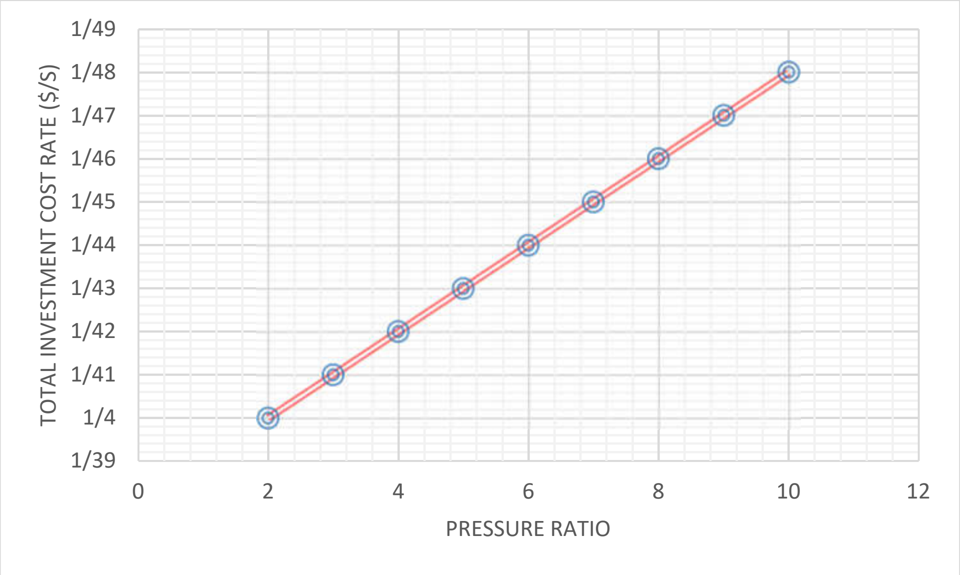

Figure 5- Total Investment Cost Rate in terms of pressure ratio

In Figures (6) and (7), the effect of changing the compressor pressure ratio on the Total Cost Rate and Exergy Destruction Cost can be seen. Increasing the compressor pressure ratio has a complex effect on the Total Cost Rate and Exergy Destruction Cost of the various components, which ultimately increases the Total Cost Rate. In this case, the Total Cost Rate decreases in all components of the absorption cycle and increases in all components of the power cycle.

In the power system, the cost of the compressor, cooling converter and production system increases and decreases in the rest of the components, which in total has the effect of more increments and increases the Exergy Destruction Cost.

