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Exergy and Economic Investigation of Different Strategies of Hybrid Systems Consisting of Gas Turbine (GT) and Solid Oxide Fuel Cell (SOFC)

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Abstract: Gas turbines and solid oxide fuel cells can be combined in two different strategies to create a new high-efficiency hybrid system. In most hybrid systems, the fuel cell is located directly before the combustion chamber (pressurized type) or after the turbine (atmospheric type). The indirect hybrid system is another compound that has been less studied. In this system, the fuel cell and the gas turbine cycle are located in two separate cycles and heat exchange was done by a heat exchanger. The main purpose of this article is to compare the exergy and economic performance of direct and indirect hybrid systems. The results show that the direct hybrid system with pressurized fuel cell has better performance than the other two types of hybrid system. High electrical efficiency, low rate of irreversibility and pollution, and low cost of electricity generation, as well as appropriate cost of purchase, installation and system setup, are the characteristics of this type of hybrid systems. Analyzes of this study showed that the only positive feature of direct atmospheric fuel cell systems is high production capacity and indirect hybrid systems are less efficient than direct systems.

Keywords: Hybrid system, micro gas turbine, thermoeconomic, solid oxide fuel cell

1. Introduction

To increase the efficiency of a heat engine, the electrochemical reactions heat obtained from a high temperature fuel cell can be used. [1]. Fuel cells are considered as novel devices in energy generation systems, among them, the Solid Oxide Fuel Cell (SOFC) has received increasing attention due to its high efficiency, combined power and heat systems, less environmental pollution, flexibility in the use of various fuels and an appropriate compatibility to be combined with other energy systems [2]. SOFC has a high operating temperature and excellent capability to be utilized in the hybrid power generation systems. Also, SOFC cells are commonly combined with various Gas Turbines (GT) [3].

The above-mentioned direct and indirect hybrid system are expected to have a great impact on energy and power generation in the near future due to its high efficiency as well as reduced pollution [4]. Note that the gas turbine and fuel cell hybrid systems could be combined both in direct and indirect way. The system is called a "direct thermal contact hybrid system" as the GT cycle and passing fluid through the fuel cell are the same [5]. On the contrary, the indirect combination is present as the FC and GT have two separate cycles and the passing operating fluid is not the same. As demonstrated in Fig. 1, this hybrid system consists of two cycles; the first cycle is connected to SOFC, which is supplied through the heated air in a recuperator. The second cycle is a gas turbine cycle. It is worth mentioning that

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*Corresponding author: jpirkandi@mut.ac.ir these two cycles can operate at different operating pressures and with various operating fluids. The use of indirect hybrid systems has many attractive over the direct ones.

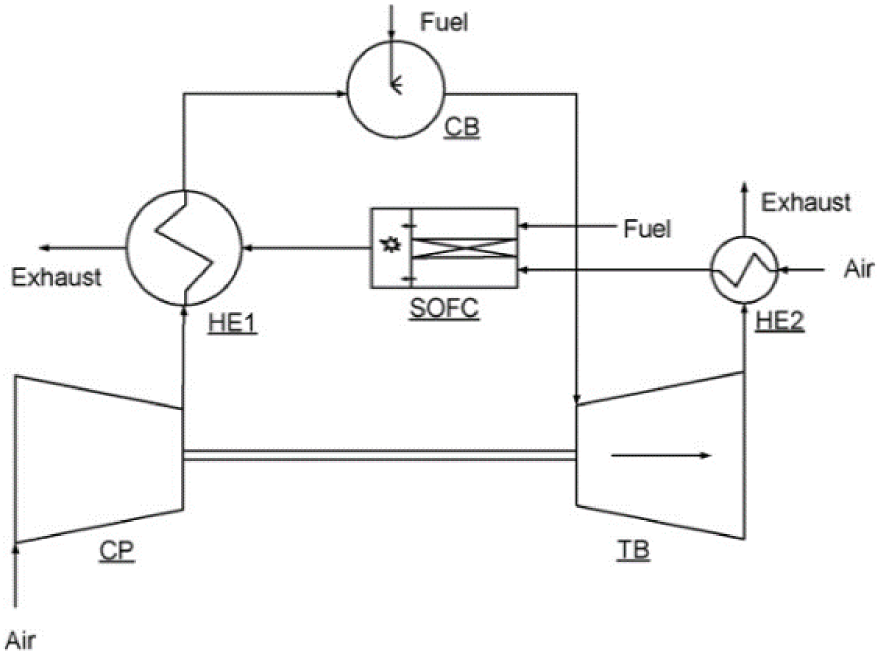
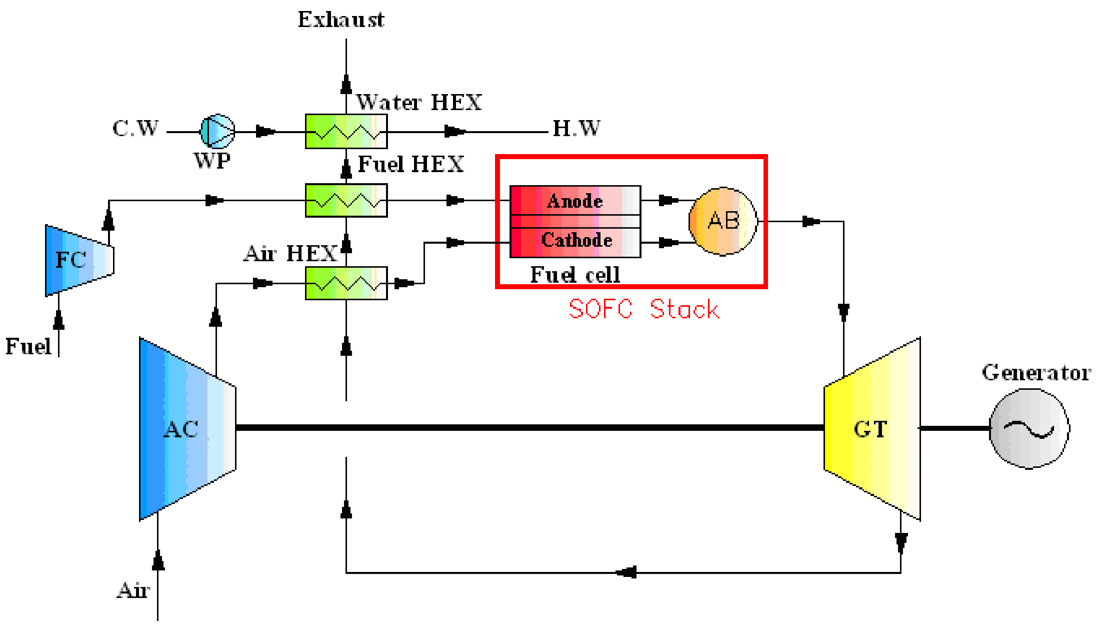


