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Thermodynamic Performance Evaluation of SOFC Based Simple Gas Turbine cycle

Anoop Kumar Shukla[1*], Sandeep Gupta[2], Shivam Pratap Singh[3], Meeta Sharma[4], Gopal Nandan[5]

Department of Mechanical Engineering,
[1,2,3,4,5]Amity University Uttar Pradesh, Noida, India-201301
Corresponding Author Orcid: 0000-0002-6744-0292

Abstract

The Solid Oxide Fuel Cell (SOFC) is the prominent technique of fuel cell to convert chemical energy into electrical energy, through an electrochemical process. The features of SOFC which led it to be considered as an effective method for the future hybrid power plants to generate power is its high operating temperature, expected to generate clean electrical energy at promising conversion rates with lower emissions of poisonous gas (NO_x and SO_x). Present paper studies the thermodynamic analysis of Solid Oxide Fuel Cell based on simple gas turbine cycle utilizing the waste heat of gas turbine to preheat the air entering the SOFC. Natural gas is utilized as fuel for this system. Heat recovery systems are used in the cycle to utilize the waste heat from SOFC and GT exhausts. Released gases from SOFC, are also utilized as secondary supply for the combustion chamber. Due to SOFC high operating temperature, less fuel is used to burn inside the combustion chamber that enhances its efficiency. The thermodynamic model for the proposed system for its major components of the cycle has been made and analyzed. The effect of the different operating parameters such as current density, fuel recirculation ratio, and fuel utilization factor on the cycle performance are investigated.

Keywords: Solid Oxide Fuel Cell (SOFC), Hybrid framework, Natural Gas, Gas turbine (GT)

INTRODUCTION

Solid Oxide Fuel Cells (SOFCs) are of great interest on these days. The features of SOFC makes them appropriate for the hybrid cycle since they operate at high working temperature, which led to achieving high efficiency when combined with the gas turbine power plant. It is viewed as an excellent device for future hybrid power plants, anticipated that would offer clean electrical energy at high conversion rates, low emissions of poisonous gas and low noise levels [1]. Since SOFC deals with high temperature which is enough to enable the direct reformation of natural gas. SOFC produces both electrical power and heat as the result of electrochemical reaction occurs inside SOFC using natural gas as fuel, the high-grade waste heat is used for the combined heat and power (CHP) system to enhance the overall efficiency of the hybrid Gas Turbine cycle.

GT hybrid model can achieve efficiency up to 50% net electrical efficiencies and have already been considered feasible for the CHP system [2]. Siemens-Westinghouse Power Corporation was the first to build the integrated SOFC-GT model that was the first advance power technology, and it has the capacity to generates 220kW of electrical power having 55% of total electrical efficiency [3].

A simple gas turbine cycle works on the Joule-Brayton cycle, that involves simple processes in order as air compression in the compressor, fuel combustion in a combustor, and expansion of high-temperature gas in the gas turbine. The essential components of the cycle are compressor, combustor, and gas turbines. The number of components can vary according to the need to achieve higher efficiency and to enhance the system performance. Gas turbine power plants are mainly used for the electrical power generation that can achieve efficiency up to 30-40%. It can be further improved by using hybrid cycle, which enhances the efficiency up to 60%.

A brief literature review shows that Mekhilef et al. [1] have performed the comparative study about the different types of fuel cell, Author described the basic design, working principles, and compared the advantages and disadvantages of the different system available for the fuel cell.

S.C. Singhal. [2] focusses on the materials and manufacturing methods used for the various fuel cell components and talk about the performance of the cell. Author has also described a new SOFC model that has a small current path, a lower cell resistance barrier and higher power outcomes than tubular one. Zhang et al. [4] studied various SOFC-GT hybrid cycle combination to enhance the overall performance of the cycle with the growing demand of clean power generation and concluded that the best tubular SOFC was manufactured by Siemens-Westinghouse. The study concluded that the use low operating temperature fuel cell is feasible in a hybrid cycle and to enhance the efficiency of the cycle. Zaccaria et al. [5] incorporated a pre-combustor model into the existing solid oxide fuel cell to keep the inlet temperature of cathode constant for a maximum time during different working conditions. They described the fuel flow regulation to the pre-combustor is an effective technique for keeping a constant temperature at cathode inlet in a step change of fuel cell load.

