HYDROGEN, FUEL CELL & ENERGY STORAGE

Multi-objective optimization of a combined heat and power (CHP) cycle with a solar collector: energy, exergy and economic point of view

Saman Abdali | Somaye Yaghoubi*

Department of Mechanical Engineering, Najafabad Branch, Islamic Azad University, Najafabad, Iran
Aerospace and Energy Conversion Research Center, Najafabad Branch, Islamic Azad University, Najafabad, Iran
* Corresponding author, Email: s.yaghoubi@pmc.iaun.ac.ir

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Abstract

In this study, the effect of different parameters on the energy, exergy and economic analysis in a combined heat and power (CHP) cycle was investigated. The optimization was based on a defined target function, exergy efficiency and total cost rate based on functional modelling in both hot and cold climates. The temperature of the condenser, turbine and pinch and also mass fraction of the heating section were used to optimize the CHP cycle using genetic algorithms. The main goal is to increase the efficiency of the exergy and reduce its production costs. To increase the power, it is necessary to increase the inlet temperature to the turbine and reduce the condenser pressure. The results showed that based on the use of the heating section and increasing the mass fraction in this section, the cycle efficiency can be increased up to 21%, in which, the production power was calculated to be 6.4 kW. The findings also showed that by improving its performance, the solar sector can improve the exergy efficiency of the cycle by reducing the fuel flow rate.

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1 Introduction

One of the most effective topics in the economic development in the modern world is the optimal consumption of energy [1, 2]. Therefore, some researchers analyze their simulations numerically [3, 4]. The move towards energy optimization has been going on in the world for many years, and industrialized countries have made significant gains in return for this move while raising environmental standards. Today, these countries consider energy optimization and management as a new source of energy [5, 6]. Meanwhile, one of the most important energy optimization strategies implemented in all these countries is the use of simultaneous generation of electricity, heat and cold with the aim of increasing energy efficiency and efficient use of fuel resources [7, 8]. The use of cogeneration systems is one of the most important solutions in the world to solve energy-related problems, such as increasing energy demand, increasing energy costs and environmental concerns [9, 10]. Simultaneous generation of electricity, heat, and cold is an energy supply system in which the required electrical energy is generated by a primary actuator and heat dissipated from the primary actuator is recovered to provide heating, hot water, and cooling [11,12]. On the other hand, the increasing consumption of limited resources of fossil fuels and their devastating effect on the environment has drawn the world's attention to the use of renewable energy [13,14]. According to the development of these strategies, in this research, thermodynamic analysis and optimization of a combined heating and power (CHP) cycle for a building coupled with solar energy in both hot and cold climates is investigated [15, 16].

Cogeneration systems are used as one of the most effective solutions to supply building energy in the commercial and residential parts. In addition to meet the energy needs of the building at the same time, these systems reduce energy consumption due to their high energy efficiency. As a result, the consumption of fossil fuels is reduced, which leads to significant savings in consumer energy costs as well as a reduction in environmental pollutants [17,18]. In recent years, various thermodynamic analyses have been performed to improve the performance and optimal use of such systems with the main non-solar and solar actuators [19, 20]. Some researches in this field will be mentioned in two groups with the main non-solar and solar stimuli as follows.

1.1 Previous researches with non-solar stimulus

These different thermodynamic analyses in the construction sector have been developed and extracted by various research groups in order to improve performance and optimal use [21, 22].

In [23] a theoretical study predicts the performance of a micro steam turbine of a bladeless jet engine, under given conditions, while an experimental study is carried out to obtain the performance factors. Turbine loss values and reasons for losses have been determined by comparing theoretical and experimental results. The results show that if the turbine performance can be increased by improving the turbine performance, the bladeless jet propulsion micro steam turbine can be used for micro-CHP systems in industrial and residential sectors.

In [24] the system including a cooling, heating and power (CCHP) system driven by a main gas turbine engine and an auxiliary boiler system (CCHP-Boiler) in a dairy plant is studied. The system under study is optimized based on three different objective functions: Exergy efficiency of the system, annual total cost of the system and comprehensive objective function.

In [25] presented an article entitled "selecting the type of primary actuator for cogeneration systems". The three primary types of propulsion investigated in this study were gas turbine, diesel engine and gas engine. For each of these three types of primary stimuli, separately, the steps of selecting the number and determining the nominal power were performed. In the end, the amount of real annual profit, to provide the specific need for power and heat, in economic operation, was achieved by choosing a gas turbine of 3.1 MW or a diesel engine of 2.3 MW or a gas engine of 3.1 MW.