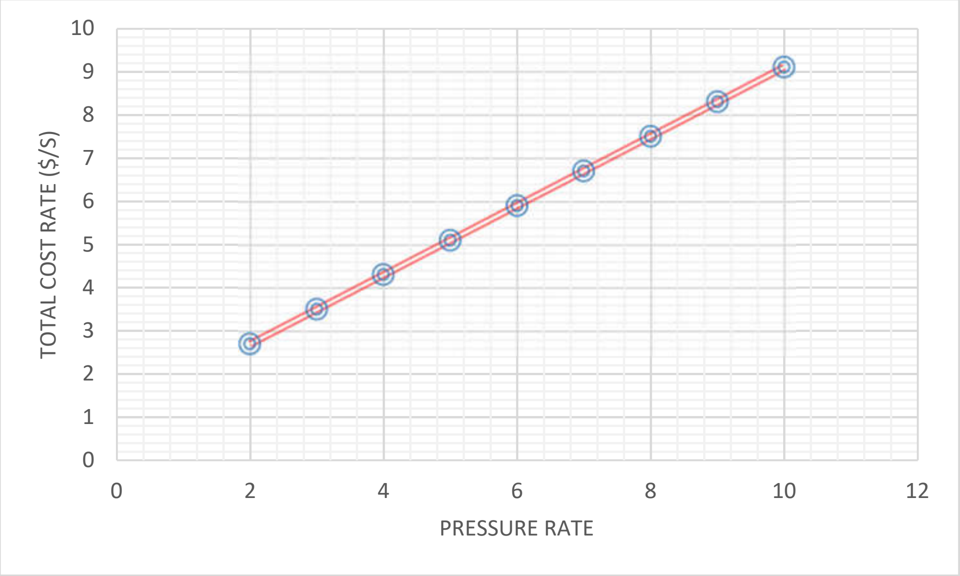

Figure 6- Total Cost Rate in terms of pressure ratio

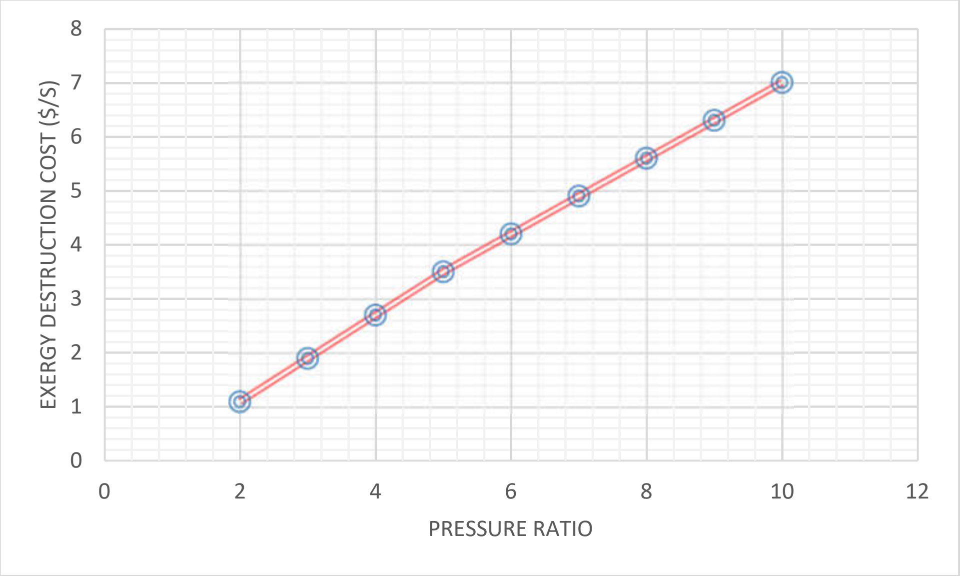

Figure 7- Exergy Destruction Cost in terms of pressure ratio

Figures (8) and (9) show how the COP changes with the temperature of the hot water entering the generator and the temperature of the cooled water entering the evaporator, respectively. As shown in Figure (9), The COP of the system increases as the temperature of the hot water entering the generator increases. The reason for this increase is that as the temperature of the hot water entering the generator increases, the refrigerant in the generator is easily separated from the solution and its quality increases, which has a positive effect on the COP of the system. The COP of the system also increases as the temperature of the cooled water entering the evaporator increases. This increase occurs because if the temperature of the cooled water entering the evaporator increases, the heat absorbed by it is increased by the refrigerant and an increase in the amount of heat absorbed increases the COP of the system.