Saisirirat [6] developed a hybrid SOFC-GT model and perform simulation in MATLAB. The author proposed the thermodynamic modeling and analyze few configurations with respect to SOFC power and at high GT inlet temperature. Arsalis [7] has performed thermodynamic, and cost analysis of combined tubular SOFC, gas turbine and steam turbine-based plants at the different size which ranges from 1.5 to 10 MWe. He considered four different type of steam turbine cycles based on triple pressure, a dual-pressure, and a single pressure for performance evaluation operating on full load and partial load conditions.

Minutillo [8] studied the performance of hybrid SOFC-GT cycle using biogas as fuel based on the modern technologies. He proposed three system configurations as biomass gasification(G), micro gas turbine(MGT), and a thermal heat recovery system. He has carried out the numerical analysis and concluded that the higher thermal efficiency can be achieved by utilizing biogas as a fuel for the hybrid cycle.

Calise [9] has done the exergy analysis of a hybrid SOFC-GT cycle with certain assumptions and concluded that for a 1.5 MW system, it can achieve efficiency up to 60%, and can be further enhanced to 70% using appropriate recovery system. Chinda [10] has proposed the two-different model. One is simple, and another is hybrid one based on the integrated SOFC-GT cycle. He has made the comparative study of his proposed model with another available literature work. Since the dynamic analysis of the proposed model has not been done but it can be used in future to increase the overall efficiency of the hybrid SOFC-GT cycle.

In the present paper, studies focus on the thermodynamic analysis of Solid Oxide Fuel Cell (SOFC) based on the simple gas turbine cycle utilizing the waste heat of GT to preheat the air entering inside the SOFC. The equation of the SOFC's electrochemical reaction and energy balance equation of different components of the cycle has been made and the effect of the different operating parameters such as current density, fuel recirculation ratio, and fuel utilization factor on the cycle performance are analyzed.

System Description and Thermodynamic Modelling of SOFC-GT Hybrid Cycle

Fig.1 describes the schematic diagram of combined SOFC based gas turbine cycle. It consists solid oxide fuel cell, compressors, heat exchangers, combustion chamber, and gas turbine. The ambient air firstly passes through air filter chamber to remove the impurities present in it. It further goes to air compressor where it gets compressed, further it is preheated in a heat exchanger before entering in SOFC tank. The exit temperature of fuel stream is regulated by modifying the mass flow rate of the stream to meet the requirement of the inlet temperature of SOFC.

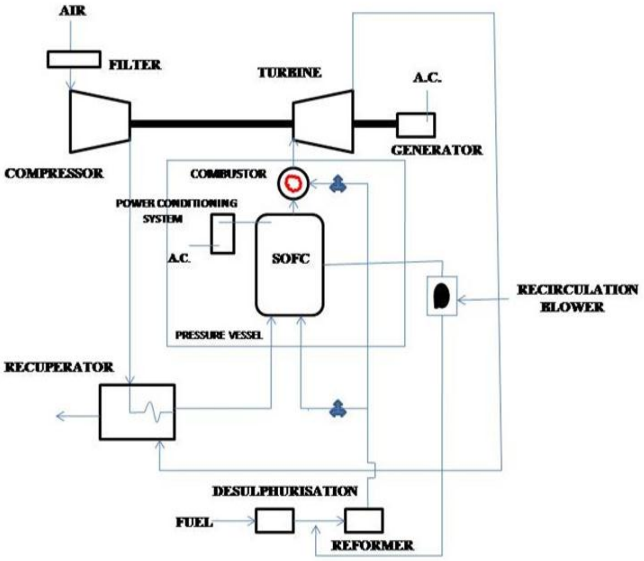

Figure 1. Schematic diagram of basic gas turbine cycle coupled with SOFC

It is assuming that the chemical reaction occurs at the same pressure as the fuel enters the SOFC chamber have a same pressure to that of air. The fuel is partially reformed in pre-reformer before reforming in the SOFC. The conversion of chemical energy to electrical energy takes place in SOFC by electrochemical reaction. The SOFC exhaust goes to the combustion chamber where residual hydrocarbon and hydrogen are burned. The heat of SOFC exhaust is exploited to raise the temperature of the combustion chamber so that it requires a low amount of fuel to burn it inside the combustion chamber and the discharge air passes through the gas turbine and the exhaust air is utilized to pre-heat the air compressor discharge air before passing through the SOFC tank.