In [26] probed a CHP and their results showed that using this system can provide all the thermal and electrical needs of a building and its overall efficiency is higher than individual systems.

In [27] optimized and designed a home-scale cogeneration system. Several different modes were considered to provide the heating and electrical needs of the building and their results led to a reduction in fuel consumption and environmental pollution.

In [28] optimized the fluidity of the combined cooling, heating and power system for residential applications. In this study, they selected the common working fluids, R-134a, R-11, R-123, R-16, to recover the wasted heat in the internal combustion engine through the exhaust gas, and observed that R-11 was a good fluid to maximize efficiency and exergy and minimize the total cost of the system.

In [29] evaluated the energy, exergy and economics of a CCHP system using internal combustion engines and gas turbines as the main drivers for a residential complex in Iran. For this purpose, three types of gas engines, diesel engines and gas turbines as the main actuators were presented separately and simultaneously in six different scenarios. Finally, a suitable scenario was chosen for the CCHP system, which is a combination of a gas engine and a diesel engine. In this case, energy efficiency was 87%, exergy efficiency was 62.8% and operating cost reduction was about 80%. They also calculated the payback period of 6.3 years without considering the interest rate and 1.36 years without considering it.

A novel ammonia-water mixture CCHP system by a low temperature heat source, which is a modified version of a Kalina cycle, was proposed in [30]. The energy and exergy efficiencies of this system are 49.8% and 27.7%, respectively. It is also found that the condenser has a major share in the irreversibility of the system with an exergy degradation.

The thermodynamic analyses of different scenarios in a CCHP system with micro turbine–Absorption chiller, and heat exchanger have been investigated in [31]. In this study, not only the thermodynamic parameters but also the amount of carbon dioxide emitted from the power plant are evaluated based on different scenarios.

1.2 Previous researches with solar drive

The design of a smart building energy system is presented in [32], where solar photovoltaic thermal (PVT) panels are integrated with a heat storage tank to supply a significant part of the building's heat and power needs. The proposed system has no batteries, and may interact bi-directionally with both local heat and power grids. The results show that the presented system supplies the entire building with annual domestic hot water, as well as produces 402.8 cubic meters of hot water at 40 °C for sale to the district heating network. 2,083 kWh of electricity was bought from the grid, against 1,938 kWh of electricity sold, in other words, the annual electricity cost of the building is almost compensated.

Numerical and experimental study of energy and exergy performance of thermal, photovoltaic and solar thermal photovoltaic modules based on roll-band heat exchangers with three different channel geometries was performed in [33]. Simulation of PV/T electrical properties with all three types of absorbers showed the highest average solar-to-electric energy efficiency (14.5%) in bionic adsorption mode compared to PV/T with parallel and series absorbers (14.4%, and 14.3%, respectively).

In another study, in [34] performed a thermodynamic evaluation of a new combined cooling, heating, and power system of electricity generation, heating and cooling driven by solar parabolic collector collectors for the Faculty of Engineering, Urmia University. For summer, energy and exergy analyses show that the energy efficiency of the system in solar, storage and storage are 98%, 47.3% and 98%, respectively. Based on this, exergy efficiencies are 17%, 8.3% and 17%, respectively.

In [35] evaluated the energy and exergy of a new CCHP system based on a parabolic solar stud collector in a building. They showed that the cooling, heating and electricity production of this system are equal to 8.55 kW, 9.35 kW and 7.16 kW, respectively, with an exergy efficiency of 9.8%.

In [36] performed energy, exergy and environmental analysis of a hybrid combined cooling heating and power system integrated with compound parabolic concentrated-photovoltaic thermal solar collectors. The results showed that energy and exergy efficiencies in design conditions are 63.3% and 21.8% in summer and 61.8% and 27.1% in winter, respectively. Compared to solar-free CCHP, the hybrid system has more flexibility in adjusting the heat-to-electricity ratio.

In [37] investigated the performance of a hybrid system consisting for combustion in internal engine, heat pump for absorption, solar collectors for heating and a heat storage tank based on energy analysis, exergy, economic exergy and environmental exergy. According to the results of their study, if it is compared with a CCHP system, the hybrid system consumes 11.3% less natural gas, which reduces CO_2 emissions and the payback period to 1 year.

