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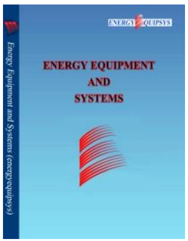

Evaluation of the optimum pressures of gas turbines based on energy and exergy analyses

Authors

Tohid Adibi[a]*
Omid Adibi[b]
Suvash Saha[c]

[a] School of Mechanical Engineering, University of Bonab, Bonab. Iran

[b] Energy Management Group, Energy and Environment Research Center, Niroo Research Institute, Tehran, Iran

[c] School of Mechanical and Mechatronic Engineering, University of Technology Sydney (UTS), Sydney, Australia

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ABSTRACT

The irreversible Brayton cycle is usually used in gas turbine-based power plants. In this study, energy and exergy analysis has been performed for an irreversible Brayton cycle with a regenerator, reheater, and intercooler for the first time. The influence of different parameters such as the efficiency of the cycle's components is examined based on the first and the second laws of thermodynamics. The lost exergy in different components and the total exergy loss of the irreversible Brayton cycle are calculated for various conditions. The optimum pressure of the intercooler and the reheater is obtained for different cases. An irreversible Brayton cycle with regenerator, reheater, and intercooler is simulated in engineering equation solver software and the optimum pressure in each simulation is determined based on the first and the second laws of thermodynamics. Furthermore, the obtained optimum pressures are compared with the geometric mean of the low and the high pressure of the cycle in each simulation. The results show that the optimum pressure of the intercooler changes between $0.69\sqrt{P_{mean}P_{\max}}$ *and* $0.98\sqrt{P_{mean}P_{\max}}$ *based on exergy analyses and changes between* $0.98\sqrt{P_{mean}P_{\max}}$ *and* $2.97\sqrt{P_{mean}P_{\max}}$ *based on energy analyses.*

Keywords: Irreversible Brayton Cycle; Efficiency; Exergy; Optimum Pressure; Energy.

1. Introduction

Exergy and energy are very important topics for researchers because these parameters are important for our life in the new century[1]. Ghaebi and seyedmatin [2] had been done energy and exergy analysis on a combined system containing cooling and power generation systems. Different working fluids were considered in this work like R245fa, R717, and R141b. the results showed a 48% reduction in energy consumption. Ghaseminejad et al. [3] had done energy and exergy analysis on energy storage systems that work with liquid air. The parametric study had been done to find the optimum state. The results demonstrated that the lower inlet temperature for compressors leads to the high efficiency of systems.

Using renewable energy like solar energy is a good way to provide the exergy demand[4]. The other was is the optimization of the energy systems to reduce the exergy destruction. Bryton cycle (BC) is used widely to produce electrical energy. This power cycle can use different fuels, especially renewable ones such as biogas[5]. Bryton cycles are also used along with other cycles to improve the efficiency of the combined cycle such as refrigeration and desalination cycles[6]. According to the wide

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* Corresponding author: Tohid Adibi
School of Mechanical Engineering, University of Bonab, Bonab. Iran
Email: tohidadibi@ubonab.ac.ir

use of the BC in power plants all around the world, increasing Brayton cycle efficiency (BCE) is very important. Also, exergy analysis is necessary for all systems, and every system must be redesigned and modified to reduce the total exergy destruction in it.

Fakhari et al.[7] had been simulated as a combined power plant in conjunction with a system that was used to recover the heat. The economical and environmental views of this combined cycle were considered in this work. The maximum efficiency was reported equal to 50% based on the second law of thermodynamics. Moghadam and Farzaneh [8] had been proposed a new combined cycle with high exergy efficiency. This cycle produced hydrogen, heat, and power simultaneously. The analysis was done based on thermodynamics laws and economic considerations and optimum conditions were determined. The produced power and the produced heat were 20MW and the produced hydrogen was 12 kilograms per hour at the optimum point. Rezaei et al. [9] worked on the performance of the gas station. The pressure of the gas decreases in this gas station. The novel turbo-expander was proposed to be used in the inlet line. Then the new system was analyzed and compared with the current one. Results demonstrate that the maximum exergy efficiency in the proposed system was equal to 40%. The proposed system was surveyed economically too. The results demonstrated that the payback period will be four years.

Chen et al. [10] worked on the performance of an irreversible closed BC coupled to constant-temperature heat reservoirs by using the theory of finite-time thermodynamics. Martinaitis et al. [11] developed the possibilities of exergy analysis for a heat recovery exchanger while the variable reference temperature was considered. Değerli and Özilgen [12] performed an exergy analysis for microorganisms. They found the highest exergy utilization for their proposed system. Yilanli et al. [13] performed energy and exergy analysis of the fuel system of the aircraft turbojet engines to investigate the variation of flow and heat energies of fuel and noted that thermal balance formed by many different components of aircraft systems using heat management is significantly affected by aircraft performance.

Fakheri et al. [14] simulated a combined cycle that contains a heat recovery system generation, a heat exchanger, some solar collector panels, two gas turbines, two compressors, and an auxiliary combustion chamber. The explained combine cycle was connected to an organic Rankine cycle and a double effect absorption system. The economic and environmental analysis had been done and the results showed that the efficiency of the heat recovery system was equal to 20% according to the second law of thermodynamics and the efficiency of the complete system was equal to 46% based on the second law of thermodynamics analysis.