Modeling of Planar Solid Oxide Fuel Cell

Figure 2 depicts the schematic of the solid oxide fuel cell. The fuel cell has been modeled to work on syn-gas at an elevated temperature of around 1150K. The assumptions related to the thermodynamic analysis of the proposed Planar SOFC are as enumerated below:

- Composition of Natural gas (CH_4 79%, C_2H_6 13.5%, C_3H_8 3.92%, CO_2 0.64%, N_2 3.04%)
- Composition of Air = 21% and = 79%
- Operates at 1150K in isothermal conditions.
- Steady-state model of analysis.
- No thermal interaction with the environment as a fuel cell is completely isolated.
- Heat transfer due to radiation between the gas channels and solid structure has been ignored.
- Pressure drop in the flow stream has been neglected.

- The temperature of all inlet channels is same, and the temperature of all exit channels are also same.
- Contact resistance within the cell has been ignored.
- Hydrogen has been assumed to be an only active component of fuel in the electrochemical reaction while CO is converted into and by water gas shift reaction.

A single cell considered during analysis has been shown in Fig 2. Fuel mixture (natural gas) enters the fuel channel and the outlet gases from anode have been re-circulated such that fuel and re-circulated gases continue to enter the anode. At the anode, water gas shift, steam reforming of methane, and electrochemical reaction occurs at the same time. The gases exiting the fuel channel contains a high level of water vapor and is hence re-circulated. Cathode reaction is where oxidation takes place due stripping of electrons from O_2 where after O^{2-} ions diffuses through cathode-electrolyte interface (CEI) and migrates across the electrolyte to reacts with H^{2+}which has diffused from the anode to the anode electrolyte interface (AEI) to produce current.

The electrochemical reactions occurring in the fuel cell is as under [10]:

$$H_2 \rightarrow 2H^+ + 2e^- \quad \text{At AEI} \qquad (1)$$

$$2H^+ + O^{2-} \rightarrow H_2O \quad \text{At CEI} \qquad (2)$$

$$CH_4 + H_2O \Leftrightarrow CO + 3H_2 \qquad (3)$$

$$CO + H_2O \Leftrightarrow H_2 + CO_2 \qquad (4)$$

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \qquad (5)$$

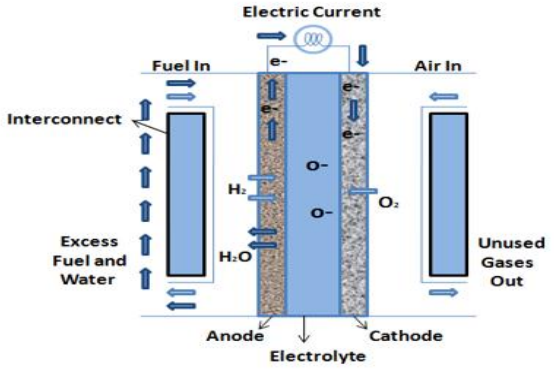

Figure 2. Schematic diagram of solid oxide fuel cell

$$V_N = -\frac{\Delta G_T^0}{n_e F} + \frac{RT}{n_e F}\ln\left(\frac{X_{H_2}X_{O_2}^{0.5}}{X_{H_2O}}\right) + \frac{1}{2}\frac{RT}{n_e F}\ln\left(\frac{P}{P^0}\right) \qquad (6)$$

Where V_N varies between 0.99 -1.01V.

In the cell, the actual voltage diminishes because of the essence of irreversibility. This irreversibility is because of different losses additionally named as "polarization". Here three sorts of polarizations (activation, concentration, and ohmic) happen and discussed ahead.

