ISME

Iranian Journal of Mechanical Engineering
The Iranian Society of Mechanical Engineers
Research Paper
DOI: 10.30506/jmee.2021.83885.1124

Thermo-economic Performance of an Indirect Hybrid System of Solid Oxide Fuel Cell and Micro Gas Turbine

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The aim of this research is to present a thermo-economic model of an indirect hybrid system of solid oxide fuel cell and micro gas turbine to be used in the combined heat and power generation system. In order to have more accurate results, complete electrochemical, thermal, and thermodynamic calculations in the fuel cell are conducted. Complete electrochemical, thermal, and thermodynamic calculations in the fuel cell are calculated. The results show that the overall efficiency of indirect hybrid system is almost 56% and its electrical efficiency is around 39%. On the thermo-economic results, it can be said that the cost of power generation based on the Lazaretto's simple model is about USD 14.93 cents/kWh and, based on the full economic model, it is about 22.89 cents/kWh. The purchase and installation cost of the hybrid system is about 1972 USD/kW.

Keyword: Cogeneration System, Hybrid System, Micro turbine, Solid Oxide Fuel Cell, Thermo-economic

1 Introduction

Today, fuel cells are considered as a new technology in energy generation, among which solid oxide fuel cell (SOFC) has received more attention due to its high efficiency, lack of environmental pollution, combined heat and power (CHP) generation, use of various fuels, and combination with other energy systems. SOFC is one of the cells with high operating temperature and greater capability to be use in the hybrid power generation systems. One of the most widely used cases of SOFC is the combination of these cells with various gas turbines (GT) [1]. Due to the high efficiency of this type of hybrid systems and also to reduce pollution, the mentioned hybrid systems will have a great impact on power and energy generation in the near future [2-3].

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Receive : 2018/04/06 Accepted : 2021/01/26

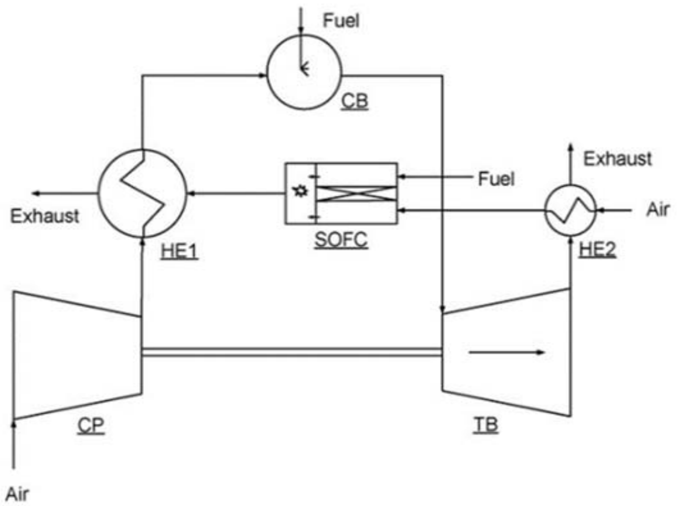

Figure 1 Indirect Hybrid System of Solid Oxide Fuel Cell and Gas Turbine Schematic [1]

The gas turbine and fuel cell hybrid systems can be combined both directly and indirectly. When the passing operating fluid through the fuel cell and gas turbine cycle is the same, the system is called a hybrid system with direct thermal contact [1]. The indirect combination, examined in this study, is formed when the fuel cell and gas turbine have two separate cycles and the passing operating fluid is not the same in both. As shown in Fig (1), this hybrid system consists of two cycles. The first cycle is related to SOFC, which is supplied through the heated air in a recuperator, and the second cycle is a gas turbine cycle. It should be noted that these two cycles can operate at different operating pressures and in various operating fluids. The use of indirect hybrid systems has many advantages over the direct ones.

The indirect hybrid system has two separate and independent power generation systems. In fact, it can be stated that in the indirect hybrid system, the second cycle can supply a part of the required thermal and electrical load, while in the direct hybrid system, both cycles are completely dependent, and inappropriate operation of a cycle will reduce the overall performance of the hybrid system. Based to the above-mentioned factors, the independence of two cycles in indirect hybrid systems will be an important advantage for them in comparison with direct hybrid systems [1]. Designing an optimum heat exchanger and its proper insulation can promote the efficiency of this cycle. Numerous studies have been conducted on hybrid systems in recent years. Araki et al. (2006) [4] investigated a hybrid power generation system consisting of two high-temperature and low-temperature solid oxide fuel cell stacks. Musa et al. (2008) [5] studied the performances of hybrid cycles with two high-temperature and medium-temperature solid oxide fuel cells. Arsalis (2007, 2008) [6-7] investigated four different steam turbine cycles. The models have been developed to function both at design and off-design conditions. Cheddie (2010) [8] proposed SOFC for integration into a 10 MW gas turbine power plant, operating at 30% efficiency. Cheddie et al. (2010, 2011) [9-10] proposed direct, semi-direct and indirectly coupled of SOFC and a 10 MW power plant. Pirkandi et al. (2017) [11] presented an optimal configuration for solid oxide fuel cell-gas turbine hybrid systems based on thermo-economic modelling. In this research, four different designs of direct hybrid systems with pressurized and atmospheric fuel cells have been presented. Pirkandi et al. (2017) [12] presented two different configurations for hybrid gas turbine-fuel cell systems of direct type and to analyze these systems based on the thermodynamic and thermo-economic models. Buonomano et al. (2015) [13] presented a comprehensive review of the possible layout configurations of hybrid power plants based on the integration of solid oxide fuel cells and gas turbine technologies.

Mehrpooya et al. (2017) [14] configured and analyzed a novel integrated system, including air separation unit, coal gasification, solid oxide fuel cell, carbon dioxide and steam cycle with liquefied natural gas. The review of the studies shows that most of them have been conducted on direct hybrid systems, and 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. According to what have been said, the main purpose of this study is the thermos-economic modeling of a sample appropriate configuration for an indirect hybrid system of micro GT and SOFC to be used in a sample CHP system. Due to the importance of cell operating temperature in its performance, in contrast to most of the studies the cell temperature is not supposed to be constant in this study and its value is calculated in various conditions. In the economic analyses conducted in this research, two economic models of total revenue requirement and simple are used to calculate power generation and other related costs. The total revenue requirement model is a complete and accurate model for economic analyses and calculates all the capital and current costs of the system.

2 The proposed hybrid systems

The hybrid system's schematic representation analyzed in this study 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 and entering the fuel cell. The hydrogen obtained from natural gas reacts with the oxygen in the air that has passed another recuperator and entered the fuel cell. Then, the exhaust gases of the cell enter the afterburner chamber and react with each other. The hot output products enter a heat exchanger and heat the gases in the GT cycle.