Ashouri et al.[15] simulated an organic Rankine cycle with a regenerator based on exergy and energy. They used water in their cycle as a working fluid. Ahmadi et al. [16] optimized the regenerative organic Rankine cycle according to the evolutionary algorithm. They considered two objective functions. The first case was based on energy and the second one was based on exergy. Elahifar et al. [17] simulated a power plant that works based on an irreversible Rankine cycle. They considered a power plant in Kerman city in Iran as the case study. Manesh and Rosen [18] applied exergy analysis, thermo-economics, and combined pinch and exergy analyses simultaneously to the Neka combined-cycle power plant. Lingo and Roy [19] investigated geo-solar storage technology based on exergy analysis. Atif and Sulaiman [20] carried out energy and exergy analyses of a recompression supercritical carbon dioxide BC integrated with a solar tower and a two-tank thermal storage system. Kumar et al. [21] considered the methods of increasing the activity of a gas turbine. They proposed the most general way of reducing the inlet air temperature to 15°C. They suggested that implementing an alternative regenerator configuration along with intake air cooling may enhance the efficiency of gas turbine power plants. Oyedepo et al. [22] studied the design and performance of eleven gas turbine power plants using the first and second laws of thermodynamics. They calculated energy loss and exergy destruction of each main section of the gas turbine plant based on operating data collected from the power plants. Energy analysis disclosed that the combustion chamber and the turbine were the components with the highest amount of energy loss in the plants. Hajabdollahi [23] optimized a gas turbine power plant with variable ambient temperatures. They selected eight parameters as the design variables and used a genetic algorithm. Their purpose was to maximize exergy efficiency. Noorpoor et al. [24] proposed a new solar system. They simulated it and calculated energy and exergy efficiency. They benefited from the exergy optimization to find optimum points. Hanafizadeh and Maghsoudi [25] simulated a plate-fin recuperator of a 200-kW microturbine powerplant. In their study, exergy efficiency lost pressure and total cost were selected as the three important objective functions. They used genetic algorithms in their research. Adibi et al.[26] focused on the intercooler of an irreversible regenerator Brayton cycle (IRBC). Using energy analysis, the influence of the intercooler on the efficiency of the cycle, as well as the compressor work was surveyed.

In this study, the IRBC with regenerator, intercooler, and reheater is simulated utilizing the engineering equation solver (EES) software. Energy and exergy analysis of the whole cycle is considered and the total exergy loss and the efficiency of the IRBC are considered as the main parameters of the simulations. These parameters depend on the efficiency of the components such as turbines, compressors, intercoolers, regenerators, and reheater, and in this paper, this dependency is examined. Owing to the inevitable effect of the pressure of the intercooler and the reheater on the total exergy loss and the efficiency of the IRBC, the optimum pressure (if there exists any) is determined for different conditions for the first time. Also, the total exergy loss and the efficiency of the IRBC depend on the pressure of the intercooler and the reheater. Therefore, in the present study, the optimum pressure (if there exists any) is determined for different conditions for the first time. The optimum pressure is defined in two ways in this paper: the pressure at which the efficiency of the IRBC becomes maximum and the pressure at which the total exergy loss of the IRBC becomes minimum. The results of this study can be used in power plant optimization by choosing the optimum pressure on the intercooler and reheater of power plants.

2. Governing equations and modeling

The IRBC with regenerator, intercooler, and reheating is shown in Fig. 1.

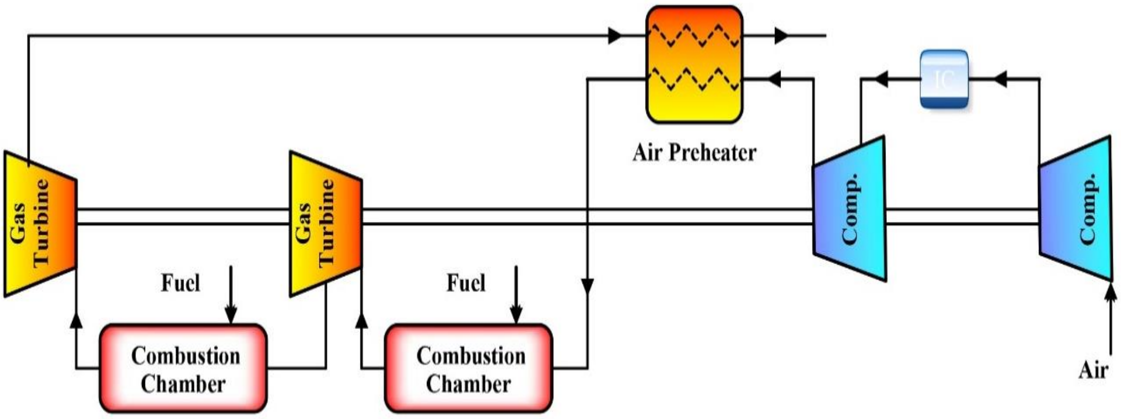

Fig. 1. IRBC with reheater, regenerator, and intercooler

In this cycle, air enters the low-pressure compressor. The pressure of air rises in the low-pressure compressor. Temperature and specific volume of air decrease in the intercooler. Compressor work decreases when the specific volume of the fluid decreases. The pressure of the air rises in the high-pressure compressor and high-pressure air gets heat in the regenerator and the combustion chamber. Air with high pressure and temperature enters the high-pressure turbine. Air receives heat again in the second combustion chamber and enters the low-pressure turbine. Power produces in high and low-pressure turbines. The high and low-pressure compressors consume a part of produced power. In this paper, different states of IRBC are simulated. The compressor work is calculated as follows:

$$w_{c1} = \dot{m}\left(h_2 - h_1\right) \tag{1}$$

$$w_{c2} = \dot{m}\left(h_4 - h_3\right) \tag{2}$$

$$w_c = w_{c1} + w_{c2} \tag{3}$$

To determine the transferred heat in the combustion chamber, the following formulas are used:

$$q_1 = \dot{m}\left(h_6 - h_5\right) \tag{4}$$

$$q_2 = \dot{m}\left(h_8 - h_7\right) \tag{5}$$

$$q = q_1 + q_2 \tag{6}$$

Also, to compute the turbine work, the following equations are used:

$$w_{t_1} = \dot{m}\left(h_6 - h_7\right) \tag{7}$$

$$w_{t_2} = \dot{m}\left(h_8 - h_9\right) \tag{8}$$

$$W_t = w_{t_1} + w_{t_2} \tag{9}$$

In the ideal state, the process in the turbines and the compressors is isentropic and in the real state, the compressor and turbine works are calculated as:

$$\eta_t = \frac{w_{ta}}{w_{ts}} \tag{10}$$

$$\eta_c = \frac{w_{cs}}{w_{ca}} \tag{11}$$

The flow through the intercooler, combustion chamber, and regenerator are assumed to be isobar. The regenerator efficiency is defined as:

$$\eta_r = \frac{T_5 - T_4}{T_9 - T_4} \tag{12}$$

To transfer the heat in the intercooler, a cooling cycle can be used which would have high costs in addition, if it is a compression one, the work consumed by the compressor should be taken into account, and if it is an absorption one, the compressor work and the heat transfer in the regenerator should be taken into account and all of these must be taken into account for obtaining the optimal state. However, the intercooler can be considered as a simple heat exchanger that transfers heat to the environment. We considered this consideration in this study. Therefore, intercooler efficiency can be defined as:

$$\eta_{in} = \frac{T_2 - T_3}{T_2 - T_\infty} \tag{13}$$

The BCE is obtained from the following equation:

$$\eta = \frac{w_t - w_c}{q} \tag{14}$$

The lost exergy is determined as follow:

$$W_{loss} = W_{rev} - W_{act} \tag{15}$$

For a steady process, the reversible work is calculated from the following equation:

$$\frac{\dot{W}_{rev}}{m} = \left(1 - \frac{T_\infty}{T_J}\right) q_J + \left(h_{tot\,i} - T_\infty S_i\right) - \left(h_{tot\,e} - T_\infty S_e\right) \tag{16}$$

For a steady, irreversible process, the lost exergy is obtained as follow:

$$\frac{\dot{W}_{loss}}{m} = \left(-\frac{T_\infty}{T_J}\right) q_J + T_\infty\left(S_e - S_i\right) \tag{17}$$

3. Results and Discussion

In this section, the IRBC is simulated under various conditions. The given information for the first simulation is shown in Table 1. The results of the first simulation are displayed in Tables 2 and 3.

Table 1. Given information for the first simulation of IRBC

Parameter	Value	Parameter	Value
Efficiency of turbines	0.8	P(1)	100 kPa
Efficiency of compressors	0.8	P(2)	300 kPa
Efficiency of intercooler	0.8	P(4)	900 kPa
Efficiency of regenerator	0.8	T(6)	1000 ^{0}C
T(1)	25 ^{0}C	P(7)	300 kPa
		P(9)	100 kPa

Table 2. Enthalpy, pressure, entropy, and temperature at each point of the simulated IRBC

h (kJ/kg)	P (kPa)	s (kJ/kg.K)	T (^{0}C)
298.6	100	5.699	25
436.6	300	5.765	161.6
326	300	5.472	52.33
476.8	900	5.538	201
955.9	900	6.246	647
1364	900	6.621	1000
1083	300	6.691	758.6
1364	300	6.936	1000
1083	100	7.006	758.6
592.3	100	6.387	312.5

Table 3. Results of the first simulation of the IRBC

Parameter	Value	Parameter	Value
The efficiency of the IRBC	0.3979	The lost exergy in the first turbine	20.96 kJ/kg
Heat transfer to the combustion chamber	408.4 kJ/kg	The lost exergy in the second turbine	20.96 kJ/kg
Heat transfer to the reheater	281.7 kJ/kg	The lost exergy in the combustion chamber	16.11 kJ/kg
Heat transfer from the intercooler	110.5 kJ/kg	The lost exergy in the reheater	7.068 kJ/kg
The first compressor work	138 kJ/kg	The lost exergy in the first compressor	19.5 kJ/kg
The second compressor work	150.8 kJ/kg	The lost exergy in the second compressor	19.53 kJ/kg
The first turbine work	281.7 kJ/kg	The lost exergy in the intercooler	23.39 kJ/kg
The second turbine work	281.7 kJ/kg	The lost exergy in the regenerator	26.39 kJ/kg
		Total lost exergy	424.4 kJ/kg