In higher temperature fuel cell “activation loss” is very small though, in lower and medium temperature fuel cell, it causes the larger amount of voltage drop from perfect voltage since at terminal electrolyte interface weaker response is taking place. At the cathode, the quantum of initiation loss is higher than the anode because of current density exchange is lower at the cathode. The activation loss can be resolved from Chaudhary & Murty [12] and given by:

$$V_{act} = \frac{RT}{F}\sinh^{-1}\left(\frac{i}{2i_{cd,a}}\right) + \frac{RT}{F}\sinh^{-1}\left(\frac{i}{2i_{cd,c}}\right) \qquad (7)$$

Ohmic losses occur due to the resistance offered by different cell component towards charge conduction. These losses are the combination of electronic conduction (between electrodes and inter-connector) and ionic conduction (anions and oxygen through the solid electrolyte) and it is expressed as:

$$V_{ohm} = i \cdot R_{ohm} = i \sum_j \rho j \, \delta \, j \qquad (8)$$

$$\rho j = Ai \exp\left(\frac{B_i}{T}\right) \qquad (9)$$

At the interface of electrode and electrolyte, an electrochemical reaction takes place. For estimation of Gibbs free energy, minor corrections are usually performed due to the difference in partial pressures at these interfaces. These corrections are taken care by considering the concentration polarization and is given by the following equation [11]:

$$V_{conc} = V_{conc}^{a} + V_{conc}^{c} \qquad (10)$$

$$V_{conc} = \left[\left(\frac{-RT}{n_e F}\ln\left(1 - \frac{i}{i_{as}}\right) + \frac{RT}{n_e F}\ln\left(1 + \frac{X_{H_2} \cdot i}{X_{H_2O} \cdot i_{as}} \cdot \frac{P}{P^{\circ}}\right)\right) + \left(\frac{-RT}{n_e F}\ln\left(1 - \frac{i}{i_{cs}}\right)\right)\right] \qquad (11)$$

The net voltage produced in SOFC is given as:

$$\mathrm{V} = \mathrm{V_N} - \mathrm{V_{act}} - \mathrm{V_{ohm}} - \mathrm{V_{conc}} \tag{12}$$

The current produced in the fuel cell is calculated as:

$$\mathrm{I} = \mathrm{i} \cdot \mathrm{A} = 2\mathrm{F} \cdot \mathrm{c} = 2 \cdot \mathrm{F} \cdot \left(\frac{m_{f,H_2}}{1 - \mathrm{r} + \mathrm{r} \cdot \mathrm{U_f}}\right) \tag{13}$$

In this work, fuel utilization factor (U_f) is taken as the ratio of the amount of electrochemically reacting hydrogen to the amount of hydrogen present in the inlet stream.

$$\mathrm{U_f} = \frac{n_{H2,utilized}}{n_{H_2,inlet}} \tag{14}$$

The recirculation ratio modifies the ratio of an amount of steam to the carbon fuel going to the fuel channel, which is an important parameter to control the carbon deposition at the anode catalyst.

$$\mathrm{r} = \frac{\mathrm{n_{fuel,utilized}}}{\mathrm{n_{fuel,recirculation\ line}}} \tag{15}$$

It is the fraction of unused fuel going to the fuel channel from the recirculation line. Here 'c' relies on fuel usage factor and air re-circulation ratio of the SOFC.

$$W_{fc} = I \cdot V \tag{16}$$

The electrical efficiency of the SOFC is calculated as:

$$\eta_{cell} = \bar{n} \cdot \frac{W_{fc}}{m_f \cdot LHV} \tag{17}$$

Where $\bar{n}$ is number of cell stack.

Compressors

In this study axial flow air compressor is taken with consideration of polytropic efficiency to care of various thermodynamic losses. The exit temperature at any stage of a compressor is computed by [13]:

$$\frac{dT}{T} = \left(\frac{R}{\eta_{pt,c} \cdot c_p}\right) \cdot \frac{dP}{P} \tag{18}$$

Mechanical work consumed by the compressor:

$$\mathrm{w_c} = \mathrm{m_a} \cdot (h_{out} - h_{in}) \tag{19}$$

Combustion Chamber

There are three streams are utilized to supply the fuel, compressed air, and the SOFC fumes to the combustion chamber as demonstrated in Fig.1. The natural gas (CH_4 79%, C_2H_6 13.5%, C_3H_8 3.92%, CO_2 0.64%, N_2 3.04%) is used as fuel and the following reactions taking place in the combustor:

$$\mathrm{CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O} \tag{20}$$

$$\mathrm{C_2H_6 + 2O_2 \longrightarrow CO_2 + 2H_2O} \tag{21}$$

$$\mathrm{C_3H_8 + 5O_2 \longrightarrow 3CO_2 + 4H_2O} \tag{22}$$

$$\mathrm{H_2 + O_2 \longrightarrow H_2O} \tag{23}$$

$$\mathrm{CO} + \frac{1}{2}\mathrm{O_2} \longrightarrow \mathrm{CO_2} \tag{24}$$

Heat Exchangers

In this study, heat recovery process occurs in multiple gas to gas heat exchangers and these are insulated from the surrounding environment. The actual temperature difference for both hot and cold fluids is determined by the effectiveness-NTU technique which is based on heat transfer coefficient, surface area, and type of heat exchanger. For a cross-flow heat exchanger with unmixed fluid, the effectiveness is estimated as [11]:

$$\in = 1 - \left\{\frac{NTU^{0,22}}{c}\left[exp(-cNTU^{0,78}) - 1\right]\right\} \tag{25}$$

$$\mathrm{c} = \frac{\mathrm{C_{min}}}{\mathrm{C_{max}}} \tag{26}$$

$$NTU = \frac{\mathrm{UA}}{C_{min}} \tag{27}$$

$$Q_{max} = C_{min}\,(T_{in,hot} - T_{out,cold}) \tag{28}$$

$$Q = \Delta H_{cold} = -\Delta H_{hot} = \epsilon Q_{max} \tag{29}$$

Gas Turbine

In present study polytropic efficiency is considered to take care of expansion losses in the gas turbine. The existing temperature of a gas turbine is taken as [14]:

$$\frac{\mathrm{dT}}{\mathrm{T}} = \left(\frac{\mathrm{dP}}{\mathrm{p}}\right)^{\eta_{pt,gt}\left(\frac{\gamma-1}{\gamma}\right)} \tag{30}$$

The specific work out of the gas turbine calculated by:

$$\mathrm{W_{gt}} = \eta_{pt,gt} \cdot \mathrm{m_{gt}} \cdot c_{\mathrm{pg}}(\mathrm{T_{in}} - \mathrm{T_{out}}) \tag{31}$$

Performance Parameters

The total power output of the integrated system is given by:

$$\mathrm{W_{net}} = \mathrm{P_{sofc}} + \mathrm{W_{gt}} - \mathrm{W_{aux}} \tag{32}$$

The net energy input is taken as:

$$\mathrm{Q_{in}} = (\mathrm{m_{f,sofc}} + \mathrm{m_{f,gt}})\mathrm{LHV} \tag{33}$$

The integrated cycle efficiency of SOFC based gas turbine cycle is given by:

$$\eta = \frac{\text{Total power output of integrated system}}{\text{Net energy input}} = \frac{\mathrm{W_{net}}}{\mathrm{Q_{in}}} \tag{34}$$

RESULTS & DISCUSSION

Based on the thermodynamic modeling of SOFC coupled with basic gas turbine cycle, the results have been found and presented here for studying the effect of fuel utilization factor, air utilization factor and current densities on the performance parameters of the solid oxide fuel cell and SOFC integrated basic gas turbine cycle. The input parameters considered are given in Table 1.

Table 1. Input parameters for present study [10, 11, 12, 15]

Input Parameter	**Value**
Compressor polytropic efficiency	92%
Gas turbine polytropic efficiency	92%
Temperature difference between inlet and exit (Δt)	373K
Pressure of the cell (P)	1 bar
Active surface area(A)	0.01m^2
Current density at anode (i_{cd},a)	0.65A/cm^2
Current density at cathode (i_{cd},c)	0.25A/cm^2
Diffusivity of gas through the anode (D_{aeff})	0.2 cm^2/s
Diffusivity of gas through the cathode (D_{ceff})	0.05 cm^2/s
Thickness of anode	500µm
Thickness of cathode	50µm
Thickness of electrolyte	10µm
Current density (A/m^2)	3000A
Cell operating temperature (K)	800-1200

Fig. 3 shows the variation of the temperature of SOFC with fuel utilization factor. The variation reported that the temperature of SOFC significantly reduces with increasing value of fuel utilization factor. The temperature of SOFC reduces from 1056 K to 895 K by increasing the fuel utilization factor value from 0.45 to 0.75. This occurs due to the greater amount of hydrogen is used in the electrochemical reaction.

Fig. 4 shows the variation of the SOFC voltage with fuel utilization factor. It is noted from the plot that the higher fuel utilization factor yields the lower cell voltage. The main cause of this reduction is the increased internal irreversibility of the SOFC.