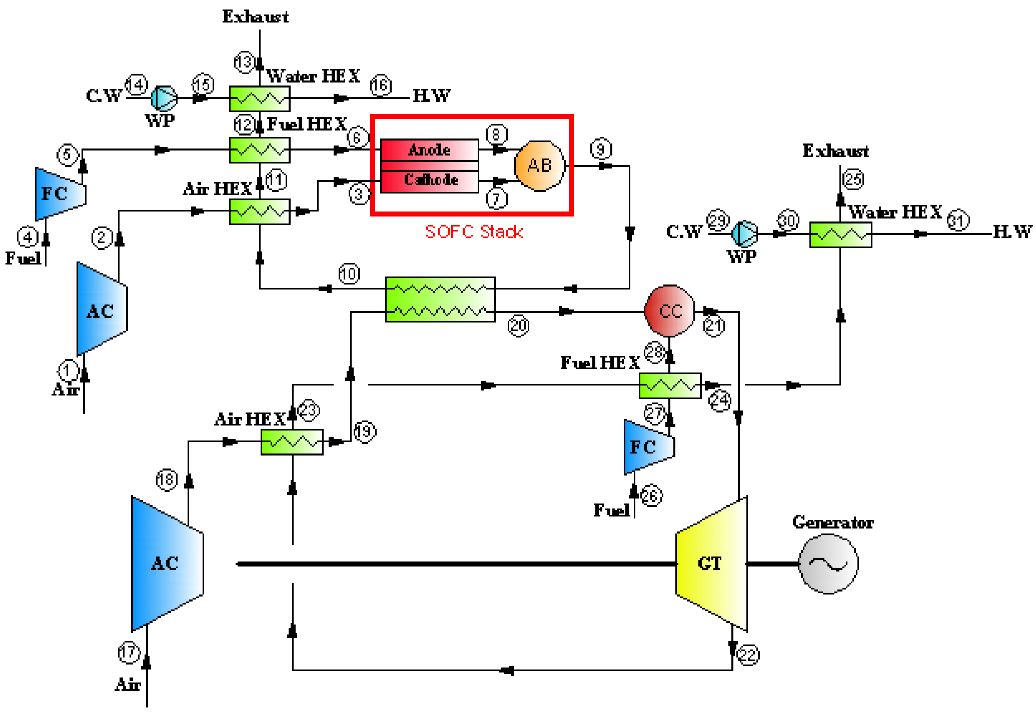

Figure 2 Schematic of the Proposed Hybrid System in this research

After this process, the hot exhaust gases of the exchanger enter three various recuperators. In the micro turbine cycle, the exhaust gases of the compressor are heated by the shared recuperator and heat exchanger, and enter the combustion chamber. After the reaction in the combustion chamber, the hot exhaust gases enter the turbine and, after generation, enter three other recuperators. The third recuperator of each cycle is used to produce hot water at the temperature range of 25 to 90°C. The fuel used in the natural gas system is 97% methane, 1.5% carbon dioxide, and 1.5% nitrogen, and the air is 21% oxygen and 79% nitrogen.
In this study, the proposed system is used as a small-scale CHP unit. The required energy of the building includes the heating, cooling, and electrical energies, and the required system should be able to supply them. The heat obtained from the fuel cell and hot water recuperators can supply the heating load and clean hot water of a building in the winter, while in the summer, this heat can be used in the generator of an absorption chiller to cause cooling and supply the cooling load of the building. The electrical power generated in the fuel cell can also be used to supply the building electrical load. The important point is the separation of the two cycles and the possibility to use each separately, which is the main feature of the indirect hybrid systems.

3 Assumptions

The following assumptions have been considered in the modeling and analysis of the introduced hybrid systems:

- Gas leakage from inside the system to the outside has been disregarded.
- A stable fluid flow has been considered in all the cycle components.
- The fluctuations of kinetic and potential energies have been disregarded.
- The behavior of all the gasses in the cycle has been assumed as that of an ideal gas.
- The distribution of temperature, pressure and chemical components within the fuel cell has been disregarded.
- A constant voltage has been considered for the cells of the fuel cell.
- It has been assumed that the fuel inside the fuel cell converts to hydrogen through internal reforming.

4 Governing equations

In this section, the governing equations of the problem have been presented in three separate areas comprising the thermodynamic, exergy and economic equations.

4.1 Thermodynamic equations

For Air and fuel compressor:
According to thermodynamic equations, the temperature of the compressor’s outflow gasses and the real work needed by the compressor can be determined [15].

$$\dot{W}_{c,a} = \dot{n}_{c,a}.\left(\bar{h}_{out(c,a)} - \bar{h}_{in(c,a)}\right) \tag{1}$$

$$\dot{S}_{gen(c,a)} = \dot{n}_{c,a}.\left(\bar{s}_{out(c,a)} - \bar{s}_{in(c,a)}\right) \tag{2}$$

Where subscript (c,a) is the air compressor and this relationship is used for fuel compressor with subscript (c,f).

For Afterburner and combustion chamber:
Since only a portion of the fuel and air that enter the system are used up in the fuel cell, an afterburner chamber is necessary for the cycle. All reactions are exothermic, and they raise the temperature of the gasses that exit the afterburner chamber [15].

$$\dot{n}_{in.ab}\bar{h}_{in.ab} - \dot{n}_{out.ab}\bar{h}_{out.ab} - \dot{Q}_{loss.ab} = 0 \tag{3}$$

$$\dot{Q}_{loss.ab} = \dot{n}_{f.ab} \times (1 - \eta_{ab}) \times LHV \tag{4}$$

$$\eta_{ab} = {f_{theoretical}}/{f_{actual}} \tag{5}$$

$$\dot{S}_{gen.ab} = \dot{n}_{out.ab}\bar{s}_{out.ab} - \dot{n}_{in.ab}\bar{s}_{in.ab} + \frac{\dot{Q}_{loss.ab}}{T_{surr}} \tag{6}$$

For Turbine:

$$\dot{W}_{GT} = \dot{n}_{GT}(\bar{h}_{in.GT} - \bar{h}_{out.GT}) \tag{7}$$

$$\dot{S}_{gen.GT} = \dot{n}_{GT}(\bar{s}_{out.GT} - \bar{s}_{in.GT}) \tag{8}$$

For Fuel Cell:
The general solutions for the conservation of mass and energy equations of the fuel cell require the evaluation of the voltage and current generated in the cell [16]. The full procedures for computing the cell voltage loss have been presented in [16-18].
Due to the high operating temperatures of solid oxide fuel cells, the fuel needed by the cell can be produced within the cell from hydrocarbons such as natural gas. In this paper, a fuel cell with direct internal reforming has been used. The heating values resulting from the reforming (Q_r), shifting (Q_{sh}) and electrochemical (Q_{elec}) reactions are obtained by means of Eqs. (9)-(11) [16].

$$\dot{Q}_r = x\left(\bar{h}_{CO} + 3\bar{h}_{H_2} - \bar{h}_{CH_4} - \bar{h}_{H_2O}\right) \tag{9}$$

$$\dot{Q}_{sh} = y\left(\bar{h}_{CO_2} + \bar{h}_{H_2} - \bar{h}_{CO} - \bar{h}_{H_2O}\right) \tag{10}$$

$$\dot{Q}_{elec} = zT\Delta S - I\Delta V_{loss} \tag{11}$$

$$\dot{Q}_{net} = \dot{Q}_{elec} + \dot{Q}_{sh} - \dot{Q}_r \tag{12}$$

With regards to Eq. (13), a portion of this residual net heat is used to raise the temperature of the cell's internal and outflowing gasses $\left(\dot{Q}'\right)$ and another portion enters the surrounding environment$\left(\dot{Q}_{surr}\right)$.

$$\dot{Q}_{net} = \dot{Q}' + \dot{Q}_{surr} \tag{13}$$

In a real condition, the processes implemented in a fuel cell cannot be considered as adiabatic whatsoever; and always there is some heat loss to the surrounding atmosphere. By considering this problem as an ideal case, it is assumed that the fuel cell is internally adiabatic and that the net residual heat is used to raise the temperature of the cell's internal and outflowing gasses$\left(\dot{Q}''\right)$In this equation, $\Delta h_{an,in}$ and $\Delta h_{ca,in}$ denote the enthalpy changes of reactants, and $\Delta h_{an,out}$ and $\Delta h_{ca,out}$ indicate the enthalpy changes of products at the anode and cathode [17].

$$\dot{Q}'' = \Delta h_{ca,in} + \Delta h_{ca,out} + \Delta h_{an,in} + \Delta h_{an,out} \tag{14}$$

To compute the temperature of the fuel cell's outflowing gasses, an iteration algorithm has been employed, and the convergence criterion has been considered as Eq. (15).

$$Q_{error} = \left| \frac{\dot{Q}'' - \dot{Q}'}{\dot{Q}'} \right| < 0.01 \tag{15}$$

After calculating the output temperature, Eq. 16 can be used to determine the amount of heat loss in the fuel cell.

$$\dot{n}_{ca.in}\bar{h}_{ca.in} + \dot{n}_{an.in}\bar{h}_{an.in} = \dot{n}_{ca.out}\bar{h}_{ca.out} + \dot{n}_{an.out}\bar{h}_{an.out} + \dot{Q}_{surr} + \dot{W}_{SOFC} \tag{16}$$