Fig. 1 - Indirect Hybrid System of SOFC and GT Schematic [3]

The indirect hybrid system has two separate and independent power generation systems. In fact, the second cycle can supply a part of the required thermal and electrical load in an indirect hybrid system, while both cycles are completely dependent in a direct hybrid system. Thus, inappropriate operation of a cycle will cause the overall performance reduction. Regarding the above-mentioned factors, the independence of two cycles in indirect hybrid systems would be an important advantage in comparison with the direct hybrid systems [5]. Designing an optimum heat exchanger and its proper insulation can promote the efficiency of the cycle. Numerous studies on hybrid systems have been investigated in recent years.

Pirkandi et al. (2018) [6] studied a hybrid solar GT power plant from the exergy and thermodynamic perspectives. Musa et al. (2008) [7] studied the medium and high temperature SOFC performances in hybrid cycle. Korlu et.al (2017) [8] studied Thermodynamic analysis of a gas turbine cycle equipped with a non-ideal adiabatic model for a double acting Stirling engine. Arsalis (2008) [9] studied 4 different cycles that operate at design and off-design conditions. Cheddie (2010) [10] investigated SOFC in order to integrate with a 10 MW GT power plant, with the efficiency of 30%. Cheddie et al. (2010, 2011) [11-12] studied the direct, indirect and semi-direct hybrid system consisting of10 MW power plant and a SOFC. Pirkandi et al. (2017) [13] studied the thermo-economic modelling of a hybrid systems consisting of SOFC and GT. In this research, four different direct hybrid systems with atmospheric and pressurized FC have been proposed. Pirkandi et al. (2017) [14] presented two different direct type configurations of hybrid GT and FC systems in order to study them from thermodynamic and economic prespectives. Mehrpooya et al. (2017) [15] analyzed a novel hybrid system, including SOFC, coal gasification, , air separation, CO2 and steam cycle with liquefied natural gas. Huang and Turan (2019) [16] studied the different fuel effects of on the performance of SOFC – GT integrated systems. Bao et al. (2018) [17] investigated the modeling of SOFC and control of SOFC and GT integrated system. Khani et al. (2016) [18] reported the genetic algorithm optimization results for a hybrid indirect SOFC and GT system. Chen et al. (2019) [19] established a framework for a novel integrated system consisting of a SOFC, a supercritical carbon dioxide GT and a Brayton cycle. Martins et al. [20] proposed the technical parametric analysis of a direct internal reforming SOFC and a GT system.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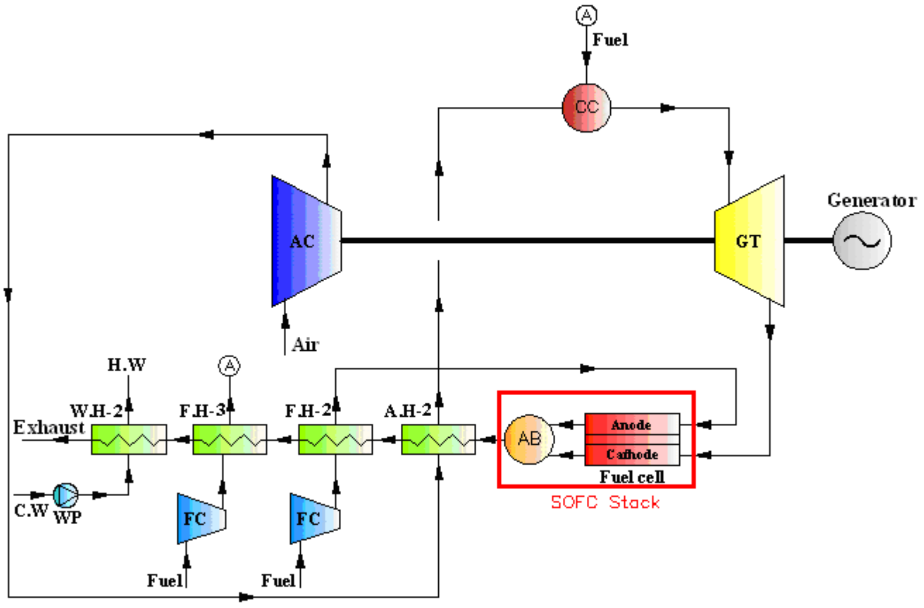
(A)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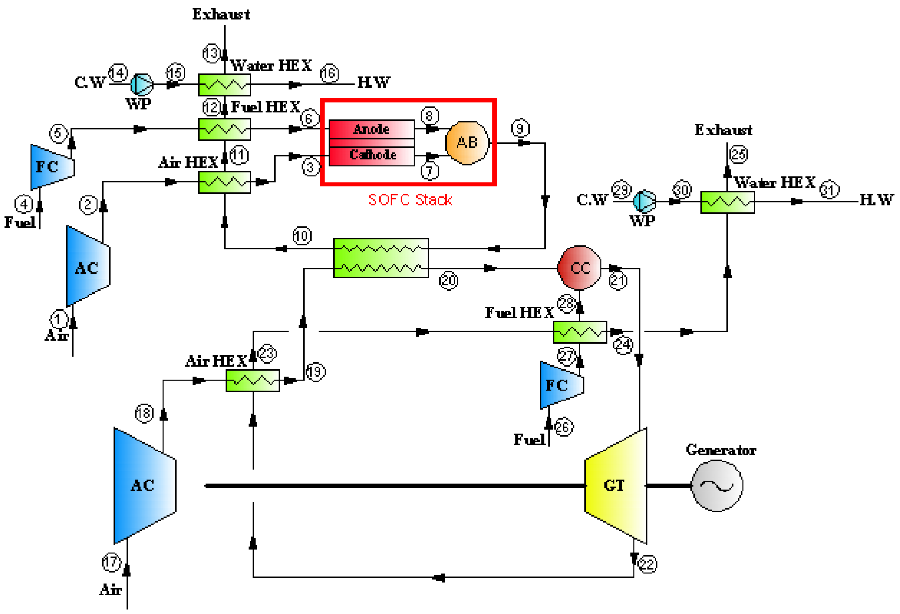
(B)