In [38] performed monthly evaluations of exergy, economic and environmental indicators, and optimization of a micro-CCHP based on the dual Rankin organic cycle using water fluids and water/copper oxide Nano-fluids. The main design parameters of this study include thermodynamic efficiencies, total product cost, and environmental impact rates (EI) for the four selected organic fluid groups. In addition, two well-known decision-making techniques including TOPSIS and Linamp have been used to identify the optimal system performance between the results obtained using the NSGA-II genetic algorithm.

1.3 Research purpose and innovation

Reviewing the research of the past years in the field of CHP and CCHP technology and multi-objective cycles, it is clear that the interest and attention to them is increasing day by day and they are a key technology to reduce energy consumption and achieve greater efficiency. The use of CHP technology in Iranian industry is up to date. So far, practical research has been done in this field, and due to energy limitations and functional importance, it requires more extensive research [39,40].

The purpose of this study is to investigate the changes in CHP cycle exergy efficiency and the effects of various component parameters on the energy, exergy and economic analysis of the cycle as well as cycle optimization based on the definition of objective functions in terms of design parameters. In this study, the optimization operation is performed with the objective functions of energy efficiency, exergy efficiency and total product cost rate based on performance modeling for the cycle. Then rate of flow in turbine, pressure drop and area ratio in ejector and some other parameters are choosing for designing the parameters. Further, analyses are performed for both hot and cold climatic conditions of Iran. In this case, the thermal radiation and the amount of heating and cooling load required for these two climates are different according to environmental conditions. These technologies are key to reducing energy consumption and achieving greater efficiency. The system examined in this research, due to the novelty of the proposed cycle, had provided the ability to use it for various purposes, so that by opening and closing several valves, the system structure can be changed from CHP to CCP. The innovation of the study is briefly stated as follows:

- Performing optimization operations based on performance modeling for the cycle.
- Investigating changes in the exergy efficiency of the CHP cycle.
- Examining the effects of different parameters of the components.
- Optimizing the cycle based on the definition of the objective functions according to the design parameters.

1.4 Research structure

In the following, after the introduction that was presented in relation to the research topic and some related backgrounds in this chapter, the problem will be stated and analysed. Then, in the third part, the results of the CHP system study are validated, reviewed and analysed. Finally, the conclusions of this study will be expressed.

2 System description and analysis

The schematic of the CHP cogeneration system is shown in Figure 1. This solar-powered system consists of two primary solar-driven subsystems and CHP, in which the collector is selected to absorb solar radiation. The primary solar actuator subsystem includes a solar collector, a heat storage tank and an auxiliary heater. Flat panel collector was chosen to gather solar energy due to its cost and widespread use. A heat storage tank is used between the supply of solar energy and the need for a heat source under the CHP system, so that the system can operate stably and continuously around the clock. The heat transfer medium within the solar collector subsystem consists of CuO/water Nanofluids. Due to the unpredictable nature of solar radiation and the possibility of failure in collector facilities, an auxiliary heater is activated to increase the outlet temperature of the heat storage tank.