For Recuperator:

$$\dot{Q}_{rec,g} = \varepsilon_{rec,w}\dot{n}_g\left(\bar{h}_{in,rec} - \bar{h}_{out,rec}\right) \tag{17}$$

$$\dot{Q}_{rec,w} = \dot{n}_w\bar{C}_p\left(T_{out,w} - T_{in,w}\right) \tag{18}$$

The amount of heating load obtained from the last recuperator is used to calculate the total thermal efficiency of the system [15].

$$\dot{S}_{gen,rec} = \dot{n}_a\left(\bar{s}_{out,a} - \bar{s}_{in,a}\right) - \dot{n}_g\left(\bar{s}_{in,g} - \bar{s}_{out,g}\right) \tag{19}$$

For Pump:

$$\dot{W}_{wp} = \dot{n}_w v_w\left(P_{out,w} - P_{in,w}\right) \tag{20}$$

$$\dot{S}_{gen,wp} = \dot{n}_w\left(\bar{s}_{out,w} - \bar{s}_{in,w}\right) \tag{21}$$

For Hybrid system:

By considering the whole hybrid system as a control volume, it's electrical, thermal, total, and exergy efficiencies will be obtained [17].

$$\eta_{ele} = \frac{\dot{W}_{net}}{\dot{n}_f LHV} \tag{22}$$

$$\eta_{exergy} = \frac{\dot{W}_{net} + \dot{E}_{out.w}}{\dot{E}_{in.a} + \dot{E}_{in.f} + \dot{E}_{in.w}} \tag{23}$$

$$\dot{W}_{net} = \left(\dot{W}_{AC-tot}\right)_{SOFC} + \left(\dot{W}_{AC-net}\right)_{GT} \tag{24}$$

$$\left(\dot{W}_{AC.net}\right)_{GT} = \left(\dot{W}_{DC.net}\right) \times \eta_{inv.gen} - \dot{W}_{wp} - \dot{W}_{c,air} - \dot{W}_{c.fuel} \tag{25}$$

The term of $\eta_{inv,gen}$ is the direct-to-alternating current conversion factor of the micro turbine generator.

4.2 The exergy equations

A subject arising from the second law of thermodynamics is the method of exergy analysis in system modelling [19-20].

$$\dot{E}_{destroyed.sys} = \dot{E}_{in.a} + \dot{E}_{in.f} + \dot{E}_{in.w} - \dot{W}_{net} - \dot{E}_{out.w} - \dot{E}_{out.gas} \tag{26}$$

$$\dot{E}_{lost,sys} = \dot{E}_{out,gas} \tag{27}$$

$$\dot{I}_{tot} = \dot{E}_{destroyed,sys} + \dot{E}_{lost,sys} \tag{28}$$

4.3 The economic equations

In order to economically optimize energy systems, it is necessary to compare the annual expenses associated with investment, fuel, operating and maintenance [21].

$$\dot{C}_{P,tot} = \dot{C}_{F,tot} + \dot{Z}_{tot}^{CI} + \dot{Z}_{tot}^{OM} \tag{29}$$

$$\dot{Z} = \dot{Z}_{tot}^{CI} + \dot{Z}_{tot}^{OM} \tag{30}$$

In this research, the generated electricity and the natural gas have been considered as the output product and the consumed fuel of the hybrid system. Eq. (31) is the objective function in the optimization problem, in which the electricity generation cost must be minimized. In Eq. (31), C_P denotes the cost of generated electricity per unit Giga Joule.

$$c_P = \frac{\dot{C}_{F,tot} + \dot{Z}_{tot}^{CI} + \dot{Z}_{tot}^{OM}}{\dot{W}_{net}} \tag{31}$$

The validity of a thermo-economic analysis depends to a large extent on the accurate computation of $\dot{Z}$ by the considered economic model [21]. The simple economic model of Lazaretto and the total revenue requirement method have been used for the economic analyses performed in this research.

4.3.1 Lazaretto's simple economic model

In this model, the sum of the initial capital investment and the operating and maintenance costs has been formulated according to Eq. (32) [21].

$$\dot{Z}_k = CRF\,\frac{\Phi_r}{3600\,N}\,PEC_k \qquad \left[\frac{\$}{s}\right] \tag{32}$$

In the above equation, PEC_k is the initial purchase cost of the k^{th} equipment (which is calculated based on the thermodynamic parameters), Φ_r is the operating and maintenance cost (1.06-1.1), N is the total annual operating hours of the system under full load (85% of total work capacity, and equal to 7446 h), and CRF is the capital recovery factor. The capital recovery factor is itself a function of the interest rate (i) and the number of years the machineries have been in operation (n), and it is calculated based on the values of these two parameters [21]. In thermo-economic analyses, the CRF normally has a range of 0.147 to 0.18. In Eq. (33), the interest rate or the discount factor has been considered in the range of 0.1 to 0.12.

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{33}$$

The economic model of the total revenue requirement method

In this method, based on the economic hypotheses, the equipment and land purchase costs, cost of engineering services, facilities construction cost, fuel cost, repair, maintenance costs and so on are computed and levelized on an annual basis over the system's operating period [21].

$$\dot{Z}_k = \frac{CC_L + OMC_L}{\tau} \times \frac{PEC_k}{\sum_k PEC_k} \tag{34}$$

$$CC_L = TRR_L - FC_L - OMC_L \tag{35}$$

$$TRR_L = CRF \sum_{j=1}^{n} \frac{TRR_j}{(1+i)^j} \tag{36}$$

In the above equation, TRR_j is the total revenue requirement in the j^{th} year of system operation; and the detailed procedure regarding its computation has been given in [9].

$$\dot{Z}_{tot} = \dot{Z}_{tot}^{CI} + \dot{Z}_{tot}^{OM} = \frac{CC_L + OMC_L}{\tau} \tag{37}$$

$$\dot{C}_{p,tot} = \frac{CC_L + OMC_L + FC_L}{\tau} = \frac{TRR_L}{\tau} \tag{38}$$

$$c_p = \frac{TRR_L}{\tau \times \dot{W}_{tot}} \tag{39}$$

The purchase, installation, and start-up costs of a power generation unit are obtained by Eq. (40).

$$c_{pp} = \frac{PEC_{tot} + 0.46PEC_{tot}}{\dot{W}_{tot}} \tag{40}$$

5 The solution method

In view of the equations mentioned in the previous sections, a computer program has been written for analyzing the problem. The first part of this computer code contains the hybrid system's input information including its working pressure and the air flow rates and fuel entering the system. At this point, because of the cell's working temperature not being constant, an arbitrary cell temperature is initially guessed. Using this guesstimated cell temperature, in the next step, the nonlinear reforming and electrochemical equations as well as the cell's thermal equations are solved simultaneously, and the desired outcomes including the composition of produced chemical components and the values of temperature, voltage loss, real voltage, electrical current, power, efficiency, and other considered parameters in the fuel cell are obtained. The equations of the other system components are also analyzed along with the solutions of fuel cell equations. After analyzing the whole system, the new cell temperature is determined by considering the given conditions. In case the convergence condition of the cycle is not fulfilled, the analysis will be repeated with a new temperature. Following the thermodynamic analyses, economic analyses are also carried out for the system in the final section.

6 Results

For the validation of the developed code, it is required to compare the results of the developed code to the laboratory or numerical results of a certain sample. In order to examine the accuracy of the results related to the thermo-economic section, the results of Masardo's economic analysis [23] performed on a simple GT cycle are compared to the results of the present code. Masardo used a simple economic model in his study. The agreement between these results (Table (1)) confirms the accuracy of the present method and 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.

6.1 Thermodynamic Analysis Results

In this section, the effects of compressor pressure ratio and ratio of the airflow passing from the fuel cell cycle to micro GT cycle are examined as two important parameters. It should be noted that in the conducted analyses, the effects of operating pressure change are investigated separately in both cycles. The constant parameters used for the proposed system are presented in [15-17].