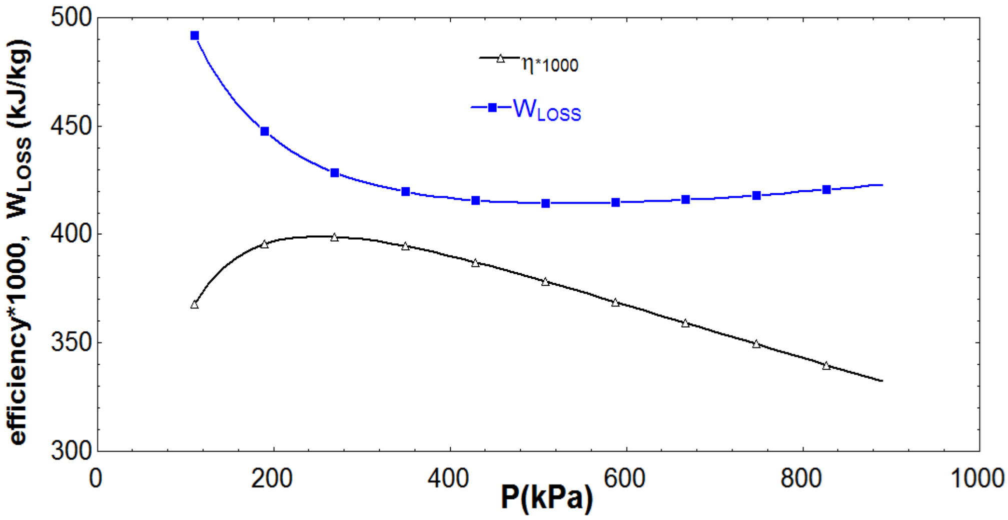

Fig. 2. Efficiency and total exergy loss of the IRBC versus the pressure of the intercooler

The variations of the total exergy loss and efficiency of the IRBC with the pressure of the intercooler are shown in Fig. 2 Both of them have an optimum point. However, these optimum points are not the same.

The variations in the total exergy loss and efficiency of the IRBC versus the pressure of the reheater are shown in Fig. 3 The efficiency of the IRBC becomes maximum at optimum pressure, but the total lost exergy of the IRBC decreases as the pressure of the reheater increases and it does not have an optimum pressure. The variation of the exergy loss in the compressors, the intercooler, and the regenerator with the pressure of the intercooler is displayed in Fig. 4 The exergy loss in the first compressor, the intercooler, and the regenerator increases when the pressure of the intercooler rises. The exergy loss in the second compressor decreases with increasing the pressure of the intercooler. Due to an increase in the intercooler pressure, PR for the first compressor increases and the second one decreases. Therefore, the ideal and actual works for the first compressor increase and they decrease for the second one. Consequently, exergy loss in the first compressor increases, and for the second one decreases. Moreover, increasing the intercooler pressure raises the temperature at the output of the first compressor, and therefore, the heat transfer from the intercooler to the ambient increases, and the exergy loss in the intercooler rises.

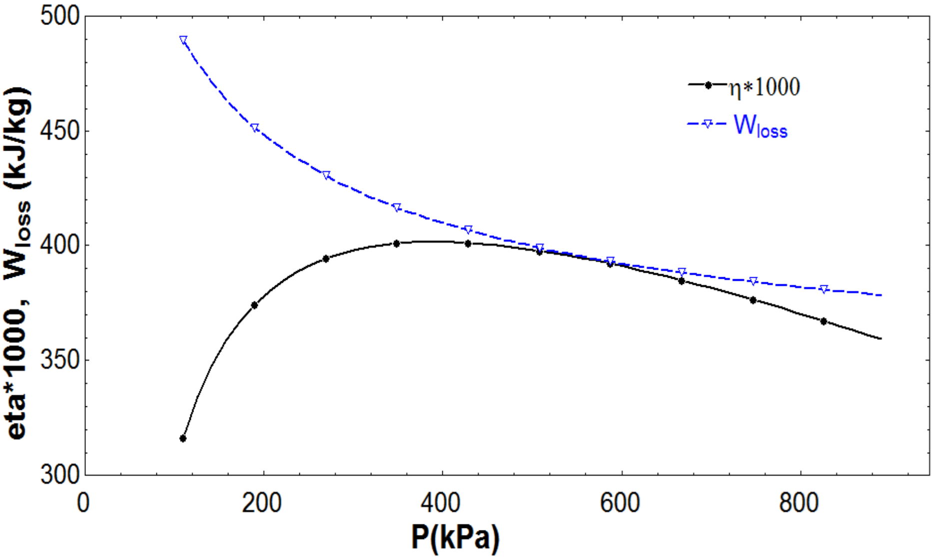

Fig. 3. Efficiency and total exergy loss of the IRBC versus the pressure of the reheater