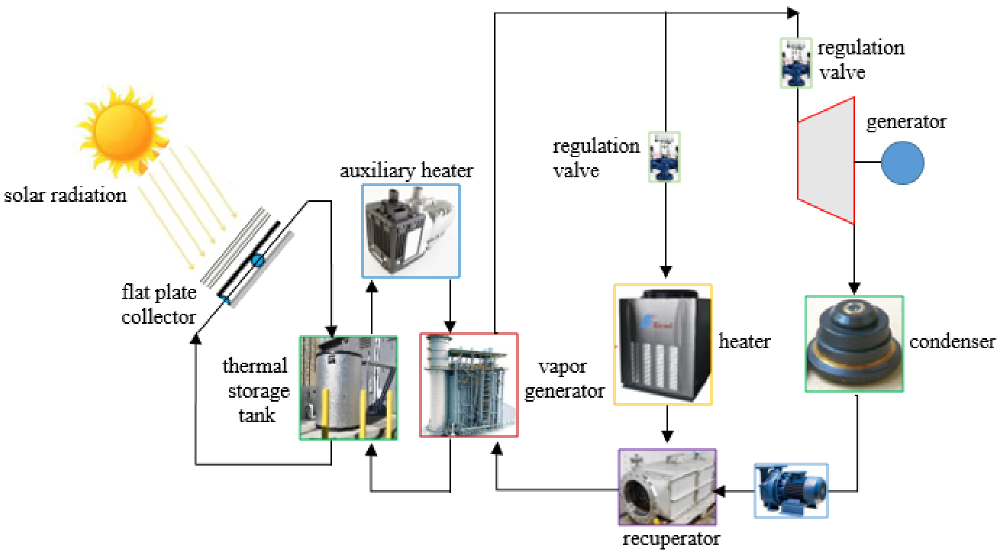


Fig. 1. CHP system studied

In this system, the solar collector absorbs the heat caused by the sun's radiation and transfers the heat to the heat storage tank through the flow of fluid in the panel through the pipes installed in it. In this subsystem, the operating fluid in the steam generation section absorbs the heat and turns into steam and enters the power generation turbine and after leaving the turbine, gives the extra heat to the heater for heating. After using the heat of the working fluid, the rest of the heat is absorbed in a cooler and the working fluid becomes liquid. For thermodynamic modeling, system temperature distributions, enthalpies, input and output exergy flow rates from each component, and exergy degradation rates are obtained.

3 Thermodynamic analysis and governing equations

In this section, for thermodynamic analysis, the equations of mass survival, energy, exergy, second law and economic analysis of the system are examined.

Mass conservation equation The law of mass conservation is a constitution in the analysis of any thermodynamic system [41]. For a typical control volume is defined as follows:

$$\sum_i \dot{m}_i - \sum_e \dot{m}_e = \left(\frac{dm}{dt}\right)_{\text{c.v}} \tag{1}$$

Energy conservation equation The energy balance equation known as the law of conservation of energy, is defined for a control volume with one input and one output [42, 43]:

$$\left(\frac{dE}{dt}\right)_{\text{c.v}} = \dot{Q} - \dot{W} + \dot{m}_i\left(h_i + \frac{v_i^2}{2} + gz_i\right) - \dot{m}_e\left(h_e + \frac{v_e^2}{2} + gz_e\right) \tag{2}$$

Entropy equation The entropy equation is related to system losses [44]. The entropy produced in processes is named entropy production with the symbol S_{gen} and then is defined a control volume by the following equation:

$$\dot{S}_{\text{gen}} = \sum_e \dot{m}_e s_e - \sum_i \dot{m}_i s_i - \sum_k \frac{\dot{Q}}{T_k} + \frac{dS_{\text{c.v}}}{dt} \tag{3}$$

Efficiency of thermodynamics first law This efficiency is defined as net work rate of production to input energy rate. This is called efficiency of thermodynamics first law [45, 46].

Efficiency of the second law The definition of this efficiency is the rate of exergy consumed to the rate of exergy received.

Heat transfer exergy The exergy of heat transfer from a control volume is equal to what can be achieved by the interaction of heat and the outside environment [47, 48]. For a heat transfer rate Q at transfer temperature T, the maximum available work is:

$$\dot{E} = \dot{Q}\tau \tag{4}$$

In the above relation, τ is called dimensionless exergy temperature, and in the case where the heat transfers between the system and the environment is at temperature T_0, it becomes the same efficiency of the Carnot cycle.

$$\tau = 1 - \frac{T_0}{T} \tag{5}$$

The terms related to flow availability b and exergy of flow e_x can be expressed as follows in equations (6) and (7), respectively:

$$b = h - T_0 S \tag{6}$$

$$e_x = b - b_0 = \dot{h} - \dot{h}_0 - T_0(S - S_0) \tag{7}$$

Economic equations The cost of each system component must be known to obtain the initial cost and maintenance of the system [49, 50]. Term $\dot{Z}_k$ is equal to the sum of investment, performance and maintenance costs of each system component and is obtained from the following relation:

$$\dot{Z}_k^T = (\text{CRF} \times \varphi)\dot{Z}_k \tag{8}$$

So that CRF and φ is the return on investment coefficient and maintenance coefficient, which is 1.06.

4 Results of CHP system investigation

The present system is a combination of power generation and heating system that provides power to the system with a plate collector and auxiliary heating system. High temperature production due to the effects of solute deposition in water and burn of pipes in plate collectors has caused the temperature above 77 degrees and steam production to be avoided. For this reason, an auxiliary heating system has been used in the mentioned system. As can be seen from Figure 1, the CHP cycle in question is separated by a valve, the output current of the generator into two parts. In Table 1, the data for system modeling are considered as code inputs. Based on the input conditions according to this table, the simulation results of the present study can be validated. In this table, the simulation results of the present study are compared with the results of those of Wang et al., [51]. It can be seen that the results have acceptable accuracy and error.