6.1.1 Pressure Change in the Fuel Cell Cycle

The results show that an increase in pressure in the fuel cell cycle raises the cell operating temperature and, as a result, increases the temperature of incoming gases to the turbine in the micro turbine cycle (Figures (3) and (4)). In general, an increase in the fuel cell causes an increase in its theoretical voltage value. By increasing the pressure ratio in the fuel cell cycle, the chemical reactions rate is raised in the cell and, consequently, the temperature and voltage are also increased. The raise in the cell temperature also increases the temperature of exhaust gases, which will heat the air in the micro turbine cycle. It can be seen in Figure (3) that pressure change in the fuel cell from 2 to 13 bar, with respect to the passing airflow rate from two cycles, will increase the cell temperature by about 50 to 100°C. According to Figure (4), due to an increase in pressure in the fuel cell cycle, the temperature of the incoming gases to the turbine will also increase.

Table 1 Comparing the results of the present computer code with the numerical results of Masardo[22]

Investigated parameters	Results obtained by Masardo et al. [22]	Results obtained by the written computer code
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

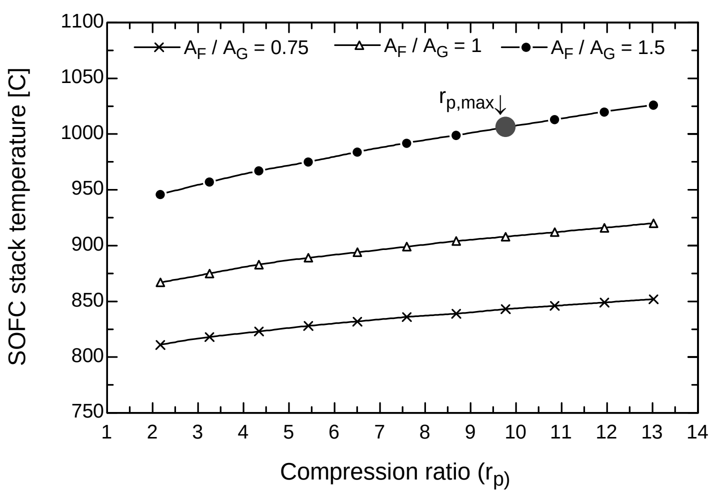

Figure 3 the effect of fuel cell compressor pressure ratio on temperature of fuel cell

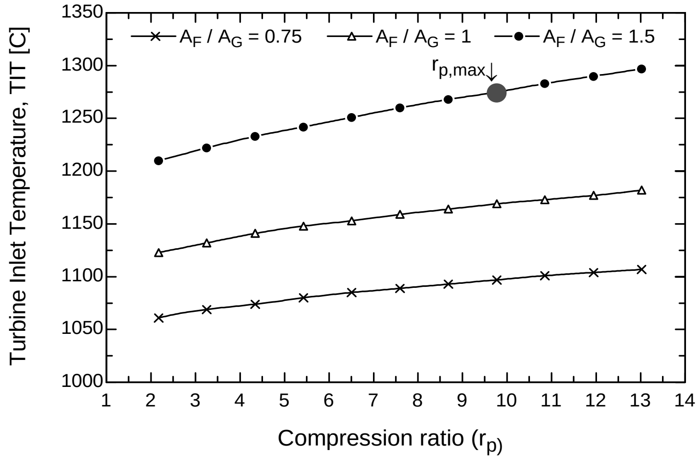

Figure 4 the effect of fuel cell compressor pressure ratio on temperature inlet turbine

Reviewing the conducted studies shows that in direct hybrid systems, in which the fuel cell is located at the turbine upstream, by increasing the compressor pressure ratio, the cell temperature will decrease due to the decreased temperature in the turbine output. As can be seen in Figures (3) and (4), by increasing the rate ratio of the airflow passing from the fuel cell cycle to the GT cycle (a decrease in the airflow passing from GT cycle in the rate of the constant airflow of the fuel cell cycle), the temperature of the incoming gases to turbine and the cell operating temperature will be raised. The important point that should be considered in reviewing the results is the constraint on cell operating temperature (800 to 1000°C) and the maximum temperature of incoming gases to the turbine. According to Figure (4), when the rate of the airflow passing from the fuel cell cycle to GT cycle is equal to 1.5, the maximum operating pressure of the system is 10 bar. The results show that at higher pressures, the cell temperature will be higher than 1000°C, which will damage the cell and causes efficiency loss. This is also true about the incoming gases to turbine in the downstream cycle. The system operating range should be considered in such a way that the turbine blades can tolerate high temperatures. The use of new technologies in construction and cooling can improve the tolerance of turbine blades as well as system efficiency. It can be concluded that in the different operating pressure ranges, the ratio of 0.75 to 1 is acceptable and the results can be examined in other charts. The conducted studies show that an increase in the operating temperature of the cell and incoming gases to the turbine causes an increase in power generation in both components. As can be observed in Figures (3) and (4), an increase in the pressure of the fuel cell cycle raises the operating temperature of the cell and incoming gases to the turbine. Despite the increase in these two parameters, the electrical efficiency and power generation of the hybrid system decrease because of the high consumption of compressors (Figures (5) and (6)).

In fact, an increase in the required operation of the compressors overcomes the increase in cell and turbine power, which causes the power losses and efficiency losses of the hybrid system. The maximum electrical efficiency and power generation of the system which can be achieved in this mode is 43.28% and 935.6 kW. The results of this section show that, in order to increase the electrical efficiency and power generation, the fuel cell should operate at its minimum operating pressure. As can be seen in Figures (5) and (6), by increasing the ratio of the rate of airflow passing from the fuel cell cycle to GT cycle (decreasing the rate of the airflow passing from GT cycle), the electrical efficiency and power generation in the hybrid system will increase. From the results in this section, it can be concluded that in this type of hybrid systems, it is better if the rate of the airflow passing from the fuel cell cycle is greater than that of the airflow passing from the GT cycle.

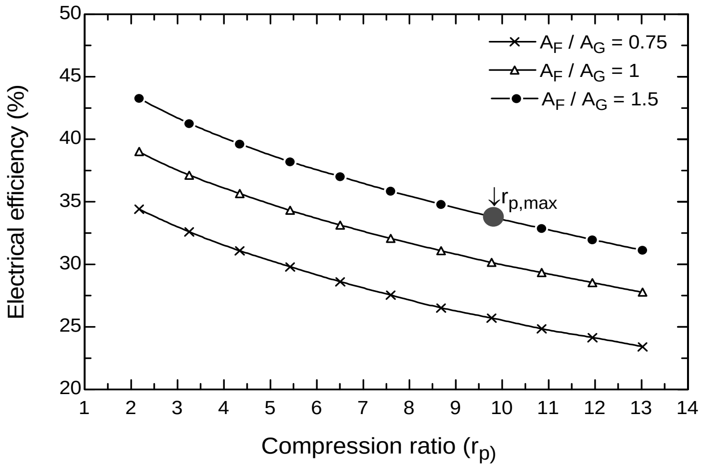

Figure 5 the effect of fuel cell compressor pressure ratio on system electrical efficiency

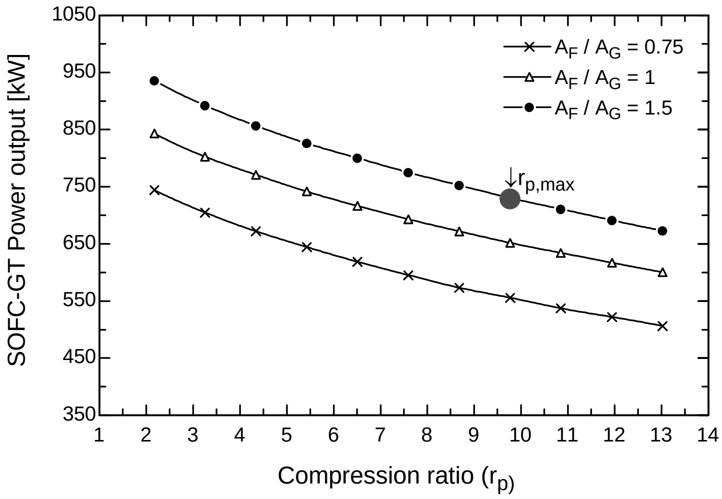

Figure 6 the effect of fuel cell compressor pressure ratio on net generated power

Below, the entropy generation and irreversibility of the hybrid system rates are shown at various pressure ratios of the fuel cell cycle. According to Figures (7) and (8), by increasing the operating pressure of fuel cell cycle, the entropy generation and irreversibility rate will increase.