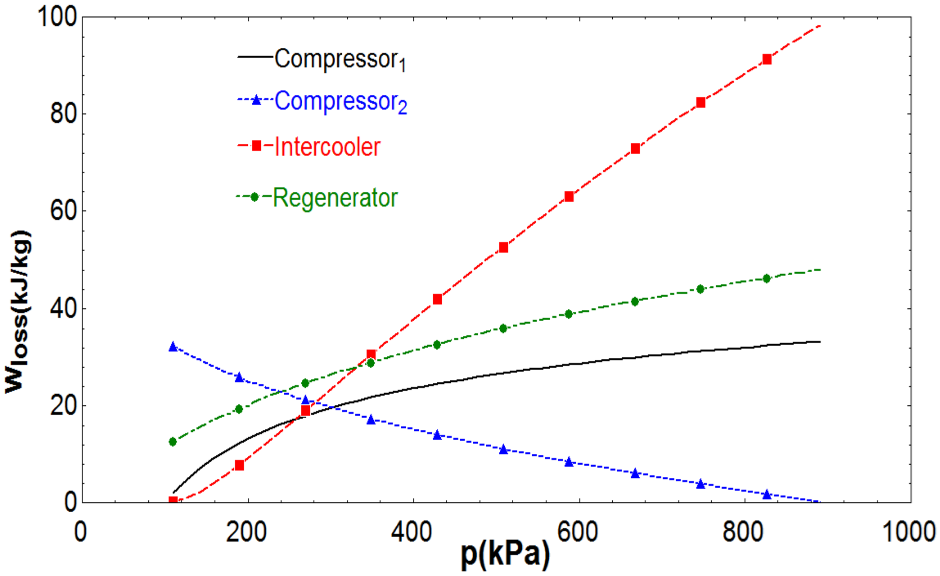

Fig. 4. Exergy loss in the intercooler, regenerator, and compressors versus the pressure of the intercooler

The variation of the exergy loss in the combustion chambers and turbines with the pressure of the reheater is shown in Fig. 5 The exergy loss in the first turbine and the second combustion chamber decreases with increasing the pressure of the reheater, but the exergy loss in the second turbine and the first combustion chamber increases when the pressure of the reheater rises. Due to a decrease in the reheater pressure, PR for the first turbine increases and the second one decreases. So, the ideal and actual works for the first turbine increase and they decrease for the second one. Therefore, the exergy lost in the first turbine increases, and that in the second one decreases. A decrease in the reheater pressure also raises the temperature at the output of the first turbine. Therefore, heat transfer to the reheater (the second combustion chamber) increases, and the exergy loss in the second combustion chamber rises. The total exergy loss of the IRBC depends on different parameters such as the efficiency of compressors. In the following, the influence of these parameters is examined. At first, the variation of total exergy loss of the IRBC with the efficiency of the compressors is shown in Fig. 6 The total exergy loss of the IRBC decreases with increasing the efficiency of compressors. The process of increasing pressure in high-efficiency compressors is nearly ideal. The ideal process for the compressors and the turbines is an isentropic one. In this condition, the exergy loss in the compressors and turbines is zero and the total exergy loss of the IRBC is minimum, as shown in Fig. 6 and Fig. 7 The variation of the total exergy loss of the IRBC with the efficiency of the turbines is shown in Fig. 7 As mentioned, the ideal process for the turbines is an isentropic one; therefore, the total exergy loss of the IRBC decreases with increasing the efficiency of the turbines.

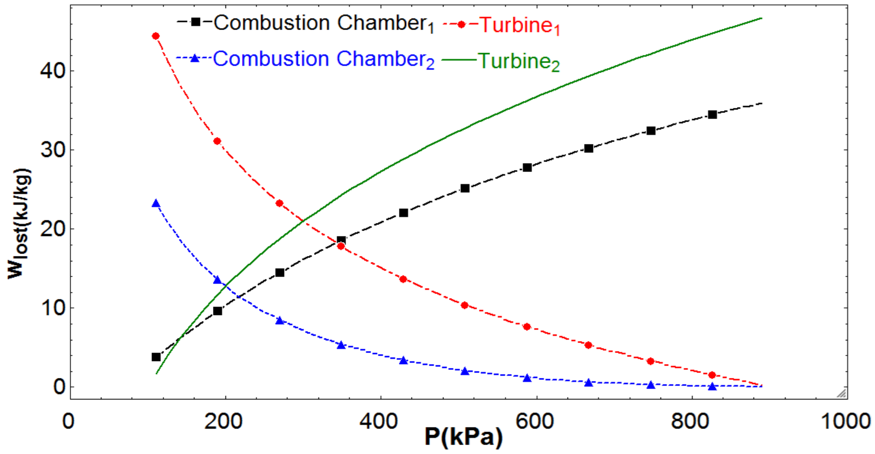

Fig. 5. Exergy loss in the combustion chambers and turbines versus the pressure of the reheater