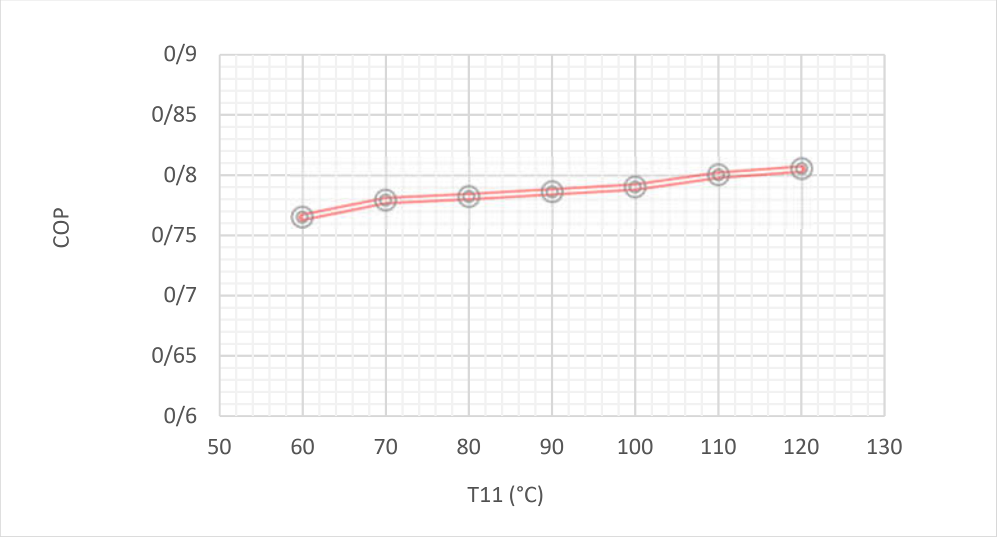

Figure 8- COP in terms of hot water temperature entering the generator

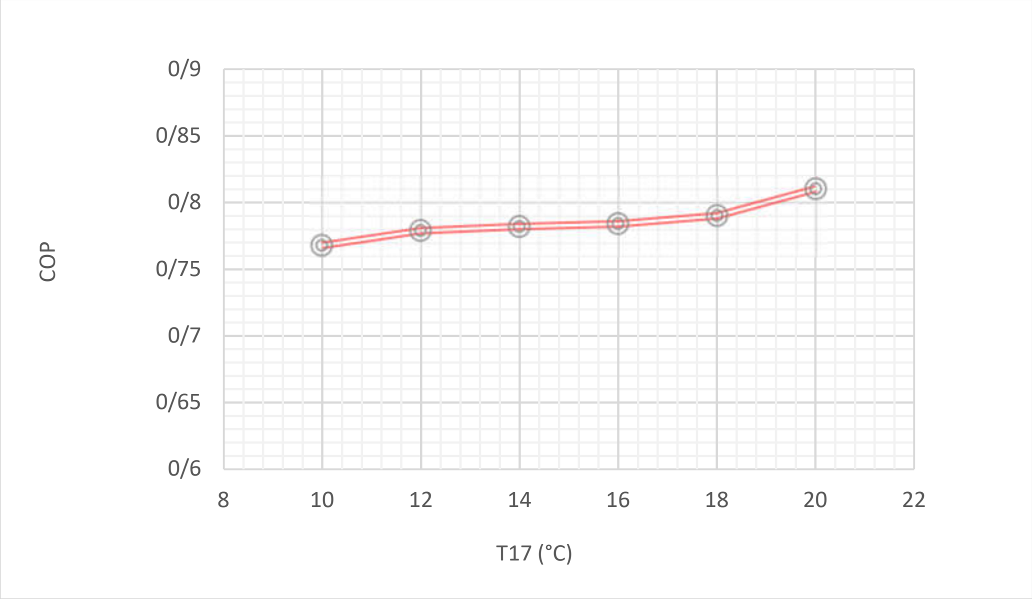

Figure 9- COP in terms of cooled water temperature in the evaporator

Figure (10) shows the exergy efficiency in terms of the hot water temperature entering the generator. Also, as Figure 10 shows, with increasing (T_{11}), the exergy efficiency decreases. This can be analyzed by the fact that although a system with a high temperature of the heat source produces hot water with a higher temperature of (T_{11}), but the amount of input exergy and the amount of exergy loss that occurs during the heat transfer process in the generator; it becomes more.

Figure (11) also shows the exergy efficiency in terms of the temperature of the cooled water entering the evaporator. Exergy efficiency decreases with increasing (T_{17}). In other words, the absorption cooling system, which has a lower cooling water inlet temperature to the evaporator, has a higher exergy efficiency. The reason for the decrease in exergy efficiency with (T_{17}) is that if low-temperature cooled water enters the evaporator, the energy expended to generate cooling decreases and thus the exergetic efficiency increases.