(C)

Fig. 2 - Schematic of The Proposed System in this research (A) Direct integrated system of GT and pressurized FC; (B) Direct hybrid system of GT and atmospheric FC; (C) Indirect integrated system of GT and SOFC

Most of the reviewed studies the direct hybrid systems, while the indirect hybrid systems have been neglected. On the other side, hybrid systems have been mostly examined thermodynamically, and the exergy and thermo-economic analyses have received less attention. Accordingly, the main purpose of this study is the thermo-economic modeling of an appropriate sample configuration for an indirect hybrid system of micro GT and SOFC and compare it with the direct configuration to be used in a sample CHP system. Due to the importance of cell operating temperature on its performance, the cell temperature is not supposed to be constant in this study and its value is calculated in various conditions in contrast to most of the reviewed articles. Here, to calculate the power generation and other related cost, simple and total revenue requirement economic models are used. Where the total revenue requirement model is more accurate and by means of that all the economic analyses and calculation of all the system's current and capital costs has been done.

2. The Proposed Integrated Systems

The integrated system's schematic representation analyzed in this article is shown in Fig.2. The proposed system has two separate cycles that exchange heat through a heat exchanger. In the first cycle, natural gas is converted into hydrogen in the anode by the reforming process after passing through the recuperator then entering the FC. The hydrogen reacts with the oxygen of the air that has passed through another recuperator and entered in the FC. Then, exhaust gases of the cell enter into the chamber of afterburner where react with each other. The hot products enter a heat exchanger and heat the gases in the GT cycle. After this process, the hot exhaust gases of the exchanger enter into three various recuperators. In the micro turbine cycle, the exhaust gases of the compressor are heated by the shared recuperator and heat exchanger, then enter the combustion chamber. After the combustion chamber reaction, the hot gases enter to the turbine and, after generation, enter three recuperators. The last recuperator of each cycle is used to produce hot water (25 to 90°C). The natural gas consists of 97% CH_4, 1.5% CO_2, and 1.5% N_2, and the air consists of 21% O_2 and 79% N_2.

In this study, the proposed system is used as a small-scale CHP unit. The required energy of the building includes the cooling, heating, and electrical energies, and the required system must be able to supply them. In winter, the heat gained from the fuel cell and hot water recuperators can supply the hot water demands of the building. In summer, this obtained heat can be used in the generator of an absorption chiller in order to supply the cooling demands of the building. The electrical power generated in the FC can also be used to supply the building electrical demands.

3. Assumptions

For the analysis and modeling of the introduced hybrid systems, these assumptions have been considered:

- The gas leakage of the system has been disregarded.
- Stable flow of fluid has been considered for all the cycle components.

- Fluctuations of the kinetic and potential energies have been disregarded.
- All the cycle gasses behavior has been assumed the same as the ideal gas.
- For the FC, a constant voltage has been considered.
- in the FC, the fuel converts to H_2 through the internal reforming.

4. Governing Equations

Here, the thermodynamic, exergy and economic equations have been presented in 3 separated parts. areas comprising the, equations. Due to the existence of governing equations in references, only the required equations are given [21-22]. Considering the integrated system as a control volume, the thermal, exergy, total and electrical efficiencies can be written: [23-24].

$$\eta_{ele} = \frac{\dot{W}_{net}}{LHV \times \dot{n}_f} \tag{1}$$

$$\eta_{exergy} = \frac{\dot{W}_{net} + \dot{E}_{out.w}}{\dot{E}_{in.a} + \dot{E}_{in.f} + \dot{E}_{in.w}} \tag{2}$$

$$\dot{W}_{net} = \left(\dot{W}_{AC.tot}\right)_{SOFC} + \left(\dot{W}_{AC.net}\right)_{GT} \tag{3}$$

$$\left(\dot{W}_{AC.net}\right)_{GT} = \eta_{inv.gen} \times \left(\dot{W}_{DC.net}\right) - \dot{W}_{c.air} - \dot{W}_{wp} - \dot{W}_{c.fuel} \tag{4}$$

The second law of thermodynamics is used in order to obtain the exergy analysis [25-26].

$$\dot{E}_{destroyed.sys} = \dot{E}_{in.a} + \dot{E}_{in.f} + \dot{E}_{in.w} - \dot{W}_{net} - \dot{E}_{out.w} - \dot{E}_{out.gas} \tag{5}$$

$$\dot{E}_{lost.sys} = \dot{E}_{out.gas} \tag{6}$$

$$\dot{I}_{tot} = \dot{E}_{destroyed.sys} + \dot{E}_{lost.sys} \tag{7}$$

4.1 The Economic Equations

To optimize the system economically, we need to compare the annual costs associated with fuel, investment, maintenance, and operation [25].

$$\dot{C}_{P.tot} = \dot{C}_{F.tot} + \dot{Z}_{CI.tot} + \dot{Z}_{OM.tot} \tag{8}$$

$$\dot{Z} = \dot{Z}_{CI.tot} + \dot{Z}_{OM.tot} \tag{9}$$

In this paper, the hybrid system's generated electricity has been considered as the output product. In the optimization analysis, Eq (10) is the objective function. where the minimization of the of electricity generation cost should be done. In Eq. (10), the Cp denotes the electricity generation cost per unit Giga Joule.

$$C_P = \frac{\dot{Z}_{CI.tot} + \dot{Z}_{OM.tot} + \dot{C}_{F.tot}}{\dot{W}_{net}} \tag{10}$$

The thermoeconomic validation depends on the accurate computation of $\dot{Z}$ [27]. In this research, the total revenue requirement method and the simple economic model of Lazaretto have been used for the economic analysis.