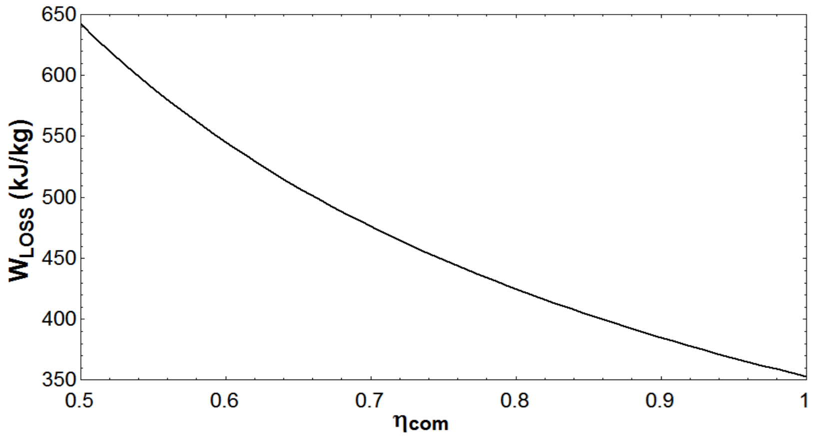

Fig. 6. Total exergy loss of the IRBC versus the efficiency of the compressors

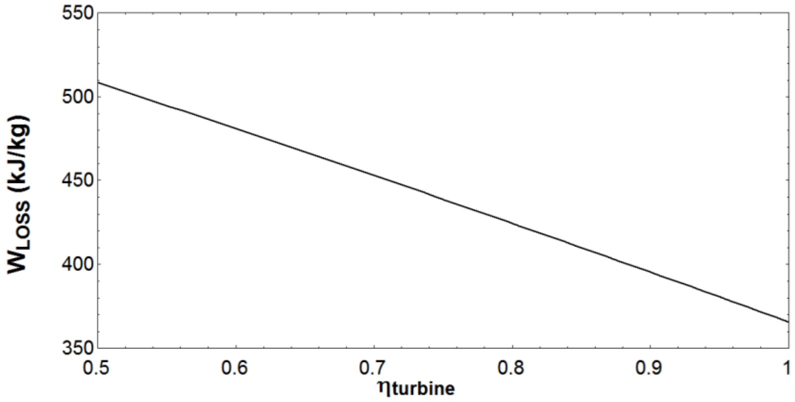

Fig. 7. Total exergy loss of the IRBC versus the efficiency of the turbines

The variation of the total exergy loss of the IRBC with the efficiency of the intercooler and regenerator is shown in Fig. 8 and Fig. 9, respectively. Similar to the variation of the total exergy loss of the IRBC with the turbine and compressor efficiencies, the total exergy loss of the IRBC decreases with increasing the efficiency of the intercooler and the regenerator. Increasing the temperature difference decreases the efficiency of the intercooler and the regenerator and at the same time increases the total exergy loss of the IRBC.

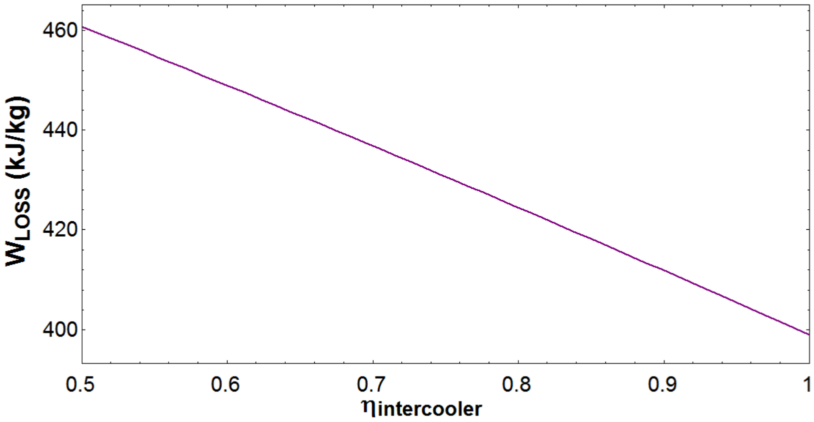

Fig. 8. Total exergy loss of the IRBC versus the efficiency of the intercooler

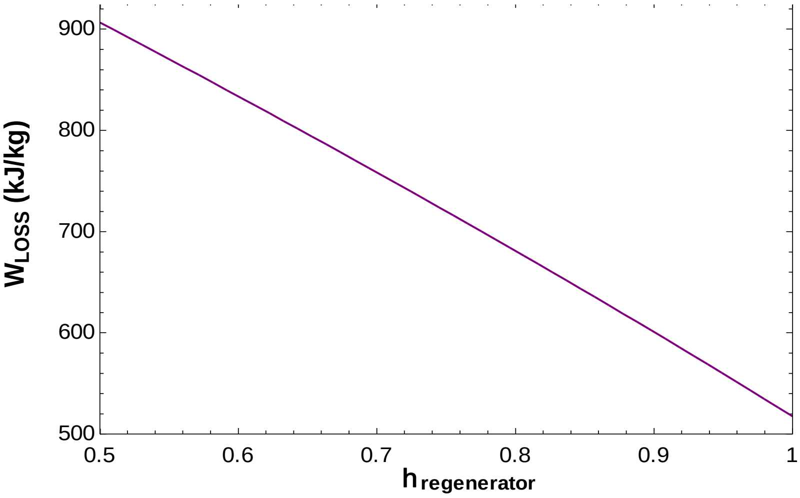

Fig. 9. Total exergy loss of the IRBC versus the efficiency of the regenerator

According to Fig. 2, there is an optimum pressure for the intercooler at which the total exergy loss of the IRBC becomes minimum and there is another optimum pressure for the intercooler at which the efficiency of the IRBC is maximum. These two optimum pressures are not the same. Also, these optimum pressures depend on the efficiency of the compressors, the turbines, the intercooler, and the regenerator. Variation of the optimum pressure with the efficiency of the compressors is shown in Fig. 10. The optimum pressure based on exergy and efficiency decreases with increasing the efficiency of the compressors. In addition, the variation of the optimum pressure based on the second law of thermodynamics (exergy) is higher than that based on the first law of thermodynamics (efficiency). Moreover, the optimum pressure based on exergy is higher than the geometric mean of the low and high pressures (GMLHP) ($\sqrt{p_{low}p_{high}}$) of the irreversible BC, however, the optimum pressure based on efficiency is lower than the GMLHP. Another point is that the slope of the curve of the optimum pressure based on exergy is higher than that based on efficiency. The results show that the optimum pressure of the intercooler changes between 0.83 $\sqrt{P_{mean}P_{\max}}$ and 0.93 $\sqrt{P_{mean}P_{\max}}$ based on exergy analyses and changes between 1.73 $\sqrt{P_{mean}P_{\max}}$ and 1.95 $\sqrt{P_{mean}P_{\max}}$ based on energy analyses.