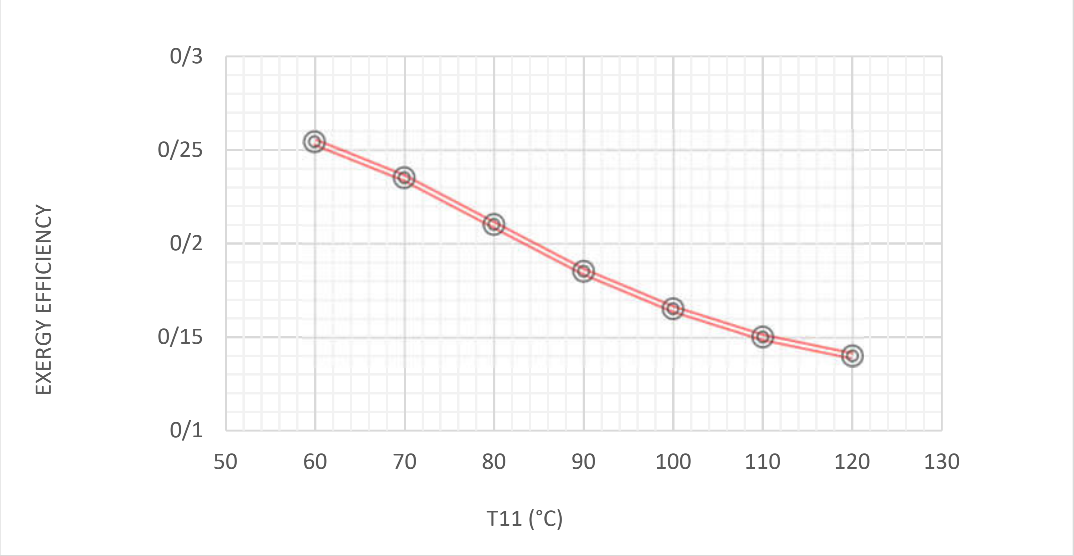

Figure 10 - Exergy efficiency in terms of hot water temperature entering the generator

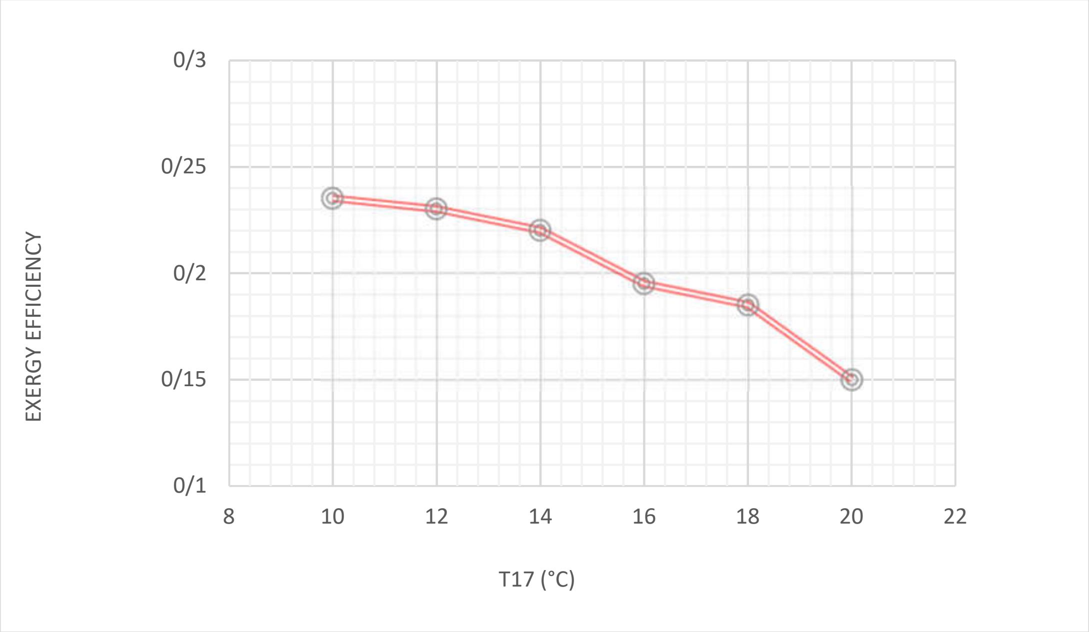

Figure 11- Exergy efficiency in terms of cooled water temperature in the evaporator

4. CONCLUSION

In the present study, the performance of the combined cycle of Allam and absorption cycle was simulated and analyzed from the perspective of energy, exergy and economics, and the results show that the total exergy efficiency was 0.72 for the combined cycle. In addition, using the first and second laws of thermodynamics, the effect of changing the system design parameters on economic parameters, coefficient of performance and exterior efficiency of the system have been investigated and compared. It was further determined that the maximum amount of exergy exergy destruction in the cooling cycle is in the combustion chamber, turbine and compressor. Turbine and cycle compressor are introduced as components that should be considered more than other components in terms of exergy, because the highest cost rate belongs to these components. Also, the results of parametric analysis are that increasing the compressor pressure ratio has a negative effect on the overall cycle performance, so that it reduces the work and overall exergy efficiency and increases the overall cost rate. Also, the study of changing the compressor pressure ratio has the greatest effect on the performance of the combined cycle, so that changing the pressure ratio in the range of 2 to 10 results in a 63% reduction in exergy efficiency. Surveys showed that as expected; The performance of the system increases with increasing temperature of the cooled water in the evaporator. Exergy efficiency works exactly the opposite of system performance.

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