4.2 Lazaretto's Simple Economic Model

In Lazaretto's simple economic model, the total initial capital investment and the operating and the maintenance costs are formulated according to the Eq. (11) [27].

$$\dot{Z} = Crf \frac{\emptyset_r}{3600n} Pec \quad [USD/s]$$
(11)

where, n is the system's total operating hours (total annual 85% of work capacity, which equal to 7446 hours) under full load, Pec is the initial kth equipment's purchase cost, Φ_r is the maintenance and operating cost which is varies from 1.06 to 1.1, of the system (85% of total work capacity, and equal to 7446 h), and crf is the capital recovery factor which is a function of the rate of interest (i) and the number of machineries operation years (n). and it is calculated as below [27]. the crf usually varies between 0.147 to 0.18 in the thermoeconomic modeling.

$$crf = \frac{i(i+1)^n}{(i+1)^n - 1} \quad (12)$$

4.3 The Total Revenue Requirement Economic Model

In total revenue requirement method, the cost consisting of land purchase, facilities construction, maintenance, engineering services, fuel and equipment purchase and repairmen, are computed annually over the system's operation [27].

$$\dot{Z} = \frac{cc + omc}{\tau} \times \frac{pec}{\sum pec} \quad (13)$$

$$cc = trr - fc - omc \quad (14)$$

$$trr = crf \sum_{j=1}^{n} \frac{trr(j)}{(i+1)^j} \quad (15)$$

Where, trr(j) is the jth year of system operation total revenue requirement.

$$\dot{Z}_{tot} = \dot{Z}_{CI.tot} + \dot{Z}_{OM.tot} = \frac{cc + omc}{\tau} \quad (16)$$

$$\dot{C}_{p.tot} = \frac{cc + omc + fc}{\tau} = \frac{trr}{\tau} \quad (17)$$

$$c_p = \frac{trr}{\tau \times \dot{W}_{tot}} \quad (18)$$

The cost of installation, purchase and start-up for power generation unit are calculated by Eq. (19).

$$c_{pp} = \frac{pec_{tot} + 0{\cdot}46 pec_{tot}}{\dot{W}_{tot}} \quad (19)$$

5. The Solution Procedure

In the previous part the formulation has been done, then here we used a computer code written for analyzing the problem. first the integrated system's input information such as the air and fuel flow rates and the working pressure were determined. Here, because the cell's temperature is not constant, an arbitrary temperature of cell is guessed initially. In the next step using this cell, the nonlinear reforming, thermal and electrochemical equations are solved simultaneously, then the desired outputs such as the temperature, electrical current, voltage and its loss, the efficiency, the power and other parameters of the FC are obtained. After this calculation for the system, the new temperature of cell is determined. until the cycle's convergence condition is not fulfilled, the calculation should be repeated with the new obtained temperature. Then the economic analyses are also carried out for the whole system in the last section.

6. Results

For the validation of the developed code, it is required to compare the outcomes of the developed code to the laboratory or numerical outcomes of a certain sample. In order to examine the correctness of the results related to the thermo-economic section, the results of Masardo's economic analysis performed on a simple GT cycle are compared to the results of the present code. Masardo [28] used a simple economic model in his study. The good agreement between the results as shown in table Table 1, confirms the accuracy of the present developed code. The economic model used in this study is a complete model and, in contrast to the model used by Masardo, provides more accurate results on economic analyses.

Table 1 - Comparison of the present computer code results with the numerical outcome of Masardo [28]

parameters	Masardo et al. results [28]	Present research Results
Specific work (kJ/kg)	300	300
Turbine Inlet Temperature(K)	1200	1200
Compressor pressure ratio	7	7
Electricity price (Cent/kWh)	5.28	5.28

Figure 3 shows the electrical efficiency of three indirect hybrid cycles, pressurized direct and atmospheric direct cycle. As can be seen, the electrical efficiency of the direct pressure integrated cycle is more than the other two cycles. The results of this section show the indirect hybrid cycle efficiency is about 25% less than atmospheric direct and 30% less than pressurized direct type. According to Figure 4, this trend is also present in the exergy efficiency. The next results are related to the total efficiency of the three analyzed hybrid systems, which are demonstrated in Figure 5. As can be seen, the direct atmospheric system's overall efficiency is more than the other hybrid systems. Also, the total efficiency of the atmospheric hybrid cycle is 5% higher than the direct integrated system and 19% more than the indirect hybrid system. This indicates that the heat absorption in the direct atmospheric hybrid system is more than the pressurized type and its total efficiency is higher. The results show that the overall efficiency of indirect hybrid systems is about 13 - 20% lower than direct hybrid systems.