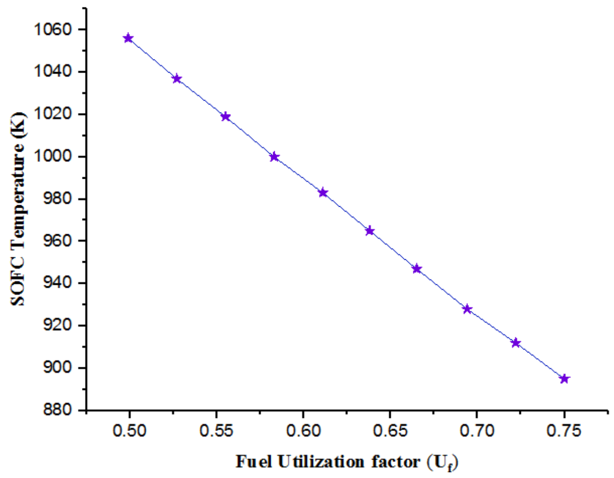

Figure 3. Effect of fuel utilization factor on SOFC temperature

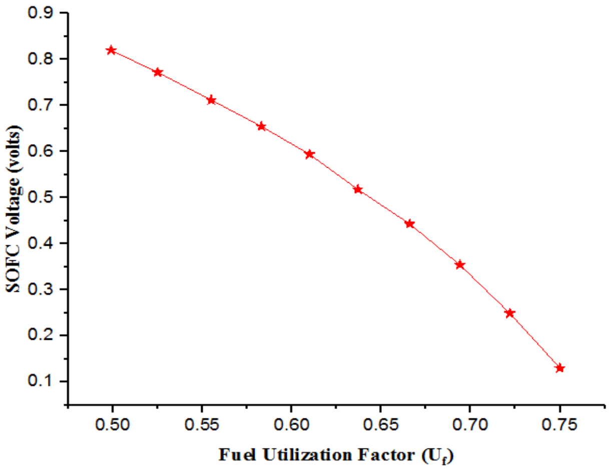

Figure 4. Effect of fuel utilization factor on SOFC voltage

Fig. 5 shows the impact of recirculation ratio at the different current density values on the air utilization ratio. It is noticed from the figure that at the chosen value of current density the air utilization ratio lowers down with the increasing recirculation ratio. Also, the air-utilization curves are diverging at the increased values of current density which reflects rapid decrement for higher current density. Though the use of a small value of air utilization ratio results in greater air flow rate to cathode section steering to improved equipment sizing, that causes to increased capital cost. In addition to this small air utilization also decreases the fuel consumption and the running cost of the SOFC.

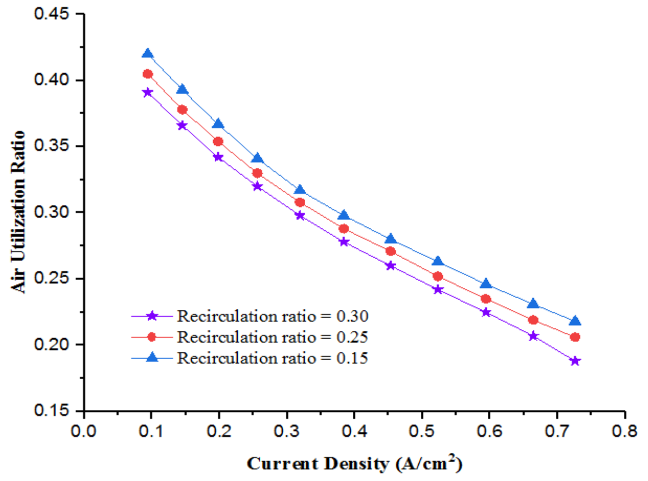

Figure 5. Effect of air recirculation ratio on cell voltage at various values of current densities

Fig.6 presents the impact of current density on the terminal voltage of the SOFC for different values of fuel utilization factor. It is seen from the figure that the substantial decrement in the terminal voltage is observed by increasing the current density. It is also noticed that at the lower value of current density the minor difference in terminal voltage is obtained for several values of fuel utilization factor. Though, at the larger current density (0.9 A /cm^2) there is substantial variation in terminal voltage occurs for selected values of fuel utilization factor. In both the cases, the terminal voltage is larger for smaller current density.