Table 1. CHP cycle validation results (s: simulation data simulated with s subunit specified)

Properties \ Points	1	2	3	4	5	6	10
T (°C)	10.34	15.66	72.55	33.67	33.67	10.11	50.00
T_s (°C)	9.96	15.29	72.55	34.94	34.94	10.11	50.00
P (MPa)	0.51	0.51	0.51	0.08	0.08	0.08	0.51
P_s (MPa)	0.65	0.65	0.65	0.08	0.08	0.08	0.65
ρ (kg/m^3)	1303.21	1364.68	27.16	4.46	4.46	1378.06	1268.18
ρ_s (kg/m^3)	1379.94	1366.04	26.21	4.44	4.44	1378.05	1268.79
h (kJ/kg)	213.42	220.32	460.42	433.21	433.21	212.98	266.32
h_s (kJ/kg)	212.98	219.88	456.74	434.38	434.38	212.98	266.32
S (kj/kg · K)	1.05	1.07	1.80	1.82	1.82	1.05	1.22
S_s (kj/kg · K)	1.05	1.07	1.78	1.82	1.82	1.05	1.22

As can be seen in this cycle, approximately 9 kW of heat is absorbed from the cycle for heating. The cycle at the turbine output has the highest entropy. Table 2 also shows the results of cycle exergy analysis. In this cycle, the exergy entering the cycle has the highest efficiency (exergy). Due to the cold season of the year and the low ambient temperature and the nature of the condenser temperature, it is observed that the exergy for the condenser points have negative values, which indicates the performance of these points in temperature and pressure below the reference point for exergy analysis.

Table 2. Results of CHP cycle continuity and exergy analysis

points	m (kg/s)	e_x (kJ/kg)	E_x (kW)
1	0.32	0.89	0.29
2	0.37	0.59	0.22
3	0.37	26.98	10.01
4	0.32	−10.20	−3.30
5	0.32	−10.20	−3.30
6	0.32	0.45	0.15
10	0.05	1.72	0.08

In Figures 2 to 5, the results of the validation show a slight difference between the simulated cycle and the reference [51], which is shown in the graph. The values obtained and the reference values for each part are rewritten as a table below each graph so that the absolute error of each part can be easily identified. Relative error values are also displayed as a percentage at the top of each graph.

In this cycle, as before, the sensitivity analysis on the cycle is done. As seen in Figure 6, with increasing solar radiation intensity in this cycle, due to the constant production power in the turbine, the exergy efficiency of the system decreases. According to the change in the exergy efficiency diagram, it can be seen that the cause of these changes is the net production power, which with the increase of solar radiation intensity, the exergy of the input fuel does not change the production of the system.

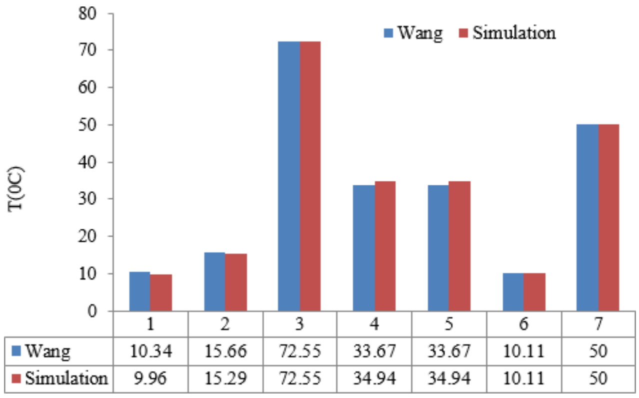


Fig. 2. Results of temperature study in CHP cycle.