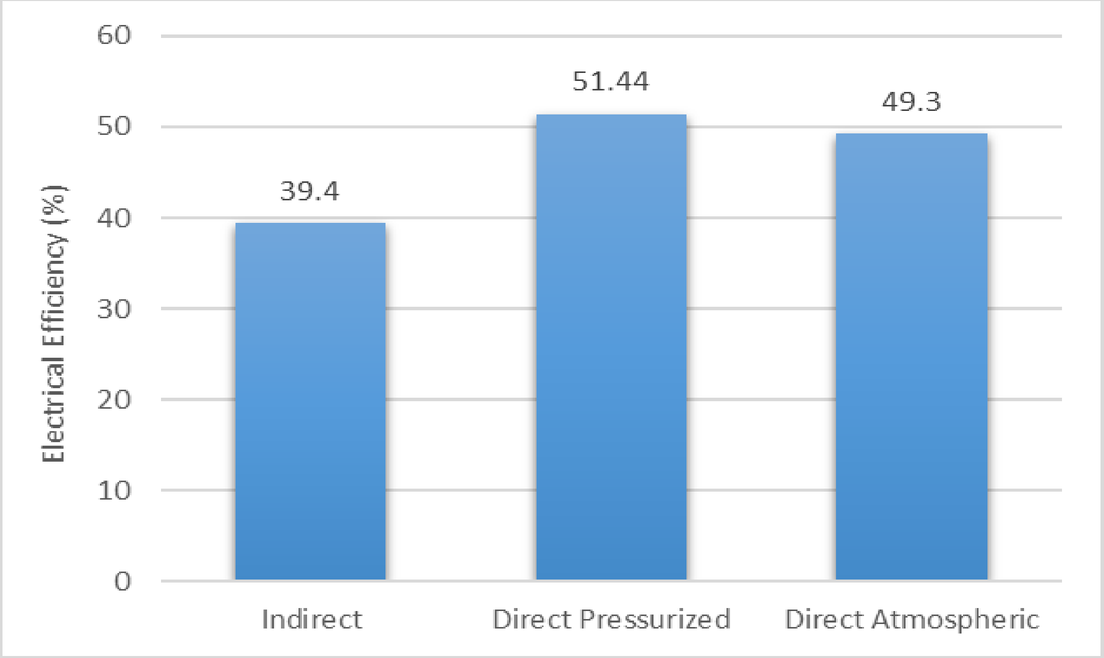


Fig. 3 - The electrical efficiency of hybrid systems

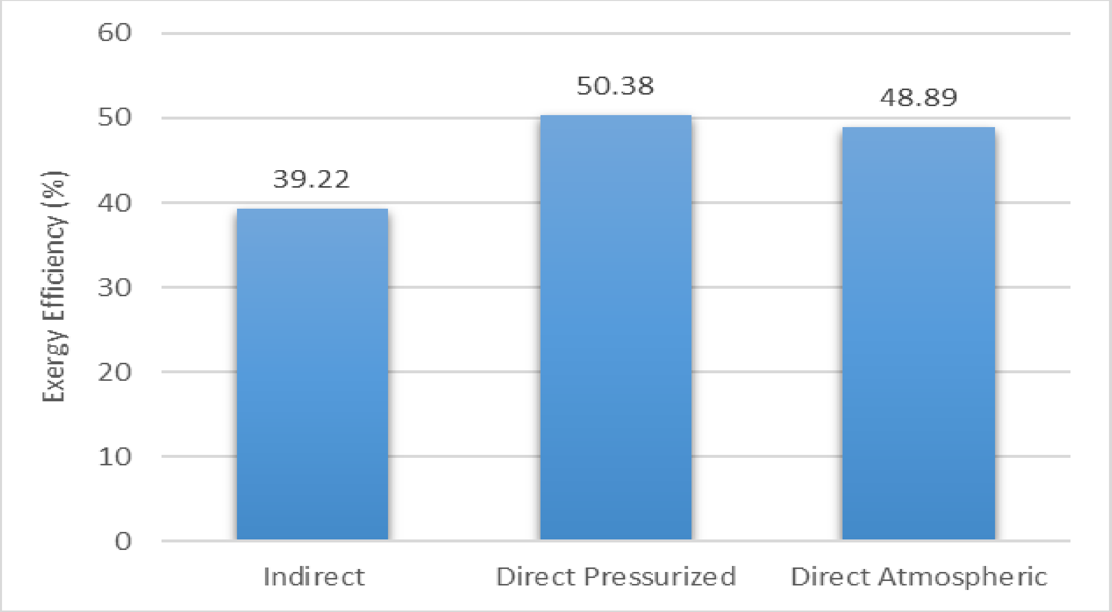


Fig. 4 - The exergy efficiency of hybrid systems

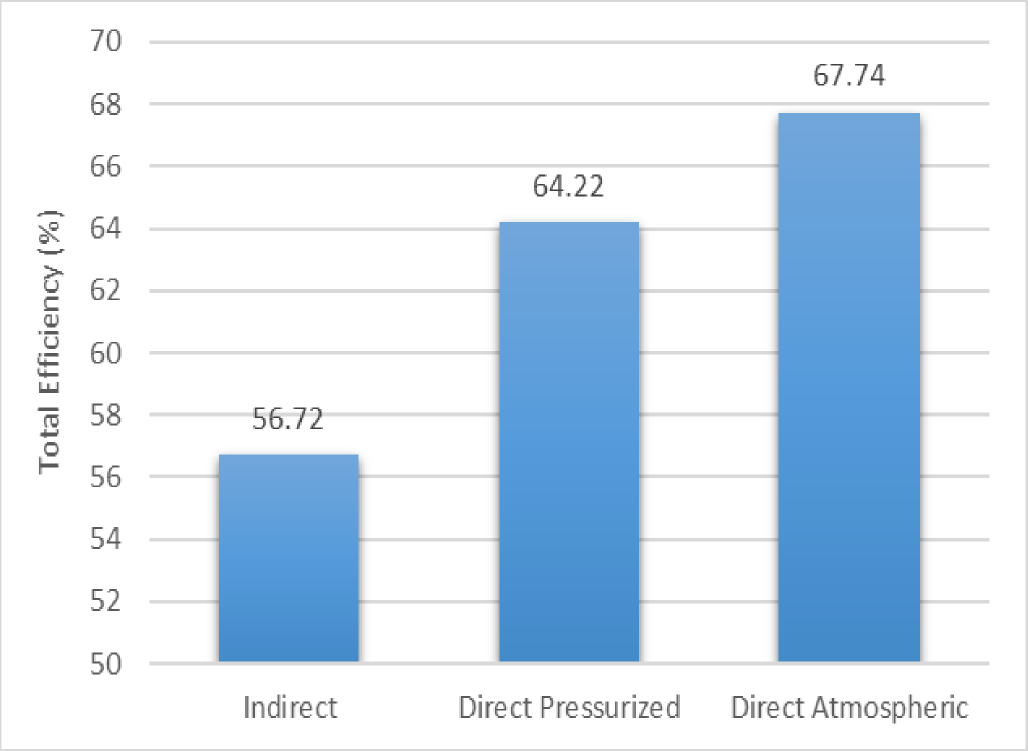


Fig. 5 - The total efficiency of hybrid systems

Figure 4 shows the power output of the analyzed integrated systems. As can be seen, the power output of the direct atmospheric hybrid system is more than the other systems which has been investigated. The results show that the output power of the direct atmospheric integrated system is about 20% higher than the pressurized type and 23% higher than the indirect type.