Variation of the optimum pressure with the efficiency of the intercooler is shown in Fig. 11 As the efficiency of the intercooler decreases, the optimum pressure based on exergy increases, however, the optimum pressure based on the efficiency decreases. In addition, the slope of the curve of the optimum pressure based on exergy is higher than that based on efficiency. Furthermore, similar to Fig. 10, the optimum pressure based on efficiency is lower than the GMLHP and the optimum pressure based on exergy is higher than the GMLHP. The results show that the optimum pressure of the intercooler changes between 0.81 $\sqrt{P_{mean}P_{\max}}$ and 0.84 $\sqrt{P_{mean}P_{\max}}$ based on exergy analyses and changes between 1.67 $\sqrt{P_{mean}P_{\max}}$ and 2.56 $\sqrt{P_{mean}P_{\max}}$ based on energy analyses.

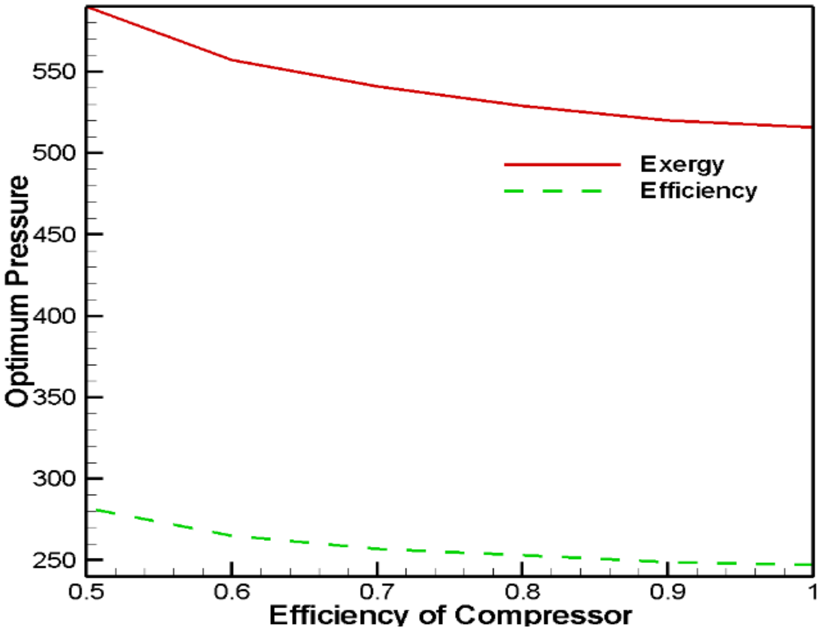

Fig. 10. The optimum pressure of the intercooler based on exergy and efficiency versus the efficiency of the compressors

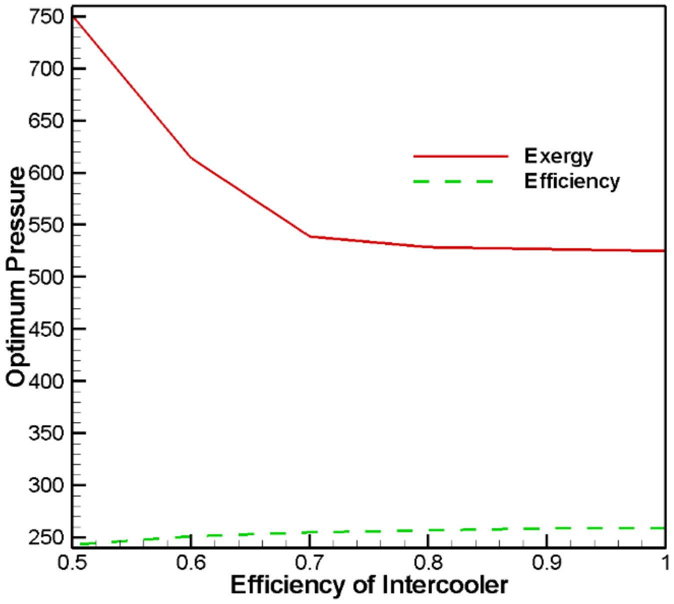

Fig. 11. The optimum pressure of the intercooler based on exergy and efficiency versus the efficiency of the intercooler

Variation of the optimum pressure with the efficiency of the intercooler is shown in Fig.12. Unlike Fig. 11, Fig. 12 is an ascendant curve for exergy-based and efficiency-based cases. Similar to Fig. 10 and Fig. 11, the slope of the curve of the optimum pressure based on exergy is higher than that based on efficiency. The other similarity between Fig. 10 and Fig. 11 is that the optimum pressure based on exergy is higher than the GMLHP and that based on efficiency is lower than the GMLHP. The results show that the optimum pressure of the intercooler changes between 0.69 $\sqrt{P_{mean} P_{\max}}$ and 0.98 $\sqrt{P_{mean} P_{\max}}$ based on exergy analyses and changes between 0.98 $\sqrt{P_{mean} P_{\max}}$ and 2.97 $\sqrt{P_{mean} P_{\max}}$ based on energy analyses.