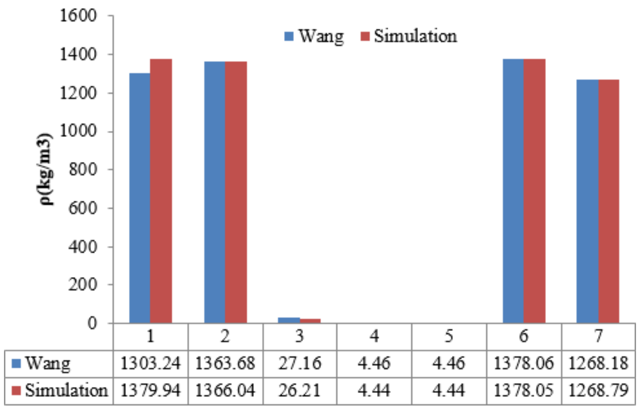
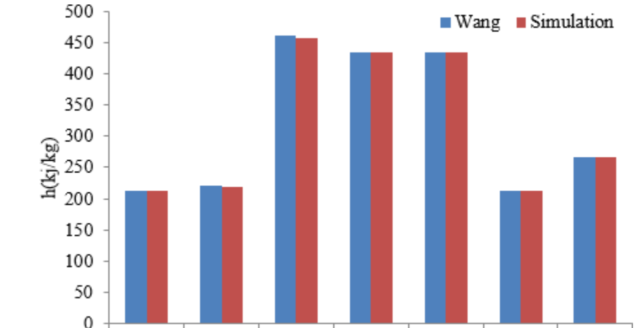
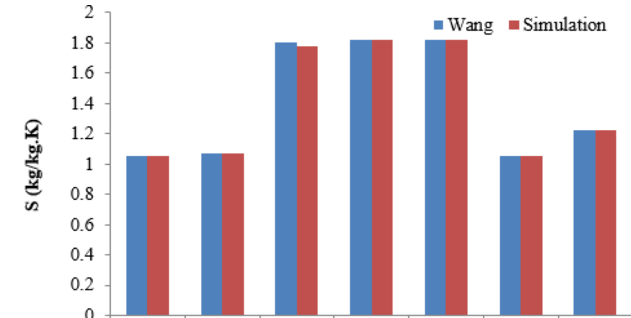


Fig. 3. Results of density study in CHP cycle.



	1	2	3	4	5	6	7
Wang	213.42	220.32	460.42	433.21	433.21	212.98	266.32
Simulation	212.98	219.88	456.74	434.38	434.38	212.98	266.32

Fig. 4. Results of enthalpy study in CHP cycle.



	1	2	3	4	5	6	7
Wang	1.05	1.07	1.8	1.82	1.82	1.05	1.22
Simulation	1.05	1.07	1.78	1.82	1.82	1.05	1.22

Fig. 5. Results of entropy study in CHP cycle.

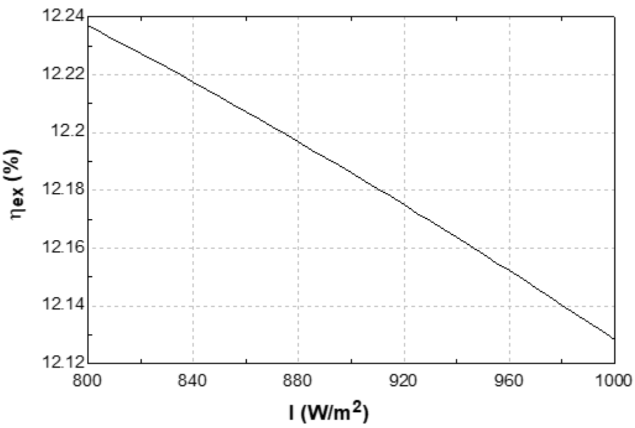


Fig. 6. Exergy efficiency changes with the intensity of solar radiation in the CHP cycle.

If the intensity of the radiation has an increasing trend, then the flow rate of the fuel consumed in the auxiliary converter will be decreasing. The reason for this is the increase in the temperature of the water leaving the plate collector. The trend of changes expressed in Figure 7 can be seen. Increasing the outlet water temperature indicates a decrease in fuel consumption, however, it was observed that the exergy efficiency has decreased due to no change in the heating product and power in the CHP cycle.

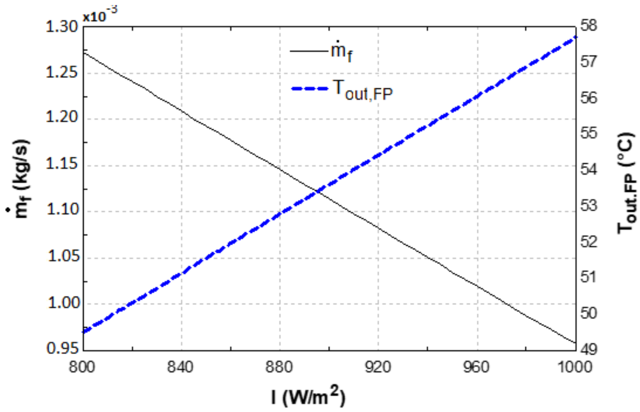


Fig. 7. Changes in auxiliary boiler fuel flow rate and outlet water temperature from plate collector by changing radiation intensity

By increasing the condenser temperature as shown in Figure 8, it can be seen that the net power of the cycle has a decreasing trend, which ultimately leads to a reduction in equipment costs. The reason for this is the increase in condenser pressure, which will increase the enthalpy of the output of the turbine and decrease the net power. As temperatures rise, so do turbine and condenser costs. This also reduces TAC costs.