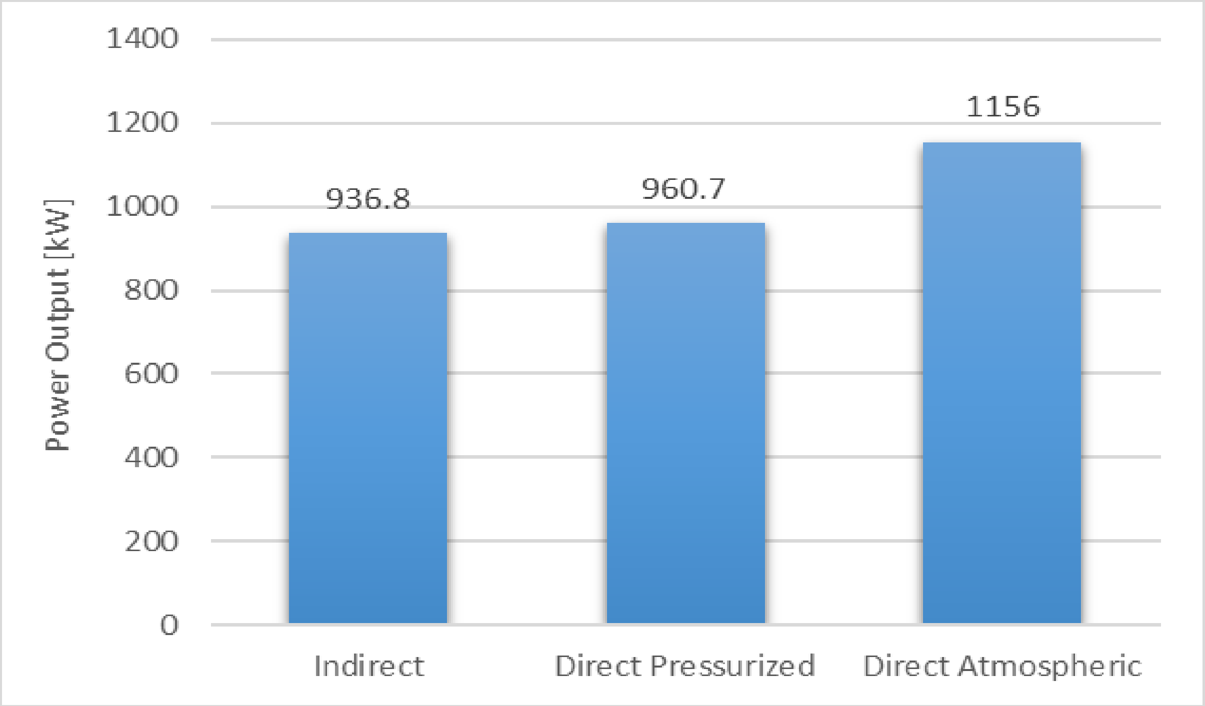


Fig. 6 - The power output of hybrid systems

Figure 7 shows the entropy generation rate for the analyzed hybrid systems. Examination of the results shows that the entropy production rate in the pressurized direct hybrid system is lower and this system is much suitable from the second law of thermodynamics viewpoint than the other two hybrid systems. The results of this section show that the indirect hybrid system has a higher entropy production rate in comparison of to the direct integrated system. The entropy production rate in the indirect integrated system is about 13% more than in the direct atmospheric hybrid system and 45% higher than in the pressurized direct hybrid direct system. The main reason for this is the combustion chamber of the GT cycle and the heat exchanger used in this system. Figure 8 shows the irreversible rate changes for integrated systems. Results show that similar to the entropy production rate, the pressurized direct integrated system has the lowest and the indirect integrated system has the highest irreversibility rate. Results show that the indirect integrated system has about 20 to 55% higher irreversibility rate.