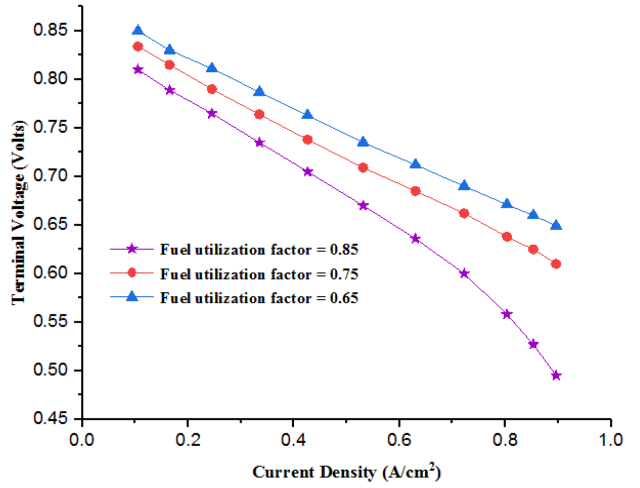

Figure 6. Variation of SOFC terminal voltage with respect to current density at different fuel utilization factor

Fig. 7 demonstrates the impact of fuel utilization factor on the efficiency of three different configurations namely SOFC, basic gas turbine and SOFC based gas turbine. It has been observed that for all the system configuration efficiency reduces with the increasing value of fuel utilization factor. It is noticed from the plot that the fuel utilization factor has a substantial impact on the SOFC efficiency and it is lowered by 71% by increasing U_f from 0.5 to 0.75. An increment of 5% in fuel utilization factor yields a decrement of 22.7% and 3.2% in the efficiency of SOFC and SOFC based GT configuration respectively.

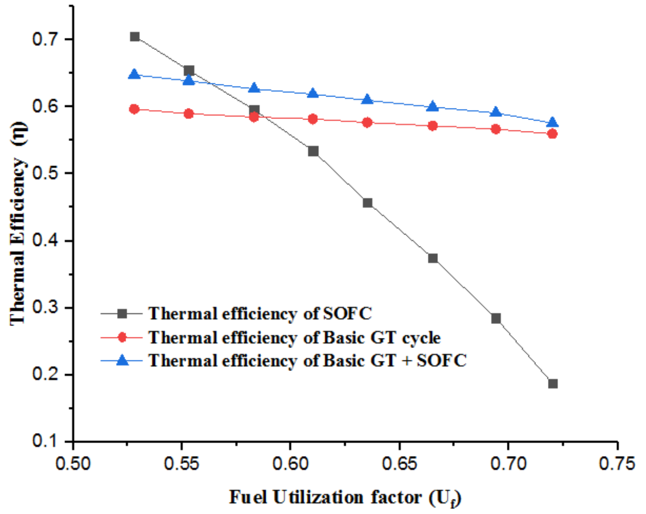

Figure 7. Effect of fuel utilization on system efficiencies

CONCLUSIONS

Thermodynamic analysis of SOFC based gas turbine cycle is carried out in which internally reformed fueled SOFC syn-gas model is employed for the study. The impact of fuel utilization factor and recirculation ratio on the performance parameters has also been examined. The study reported that the higher fuel utilization factor and lower recirculation ratio is required for the performance improvement of SOFC and SOFC based basic gas turbine cycle. The combination of the SOFC with gas turbine improves the cycle efficiency by 2.4% as compared to basic gas turbine cycle.

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Nomenclature	
A	Surface area, cm^2
$\boldsymbol{D_{a,eff}}$	Gaseous diffusivity at anode, (cm^2/s)
$\boldsymbol{D_{c,eff}}$	Gaseous diffusivity at cathode, (cm^2/s)
F	Faraday constant (C/mole)
R	Universal gas constant (J / mol. K)
h	Enthalpy (J/kg)
I	Current (A)
i	Current density (A/cm^2)
r	Recirculation ratio
η	Efficiency (%)
LHV	Lower heating value (J/mole)
n	Number of electrons
U	Utilization factor
X	Molar concentration
W	Work output
Acronyms	
GT	Gas turbine
SOFC	Solid oxide fuel cell
Subscripts	
a	anode
c	cathode
pt	polytropic
in	inlet
o	outlet
gt	Gas turbine
min	minimum
max	maximum
N	Nerst , net