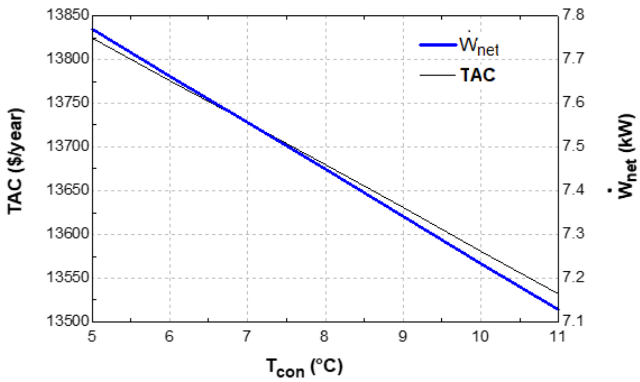


Fig. 8. Power and price changes in the cycle with changes in condenser temperature

Figure 9 shows the heating changes of the system. As the temperature of the condenser increases, then the heat absorption by the recuperate and the flow rate will increase, and this will increase the heating temperature. However, due to the decrease in production capacity, the exergy efficiency is reduced. Figure 10 shows that with increasing temperature in the condenser section, the thermal efficiency decreases. The reason for this is the reduction in production in the turbine sector.

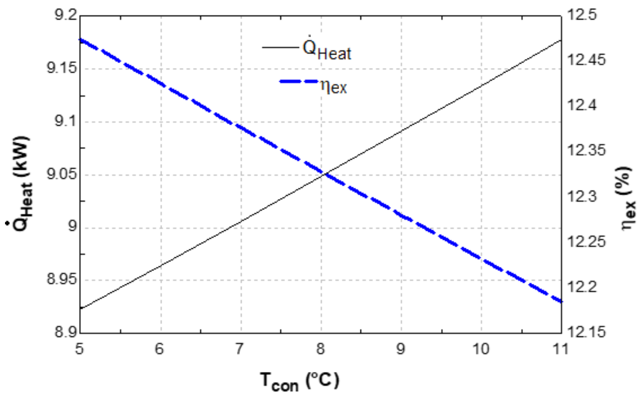


Fig. 9. Changes in system heating and cycle exergy efficiency with increasing condenser temperature

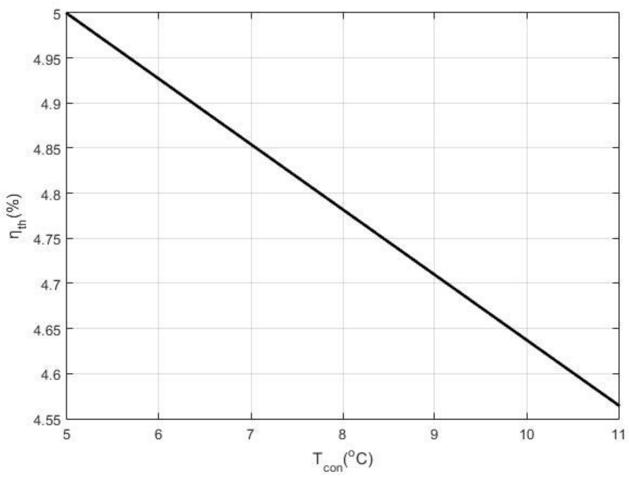


Fig. 10. Changes in thermal efficiency in the cycle with changes in condenser temperature.

In the optimization of the mentioned system, the parameters of condenser temperature, turbine temperature, pinch temperature and mass fraction of the heating section are used. In this optimization, the goal is to increase the efficiency of exergy and reduce its production costs. The results of the optimization in the beam curve are shown in Figure 11. What can be seen in this figure are the optimal points found by the genetic algorithm. In this study, one of the points can be examined and evaluated as an example. Table 3 shows the results and indicators of CHP cycle optimization.