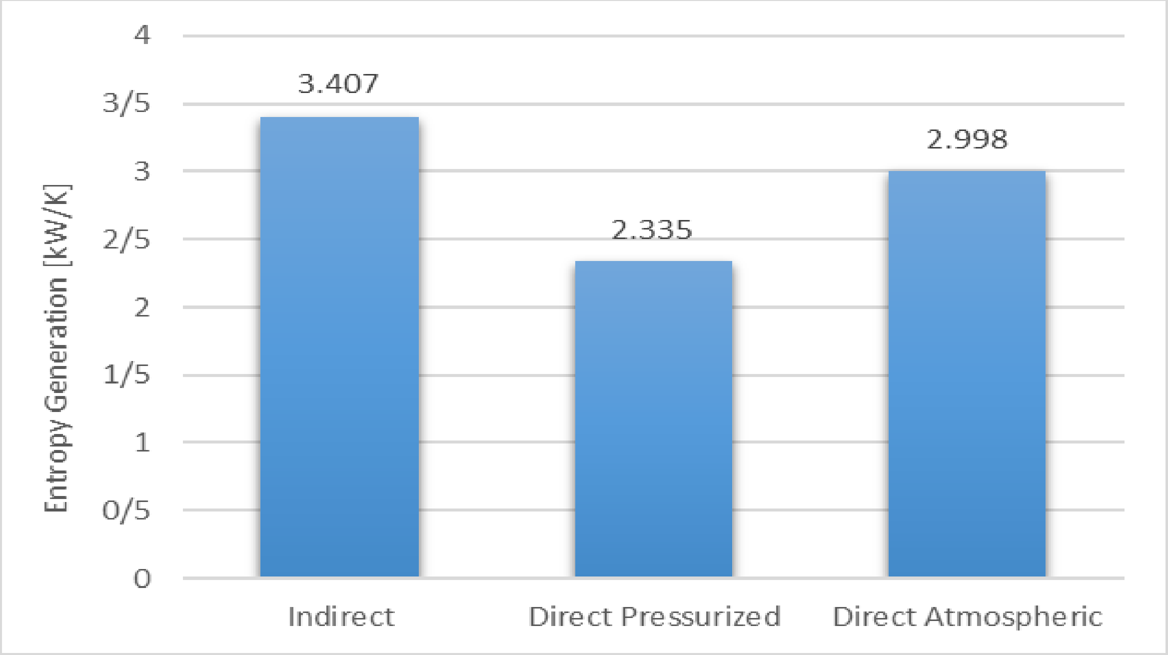


Fig. 7 - The entropy generation of hybrid

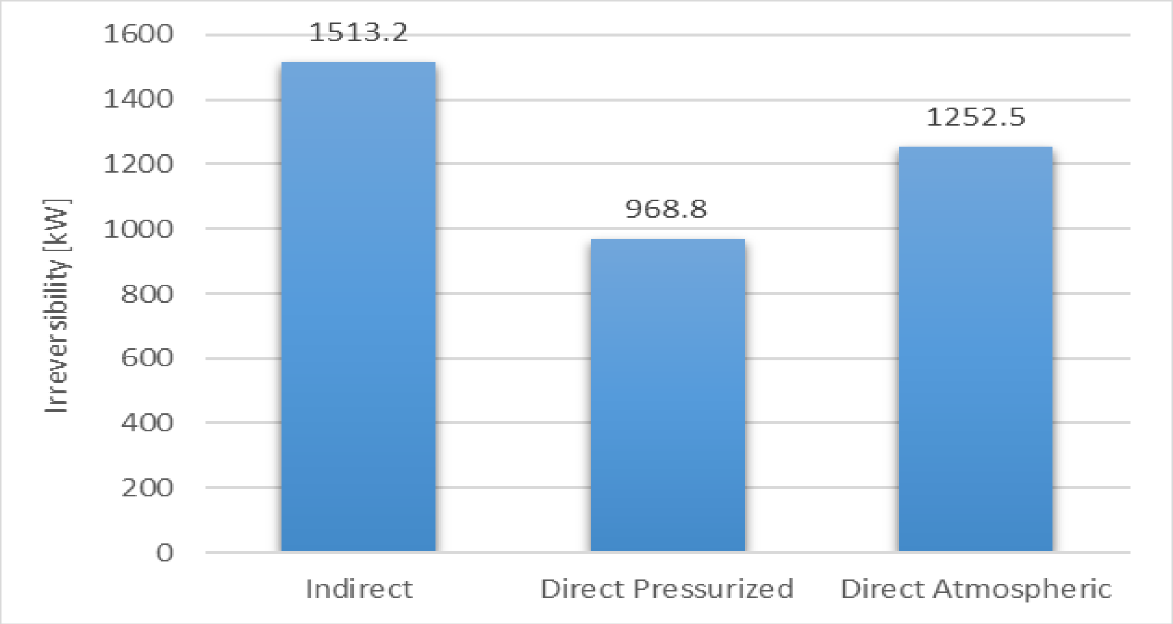


Fig. 8 - The irreversibility of hybrid systems

Figure 9 shows the emissions of the analyzed hybrid systems. As can be seen, the pressurized direct hybrid system has the lowest emission rate and the indirect hybrid system has the highest emission rate. The price of electricity generated and reducing the cost of purchase, installation and setup are other important factors in choosing a hybrid system. Examination of the results (Figure 10-11) shows that the pressurized direct integrated system has the lowest cost of purchase, installation and the cost of electricity generation. Any other way, the indirect integrated system is in the worst condition in terms of economic analysis.