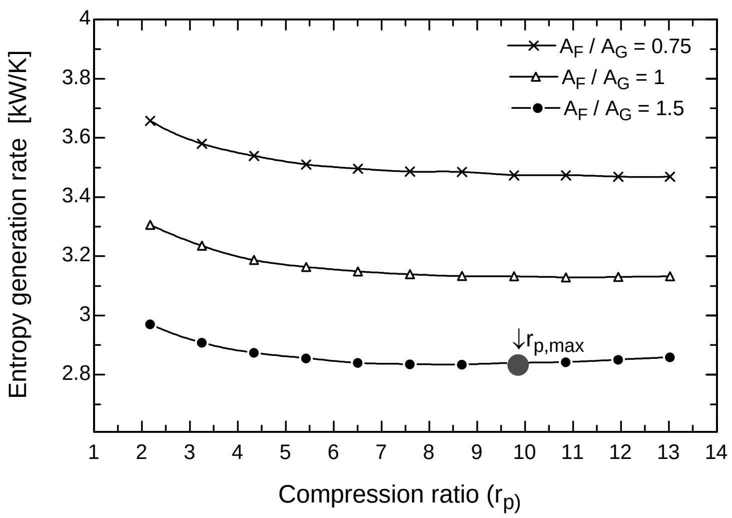

Figure 7 the effect of fuel cell compressor pressure ratio on entropy generation rate

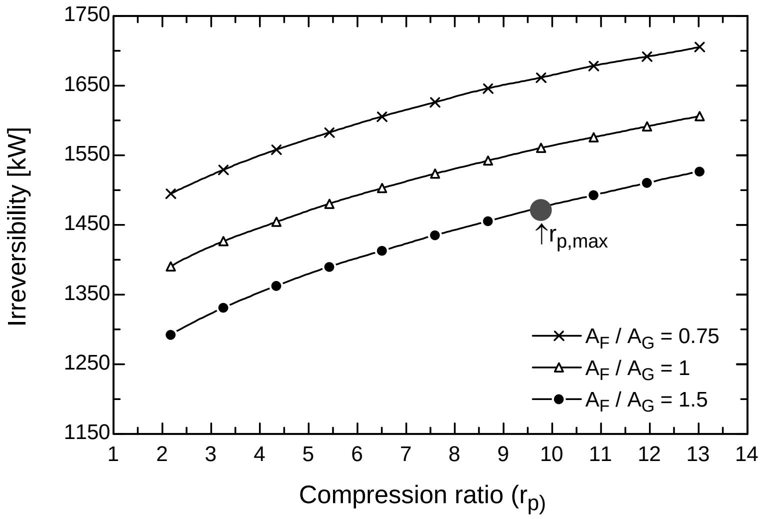

Figure 8 the effect of fuel cell compressor pressure ratio on irreversibility

The main reason of the increase in irreversibility rate is the sharp rise in exergy losses rate, which is due to the high pressure and high temperature exhaust gases of the fuel cell cycle. On the other hand, the results show that by increasing the rate ratio of the airflow passing from the fuel cell cycle to GT cycle, the system is more efficient and the entropy generation and irreversibility rates of the system decrease. As observed in this section, the increased operating pressure in the fuel cell cycle is not a useful parameter and will reduce the power and electrical efficiency of the system and also increase its irreversibility. On the other hand, by examining the figures above, it can be concluded that in the indirect hybrid systems, it is better for the rate of the passing airflow from the fuel cell cycle to be more than that of the airflow passing from the GT cycle.

6.1.2 Pressure Change in the Gas Turbine Cycle

In this section, pressure change in the GT cycle is examined as an effective parameter in the hybrid system. According to Figures (9) and (10), increasing the pressure ratio of the GT cycle reduces the temperature of cell operation and that of incoming gases to the turbine. The reason is that by increasing the pressure ratio of the compressor, pressure ratio in the turbine is decreased more, and as a result, the temperature of exhaust gases of the turbine decreases. The decrease in temperature of the exhaust gases from the turbine reduces the thermal exchange in the shared heat exchanger, which will decrease the cell operating temperature. As can be seen, in this mode depending on the rate of the airflow passing from fuel cell cycle and GT cycle, the system operation can be examined at various pressures. As shown in Figure (9), if the rate of airflow passing from the cell is twice the rate of the airflow passing from the GT cycle, it is better to use a pressure ratio greater than 4 in order to prevent excessive increase in cell temperature. By increasing the rate of the airflow passing from the GT cycle, the cell operating temperature and the temperature of the incoming gases to the turbine will decrease. Another constraint that should be noted in these analyses is the maximum allowable temperature of turbine blades, which should be decided based on the type of blades.

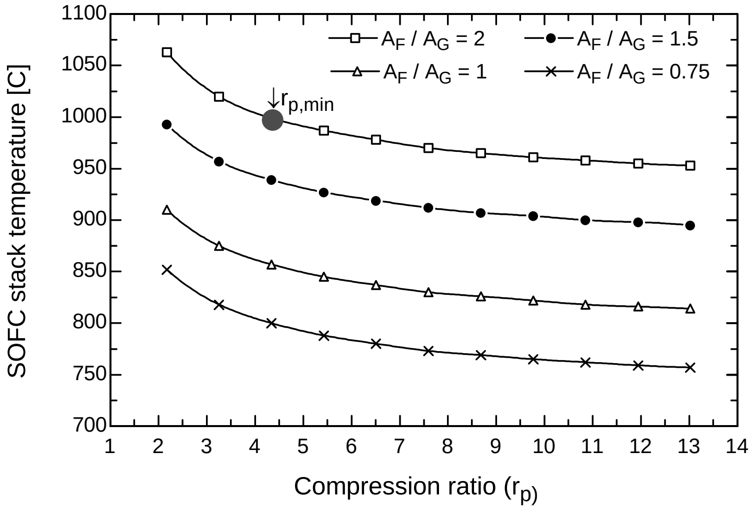

Figure 9 the effect of compressor pressure ratio of gas turbine cycle on fuel cell temperature

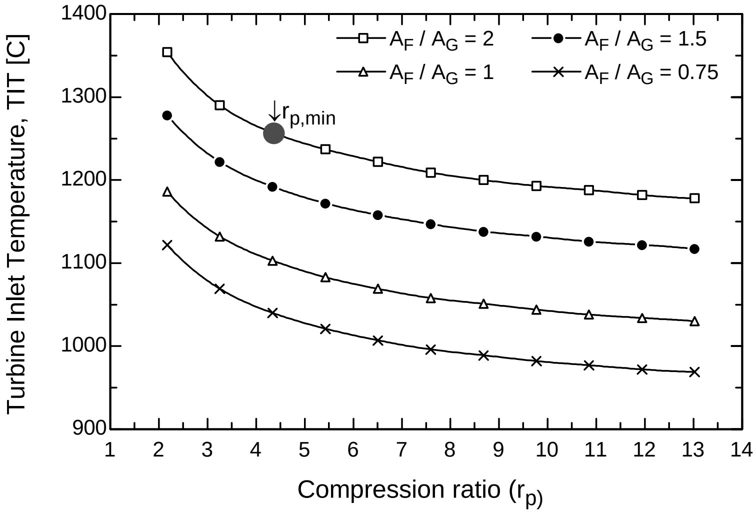

Figure 10 the effect of compressor pressure ratio of gas turbine cycle on temperature inlet turbine

In Figures (11) and (12), the effect of pressure change in the GT cycle on the electrical efficiency and power generation of the hybrid system is shown. The results show that by increasing the compressor pressure ratio in the GT cycle, the efficiency and power generation of the system slightly increase at first and, then, decrease. The reason of this loss is the decrease in operating temperature and the temperature of incoming gases to turbine, and also the the increase in the required power in the compressor. By increasing the rate of the airflow from passing the GT cycle, the efficiency and power generation of the system will decrease due to the cooling effect and also the increase in required operation in the compressor. In the optimum mode of the system, the efficiency of 42.86% and power generation of 926.4 kW can be obtained.