In this study, CHP cycle optimization is the same method as the Multi-Objective Genetic Algorithm (GAmultiobj). This method is an effective multi-purpose optimization method and has been used to find multi-objective optimization solutions. The resulting points are found in the form of optimal points, known as the Pareto front. In this optimization, each point can be specified as the optimal point. In this analysis, one of the points of optimal parameters as well as its optimal indicators are examined. In this curve, any point on the Pareto boundary is potentially an optimal solution. A larger average exergy efficiency requires a larger annual cost. The maximum average exergy efficiency is defined as design point A, where the total annual cost is also at its maximum.

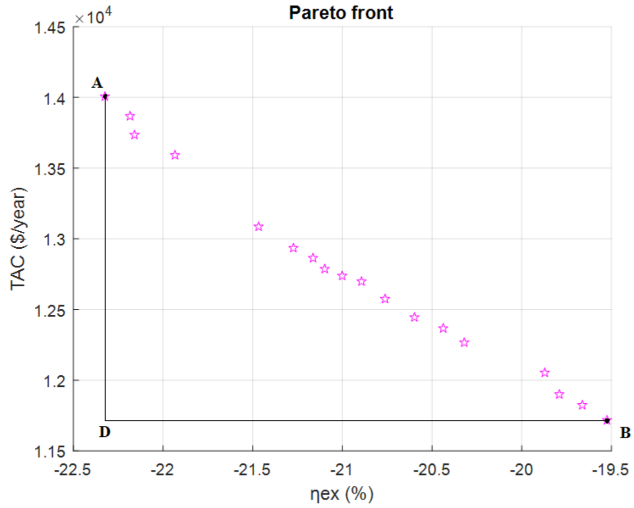


Fig. 11. Beam curve from CHP system optimization.

Table 3. Results and indicators of CHP cycle optimization

Parameter	Value
Turbine inlet temperature (°C)	17.17
Condenser temperature (°C)	7.14
Pinch temperature (°C)	11.59
Mass fraction (%)	30.0
Exergy efficiency (%)	21.46
TAC ($/year)	13085.78
Net power output of turbine (kW)	6.41
Auxiliary converter fuel consumption (kg/s)	0.0013
Heating system heating (kW)	23.04

The minimum annual cost is defined as design point B, which is also related to the minimum exergy efficiency. Design points A and B mean optimal single-objective performance solutions, respectively, with the average exergy efficiency or total annual cost selected as the objective function. Because it is impossible to achieve both goals optimally at the same time, there is no perfectly optimal multi-objective solution. The most optimal solution is multi-objective point D in the figure., which has the highest efficiency and lowest cost.

Therefore, in this research, the point that is closest to point D is the final solution in multi-objective optimization. Therefore, to achieve the final solution, the decision-making process is obtained with the help of a hypothetical point D, which is the intersection of maximum exergy efficiency and minimum annual cost. In this study, the closest point on the Pareto boundary to the hypothetical point D is considered as the final solution. At this point, the system achieves the best possible values by considering two target functions. Table 3 shows the optimal values of the objective functions and variables for the optimal point at the Pareto boundary.

5 Conclusions

In this study, an attempt was made to evaluate and optimize a CHP system. Based on coding and utilizing the properties of R245fa fluid, the mentioned system was simulated. The results showed that the choice of cycle parameters is effective in the final result in the CHP cycle. In the CHP cycle, the results showed that the condenser temperature, the inlet temperature of the turbine as well as the intensity of solar radiation are among the parameters affecting the system. In the optimization of the mentioned system, the parameters of condenser temperature, turbine temperature, pinch temperature and mass fraction of the heating section were used. In this optimization, the goal is to increase the efficiency of exergy and reduce its production costs. The optimization results were shown in the beam curve. These points are the optimal points found by the genetic algorithm. Then, the optimization indicators and parameters were expressed in a table. For this purpose, the method of multi-objective genetic algorithm (GA-multiobj) was adopted. This method is an effective multi-purpose optimization method and has been used to find multi-objective optimization solutions. The results also showed that based on the use of the heating section and increasing the mass fraction in this section, the cycle efficiency can be increased from 19% to 21% and the production capacity was calculated to be 6.4 kW. With this design, the heating system temperature reached more than 23 kW. The solar section cycle could be reduced with proper design to reduce the costs of the auxiliary system. In this study, the auxiliary system to natural gas inlet fuel was simulated. The results revealed that the solar part by improving its performance can improve the exergy efficiency of the cycle by reducing the fuel flow.

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