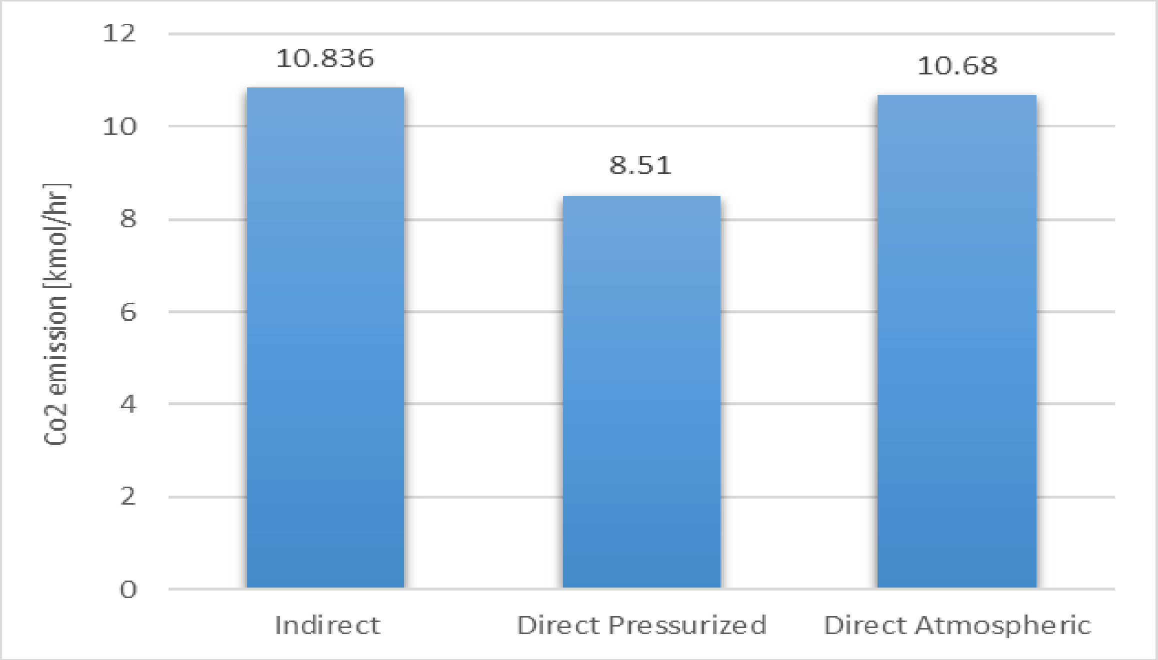


Fig. 9 - The emissions of hybrid systems

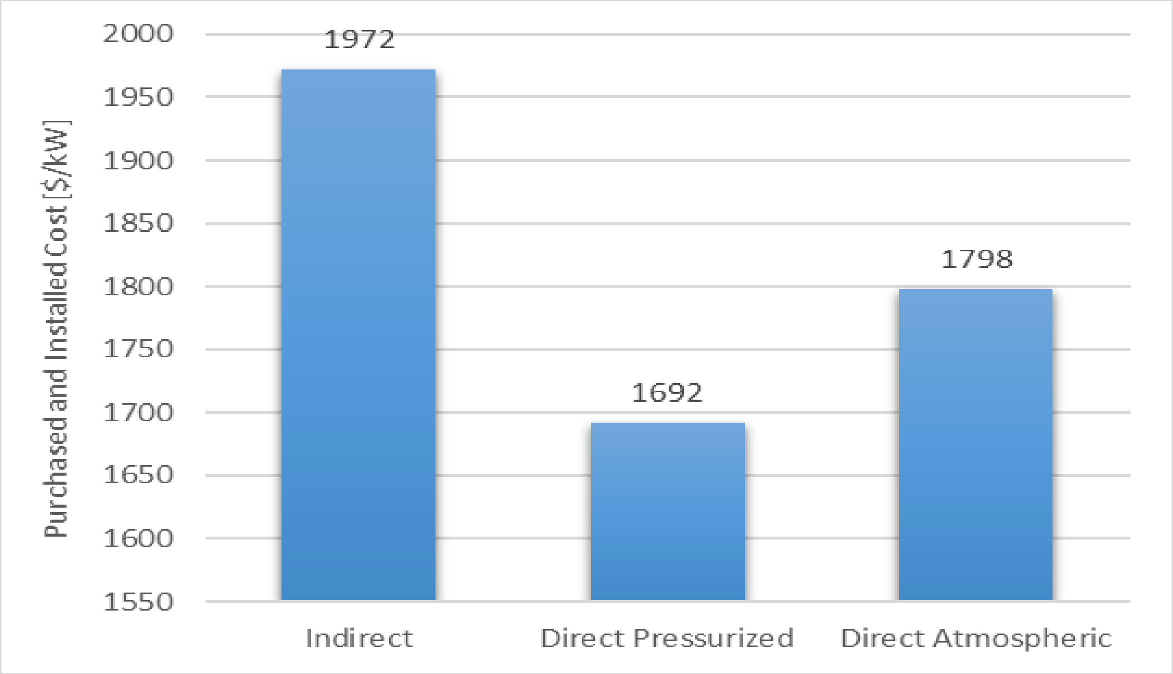


Fig. 10 - The purchase and installation cost of hybrid systems

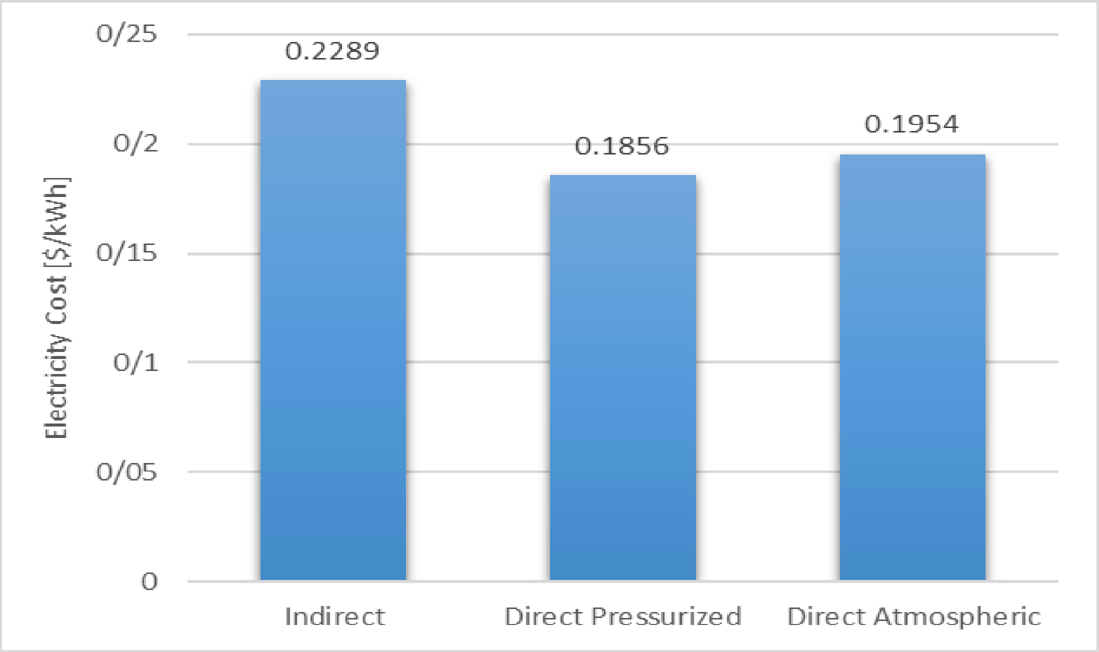


Fig. 11 - The electricity cost of hybrid systems

The results are show in the Table 2. As it can be seen, the performance of each system is determined by three options (+) suitable, (○) acceptable and (-) inappropriate. As can be seen in this table, direct pressure hybrid systems have the highest efficiency and indirect hybrid systems have the lowest efficiency.

Table 2 - Comparison of performance of hybrid systems

	system	purchase and installation cost	electricity cost	emission	irreversibility	Power output	Electrical efficiency
1	indirect integrated system	–	–	–	–	–	–
2	Pressurized direct integrated system	+	+	+	+	○	+
3	atmospheric direct integrated system	○	○	○	○	+	○

7. Conclusion

According to the information presented in this article, the following items can be suggested as the conclusion:

- Direct integrated system with pressurized FC has better performance than the other two types of hybrid system. High electrical efficiency, the low irreversible rate and pollution, low cost of electricity generation, as well as suitable costs of purchase, proper installation are the characteristics of this type of integrated systems.
- The electrical efficiency of a pressurized direct integrated system is 4% higher than atmospheric direct hybrid system and 30% higher than an indirect hybrid system. Studies show that this trend is also present in the exergy efficiency where the exergy efficiency of this system is 3 and 28% higher than the other two hybrid systems, respectively.
- The positive feature of direct integrated system with atmospheric FC is their high power generation, which has also led to their high efficiency. The power generation of direct atmospheric integrated system is about 20% higher than the pressurized type and 23% higher than the indirect type. Also, the total efficiency of the atmospheric integrated system is 5% more than the direct integrated system and 19% more than the indirect hybrid system. This indicates that the heat absorption in the direct atmospheric integrated system is more than the pressurized type and its total efficiency is higher.
- Indirect hybrid systems have lower efficiency in all analyzed parameters than the two pressurized and atmospheric direct hybrid systems.

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