In Figures (13) and (14), the entropy generation and irreversibility rates of the system are shown. As can be seen, by increasing the compressor pressure ratio in the GT cycle and also by increasing rate of the airflow passing from GT cycle, the entropy generation and irreversibility rates of the system will increase. The results show that since the turbine is not used in the fuel cell cycle, the increased pressure in this cycle is not a useful parameter, because the exhaust gases are discharged into the environment with high pressures.

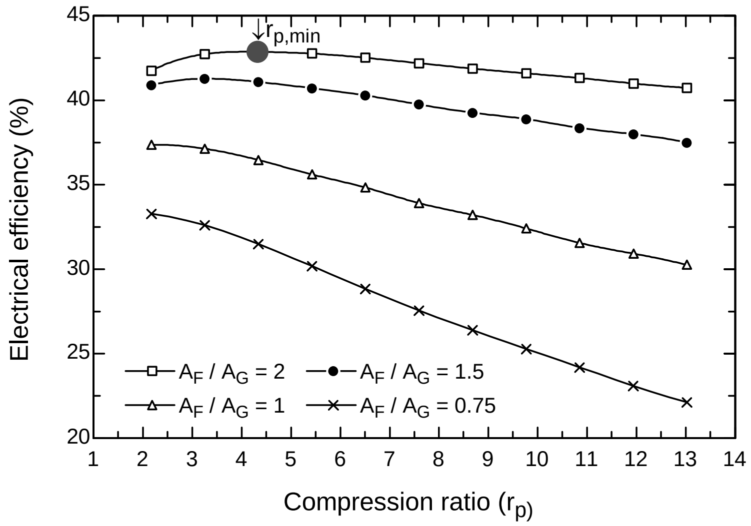

Figure 11 the effect of compressor pressure ratio of gas turbine cycle on electrical efficiency

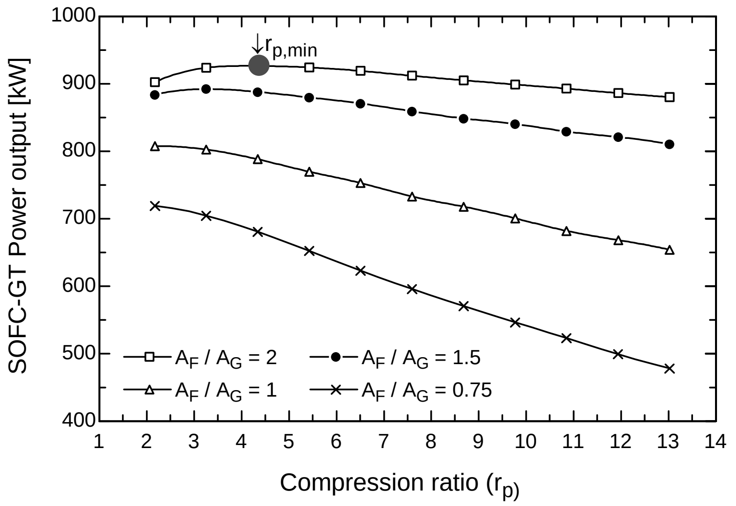

Figure 12 the effect of compressor pressure ratio of gas turbine cycle on Net generated power

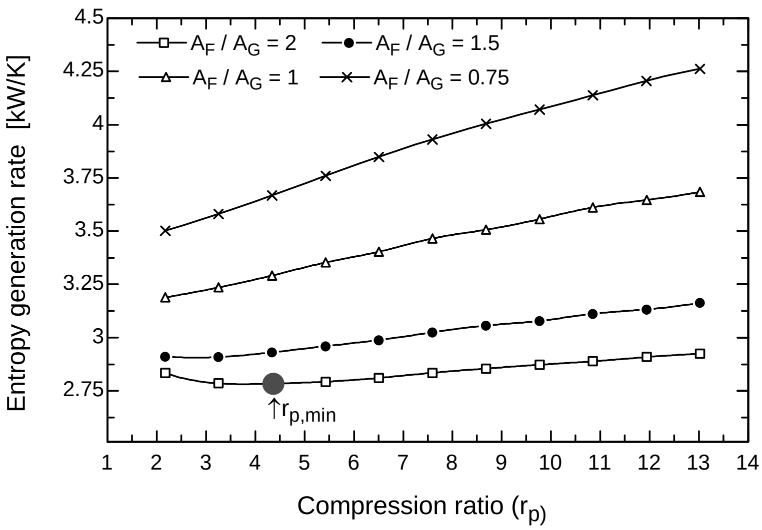

Figure 13 the effect of compressor pressure ratio of gas turbine cycle on entropy generation rate

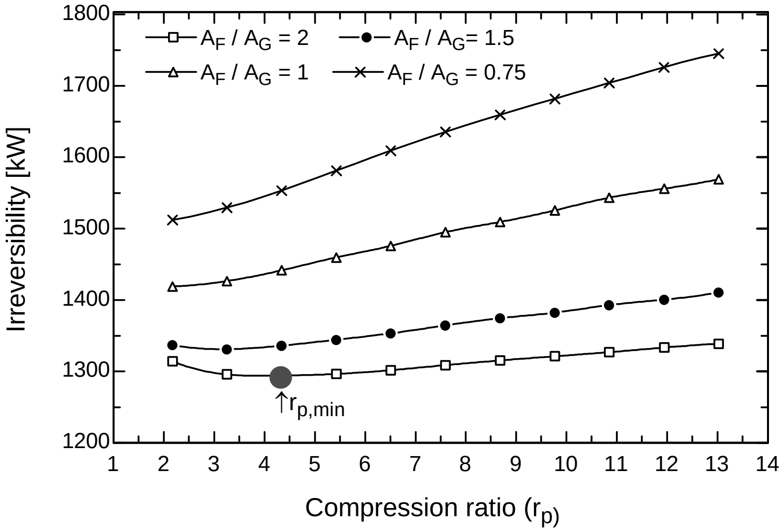

Figure 14 the effect of compressor pressure ratio of gas turbine cycle on irreversibility

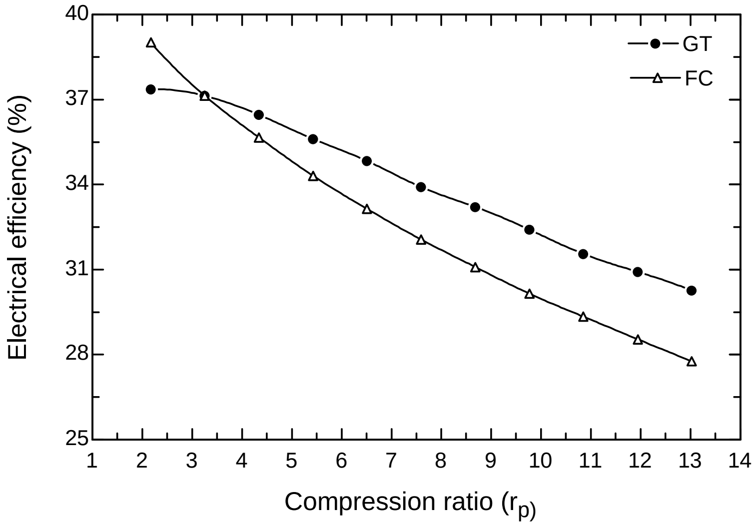

Figure 15 comparison of the effect of compressor pressure ratio on the electrical efficiency