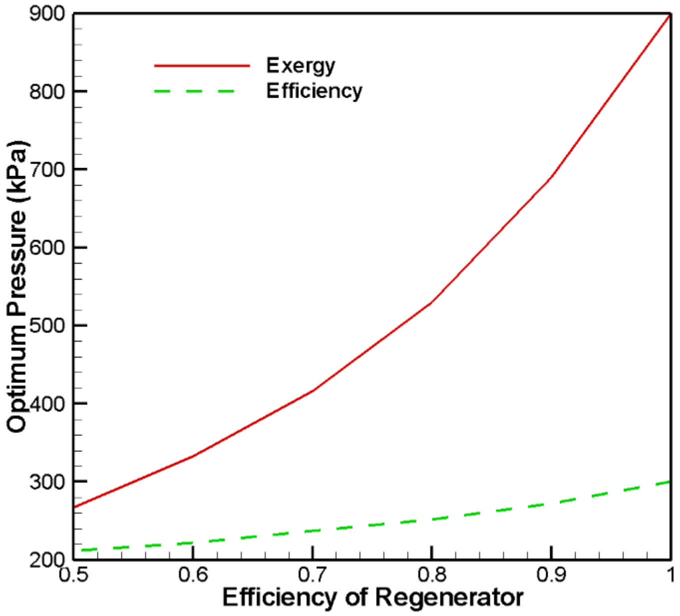

Fig. 12. The optimum pressure of the intercooler based on exergy and efficiency versus the efficiency of the regenerator

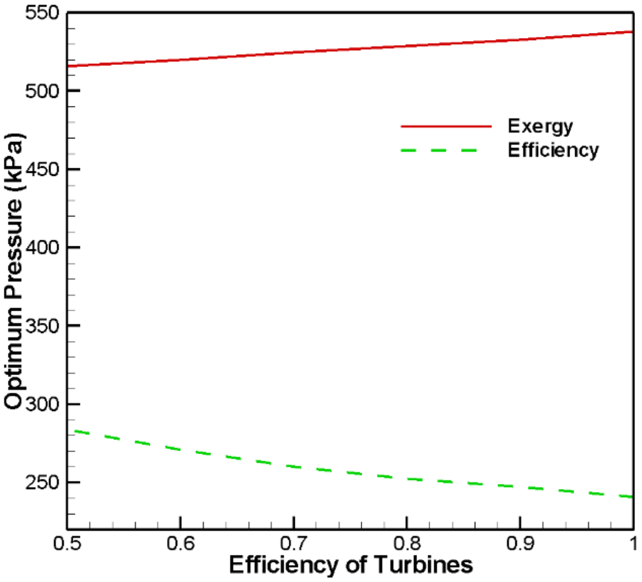

Fig. 13. Optimum pressure of the intercooler based on exergy and efficiency versus the efficiency of the turbines

Variation of the optimum pressure with the efficiency of the turbines is shown in Fig. 13 When the efficiency of the turbines increases, the optimum pressure based on exergy increases but the optimum pressure based on efficiency decreases. Furthermore, the slope of the curve of the optimum pressure based on exergy is higher than that based on efficiency. Moreover, similar to Fig. 10 to Fig. 12, the optimum pressure based on efficiency is lower than the GMLHP and the optimum pressure based on exergy is higher than the GMLHP. The results show that the optimum pressure of the intercooler changes between $0.85\sqrt{P_{mean}P_{\max}}$ and $0.94\sqrt{P_{mean}P_{\max}}$ based on exergy analyses and changes between $1.83\sqrt{P_{mean}P_{\max}}$ and 1.92 $\sqrt{P_{mean}P_{\max}}$ based on energy analyses.

4. Conclusion

In this paper, a BC with an intercooler, a regenerator, and a reheater was examined. This cycle was evaluated using the first and second laws of thermodynamics. Exergy and energy analyses were performed for each component of this cycle. Results indicated that the efficiency and the total exergy loss of the IRBC depend on the pressure of the intercooler and the regenerator. Also, results showed that the efficiency and the total exergy loss of the IRBC are a function of the efficiency of the components such as turbines, compressors, intercoolers, regenerators, and reheaters. The total exergy loss of the IRBC becomes minimum at a specific pressure of the intercooler which we named optimum pressure based on the second law of thermodynamics (exergy). Also, the efficiency of the IRBC becomes maximum at a particular pressure that we named optimum pressure based on the first law of thermodynamics (efficiency). Results indicated that these two optimum pressures are not the same and they depend on the efficiency of the components such as turbines, compressors, intercooler, regenerator, and reheater. Results also showed that the optimum pressure based on exergy is higher than the geometric mean of the low and high pressures of the irreversible BC (GMLHP) except when the efficiency of the regenerator is low, but the optimum pressure is based on efficiency is always higher than GMLHP. Moreover, results indicated that the total exergy loss of the IRBC decreases when the pressure of the reheater increases, and there is no optimum pressure based on exergy for the reheater. However, there is an optimum pressure based on the efficiency of the reheater for each condition. The efficiency of GMLHP becomes maximum at the optimum pressure based on the first law of thermodynamics. The results have shown that the optimum pressure of the intercooler changes between $0.69\sqrt{P_{mean}P_{\max}}$ and 0.98

$\sqrt{P_{mean}P_{\max}}$ based on the minimum exergy lost analyses and changes between 0.98 $\sqrt{P_{mean}P_{\max}}$ and 2.97 $\sqrt{P_{mean}P_{\max}}$ based on maximum efficiency analyses.

Data Availability Statement

Some or all data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

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