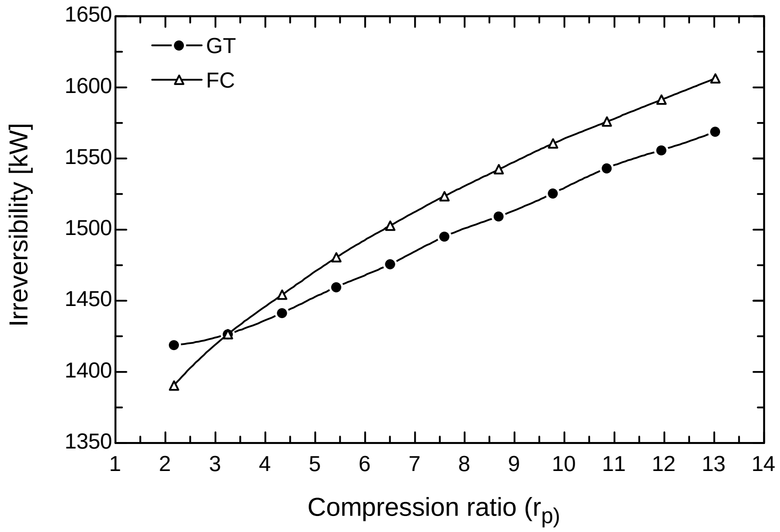

Figure 16 comparison of the effect of compressor pressure ratio on irreversibility

In this section, the effect of operating pressure change in both cycles of the hybrid system is compared by considering two parameters of electrical efficiency and irreversibility rates. As shown in Figures (15) and (16), at the pressure ratios of above 3, the pressure change in the GT cycle is better than the pressure change in the fuel cell cycle. High efficiency and lower irreversibility are the advantages of this state. At the pressure ratios of less than 3 bar, it is suggested that the pressure change happens in the fuel cell cycle.

6.2 Results of thermo-economic analysis

In this section, the effect of compressor operating pressure ratio in the GT cycle and fuel cell cycle on the cost of power generation of the indirect hybrid system is examined. In Figures (17) and (18), the simultaneous effect of operating pressure change ratio of the fuel cell cycle on the cost of power generation, electrical efficiency, and power generation of the hybrid system is shown. As can be seen, by increasing the compressor pressure ratio in the fuel cell cycle, the cost of power generation increases and the electrical efficiency and power generation will decrease. In these two figures, the airflow is considered equal in both cycles. In the indirect hybrid system, the fuel cell cycle operating at the lowest possible pressure will cause better performance, economically and thermodynamically.

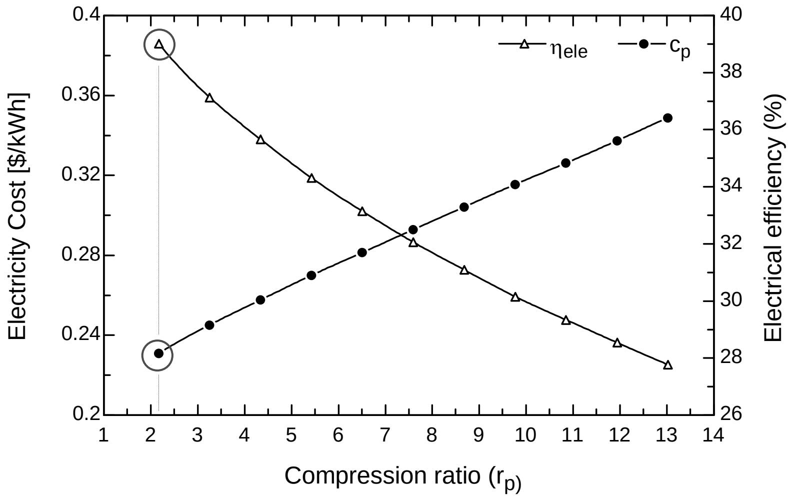

Figure 17 the effect of fuel cell compressor pressure ratio on electrical efficiency and cost

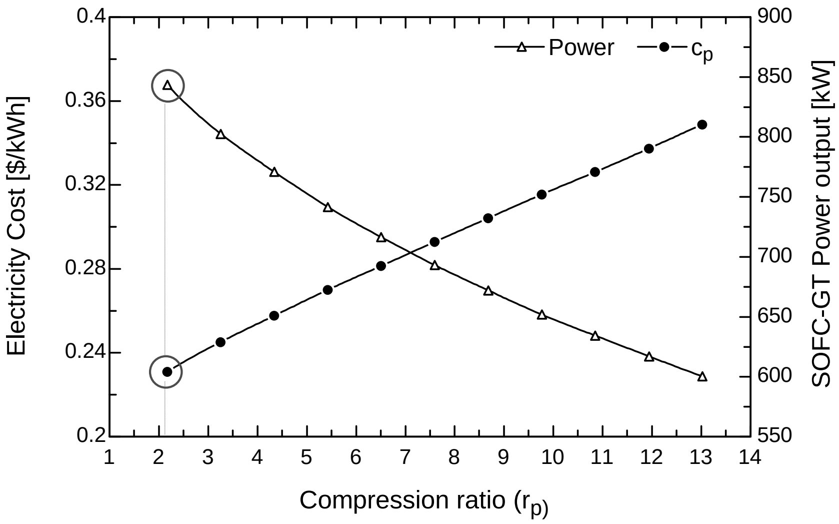

Figure 18 the effect of fuel cell compressor pressure ratio on electrical cost and Net generated power

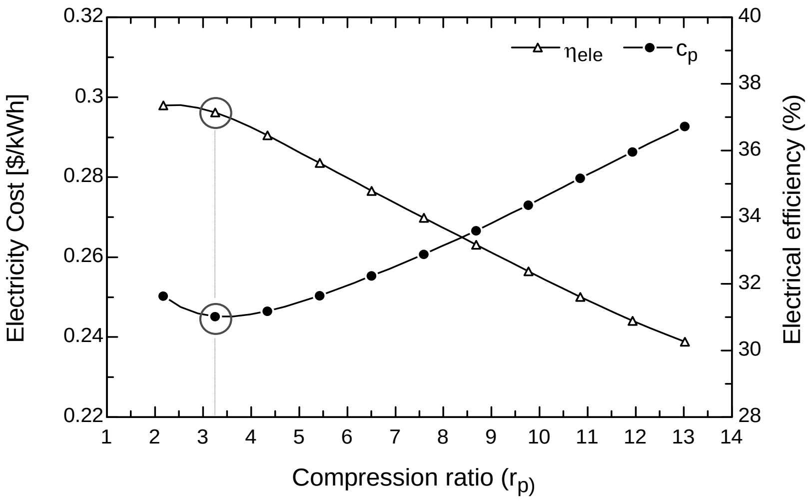

Figure 19 the effect of compressor pressure ratio of gas turbine cycle on electrical efficiency and cost

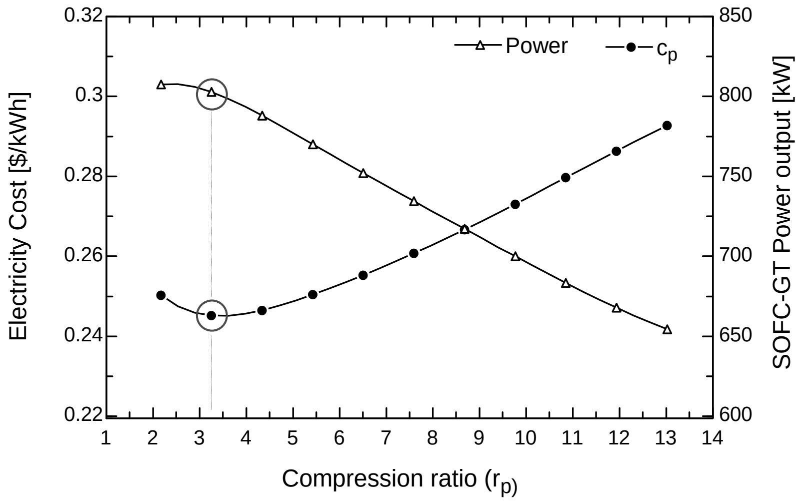

Figure 20 the effect of compressor pressure ratio of gas turbine cycle on electricity cost and net generated power

In Figures (19) and (20), the effect of operating pressure ratio of the GT cycle on the cost of power generation and hybrid system operating is shown. As can be seen, at low operating pressure, the hybrid system has low power cost, and high electrical efficiency and power generation. The only important point in this section is the optimum operating pressure range in the system. At the operating pressure ratios of 3 to 3.5, the system has the best thermodynamic and economic performance. Decrease and increase in this pressure ratio will cause an increase in power generation cost and a decrease in electrical efficiency of the system. Because the purpose of designing an optimum power generation system is to access high efficiency and lower costs of power generation, system operation is appropriate at low operating pressures. Based on the analyses in the previous sections, the results of the optimum mode of an indirect hybrid system are shown in Table (2). As seen in this table, the overall efficiency of the proposed system is about 56% and its electrical efficiency is about 39%. On the thermo-economic results, it can be said that the power generation cost based on Lazaretto's simple model is about 14.93 cents and, based on the TRR complete economic model, it is about 22.89 cents. The purchase and installation cost of the hybrid system is about 1972 USD/kW. In Table (3), the results of the indirect hybrid system performance are compared with that of the GT cycle performance. As seen in this table, the use of indirect hybrid system will cause 52% increase in the electrical efficiency and 5% increase in the overall efficiency. One of the main problems in the hybrid system is the high initial purchase cost and its installation costs.

Table 2 Indirect hybrid system in optimum operating parameters

Parameter	Amount	Parameter	Amount
Air flow rate in two cycles (kmol/hr)	150	Generated entropy (kW/K)	3.407
The main fuel flow rate at fuel cell cycle (kmol/hr)	11	Destroyed exergy (kW)	980.4
The injected fuel flow rate in two cycles (kmol/hr)	0	Exergy lost (kW)	532.8
Compressor pressure ratio in two cycles (bar)	3.255	Heat recovery rate (kW)	411.9
Cell temperature (°C)	911	Irreversibility (kW)	1513.2
Temperature inlet turbine (°C)	1200	Equipment purchase cost ($)	1265000
Electrical efficiency (%)	39.4	Cost of equipment and maintenance in one year ($)	734701
Overall efficiency (%)	56.72	Price of generated electricity ($/kWh)	0.2289
Power generated by fuel cell (kW)	975.5	Electricity price based on the simple model ($/kWh)	0.1493
Power generated by turbine (kW)	333.4	Price of electricity in the first year ($/kWh)	0.2219
Power generated by system (kW)	936.8	Purchase, installation and startup cost of the system ($/kW)	1972

Table 3 Compare the results of the indirect hybrid system with gas turbine simple cycle

parameters	indirect hybrid system	Simple cycle
Electrical efficiency	39.4	25.87
Overall efficiency	56.72	53.88
Equipment purchase cost ($)	1265000	65806
Electricity price based on TRR model ($/kWh)	0.2289	0.2141
Electricity price based on Lazaretto model ($/kWh)	0.1493	0.1955
Price of electricity in the first year ($/kWh)	0.2219	0.1666
Purchase, installation and startup cost of the system ($/kW)	1972	561.6

7 Conclusion

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

- By increasing the rate ratio of the airflow passing from the fuel cell cycle to GT cycle (decreasing the rate of the airflow passing from GT cycle), the electrical efficiency and power generation in the hybrid system will increase. It can be concluded that in this type of hybrid systems, it is better for the rate of the airflow passing from the fuel cell cycle to be greater than that of the airflow passing from the GT cycle.

- Increasing the pressure ratio of the GT cycle reduces the cell operating temperature and the temperature of the incoming gases to the turbine. In fact, it can be said that by increasing the pressure ratio of the compressor, the pressure ratio losses in the turbine increase and, as a result, the temperature of exhaust gases of the turbine decreases. The decrease in the temperature of exhaust gases from the turbine reduces the thermal exchange in the shared heat exchanger and this will decrease cell operating temperature.
- If the ratio of airflow passing from the cell is twice the rate of the airflow from GT cycle, it is better for the pressure ratio to be greater than 4 in order to prevent the excessive increase in cell temperature. By increasing the rate of the airflow passing from the GT cycle, the cell operating temperature and the temperature of incoming gases to the turbine will decrease. Another constraint on these analyses that should be noted is the maximum allowable temperature of turbine blades, which should be decided based on the type of blades.
- By increasing the compressor pressure ratio in the GT cycle, the efficiency and power generation of the system slightly increase at first and, then, decline. The reason of this loss is the decline in operating temperature and the temperature of incoming gases to the turbine and also the increase in the required power in compressor. By increasing the passing airflow rate from the GT cycle, the efficiency and power generation of the system will decrease due to the cooling effect and also the increased required operation in the compressor. In the optimum mode of the system, the efficiency of 42.86% and power generation of 926.4 kW can be obtained.
- By increasing the compressor pressure ratio in the GT cycle and also by increasing the rate of the airflow passing from the GT cycle, the entropy generation and irreversibility rates of the system will increase. The results show that, because the turbine is not used in the fuel cell cycle, the increased pressure in this cycle is not a useful parameter, because the exhaust gases are discharged into the environment with a high pressure.
- At the pressure ratios of above 3, the pressure change in the GT cycle is better than the pressure change in the fuel cell cycle. High efficiency and lower irreversibility are the advantages of this state. At the pressure ratios of less than 3 bar, it is suggested that the pressure change happen in the fuel cell cycle.
- By increasing the compressor pressure ratio in the fuel cell cycle, the cost of power generation increases and the electrical efficiency and power generation will decrease. The results show that, in the indirect hybrid system, the operation of the fuel cell cycle at the lowest possible pressure will cause better performance, economically and thermodynamically.
- At the low operating pressure, the hybrid system has lower power cost and higher electrical efficiency and power generation. The only important point in this section is the optimum operating pressure range in the system. The results show that, at the operating pressure ratios of 3 to 3.5, the system has the best thermodynamic and economic performance. Decrease and increase in this pressure ratio will cause an increase in power generation and a decrease in the electrical efficiency of the system. Due to the point that the purpose of designing an optimum power generation system is to access high efficiency and lower costs of power generation, it is suggested that the system operate at low operating pressures.
- The overall efficiency of the proposed system is about 56% and electrical efficiency is about 39%. On the thermo economic results, it can be said that the power generation cost based on Lazaretto's simple model is about USD 14.93 cents/kWh and, based on the complete economic model, it is about USD 22.89 cents/kWh. The purchase and installation cost of the hybrid system is about 1972 USD/kW.

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Nomenclature

A	Area (m^2)
CC_L	levelized capital investment cost ($)
$\dot{C}_P$	rate of power generation cost ($/h)
$\dot{C}_F$	rate of fuel cost ($/h)
E	reversible voltage of fuel cell (V)
$\dot{E}$	rate of exergy (W/h)
F	faraday's constant (96,485 C/mol)
FC_L	levelized fuel cost ($)
h	enthalpy (kJ/kmol)
i	current density (A/m^2)

I	current (A)
$\dot{I}$	rate of irreversibility (W/h)
n	molar flow rate (kmol/s)
OMC_L	levelized operating and maintenance cost ($)
P	pressure (kPa)
r_p	pressure ratio
Q	heat generation rate (kW)
Ru	universal gas constant (8.314 J/mol.K)
S	entropy (kJ/kmol.K)
T	temperature (K)
W	electrical power (kW)
$\dot{Z}^{CI}$	initial capital investment cost ($/h)
$\dot{Z}^{OM}$	operating and maintenance cost ($/h)

Greek letters

h	efficiency
υ	specific volume (m^3/kmol)
τ	average annual time at nominal capacity

Subscripts

a	air
ab	afterburner
an	anode
c	compressor
ca	cathode
cell	fuel cell
f	fuel
g	gas
gen	generation
in	inlet
inv	inverter
out	exit
rec	recuperator
surr	surrounding
th	thermal
tot	total
w	water
wp	water pump

Acronyms

CHP	Combined Heat and Power
GT	Gas Turbine
LHV	Low Heating Value (kJ/kmol)
SOFC	Solid Oxide Fuel Cell
TRR	Total Revenue Requirement cost ($)