Investigations on Integrating SOFC with Gas Turbine for Performance Enhancement and Sustainable Energy

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ABSTRACT

Direct energy conversion systems offer advantage over indirect energy systems in terms of their impact on environment but their limited capacity acts as a deterrent. Present work deals with the solid oxide fuel cell based direct energy conversion system integrated with conventional gas turbine based power generation system. It deals with thermodynamic modelling and analysis based on first law of thermodynamics. Here solid oxide fuel cell is integrated with intercooled and reheat type gas turbine for performance augmentation. Based on thermodynamic modelling the performance of considered SOFC-GT integrated system has been analyzed in respect to the fuel utilization factor, cycle pressure ratio and turbine inlet temperature. Results are obtained for arriving at optimal operating condition. The SOFC-GT integrated system under study offers 60.42 % efficiency and specific work output of 966.84 kJ/kg at cycle pressure ratio of 10, turbine inlet temperature of 1473 K and fuel utilization factor of 0.85.

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Nomenclature

1,2,3..	cycle states as shown in schematic diagram
A	area (m ²)
C	combustor
C _{p gas}	specific heat of fuel (kJ/kg K)
E	efficiency
GT	gas turbine
h	specific enthalpy (kJ/kg)
HPC	high pressure compressor
HPT	high pressure turbine
HRVG	heat recovery steam generator
I	current density (A/m ²)
LPC	low pressure compressor
LPT	low pressure turbine
LHV	lower heating value of fuel
M	mixer
m	mass flow rate (kg/s)
N	no. of cell
Q	heat generated

S	separator
SOFC	solid oxide fuel cell
T	temperature (K)
TIT	turbine inlet temperature
Uf	fuel utilization factor
V	voltage (V)
W	work output, (kJ/kg)
η	SOFC-GT system efficiency
ε	effectiveness
γ	ratio of specific heat

SUBSCRIPTS

AC	alternative current
comp	compressor
comb	combustion
DC	direct current
f	fuel
fcomp	fuel compressor
poly	polytropic
tur	turbine
tot	total

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1. Introduction

Energy requirements have been constantly increasing due to the technological advancements being energy intensive. Globally, the major share of the consumed energy is still generated by the fossil fuels. The use of fossil fuel has been causing continuous increase in pollution leading to global warming. That's why researchers are searching promising alternatives to generate pollution free energy with high efficiency. Direct energy conversion systems hold attraction due to their inherent feature of direct generation of electricity. Out of different direct energy conversion systems, the fuel cells have been seen as potential energy conversion system. Fuel cells directly transform chemical energy into electrical energy following exothermic electrochemical process and the by-products are environment friendly. Considering different fuel cells, the high temperature fuel cell (operating temperature upto 1000°C) such as solid oxide fuel cell (SOFC) is most attractive because of electrolyte being solid in nature and there exists the possibility of its integration with other power cycles due to availability of high temperature exhaust gases.

Literature review shows that the performance enhancement of integrated systems needs further studies. The study carried out by Sghaier et al. [1] concluded that the efficiency of the Gas Turbine power plant is lesser than the SOFC-GT power plant. Parametric analysis of SOFC-GT-ORC integrated system is carried out by Zhao et al. [2]. Yahyaoui et al. [3] performed modelling for the thermodynamic and electrical analysis of tabular SOFC and MTG single shaft in PSCAD software. Haseli et al. [4] carried out a thermodynamic simulation for the study of second law efficiency of a system consisting of high temperature SOFC and a recuperated conventional GT. Eisavi et al. [5] compared different SOFC-GT hybrid systems and conducted environmental, economic analysis of configurations. Calise et al. [6] performed an exergetic-study of solid

oxide fuel cell combined with gas turbine. Pirkandi et al. [7] suggested in their study that a combined system having one pressurized and one atmospheric fuel cell has high-efficiency, power generation capacity, exergy destruction and irreversibility rates as compared to direct combined system having two pressurized fuel cells. Khani et al. [8] optimized cogeneration system having solid oxide fuel cell and gas turbine integrated indirectly for different working fluids using genetic algorithm.

The present paper deals with the thermodynamic investigations of the synergetic operation of the SOFC and gas turbine. The utilization of energy available in SOFC is being maximised along with enhancing the output from gas turbine. This SOFC-GT integrated system arrangement has intercooled compression and reheating in the GT cycle along with the SOFC. The waste heat available from SOFC and GT is utilized suitably in the integrated cycle and results in improvement of the performance of the combined system.

2. System Description

Figure 1 details the schematic of SOFC-GT integrated system. Here atmospheric air is compressed in low pressure compressor and high pressure compressor. Then high pressure air, state 4, is preheated through recuperator R1 using gas turbine exhaust heat at state 20. Supplementary fuel at state 31 is added as per need into the combustor for achieving desired turbine inlet temperature. The fuel compressor compresses fuel (natural gas) from state 11 to state 12. Again fuel is preheated through recuperator R2, state 13. Hot natural gas mixes with steam generated in heat recovery steam generator, state 30 in M1. Exhaust from recuperator R2 heat the water coming into steam generator. The anode's recirculated exhaust, state 9 mixes with fuel stream for yielding steam to pre-reform methane upto 30% prior to complete reforming in solid oxide fuel cell. The air, state 5 and fuel stream, state 15 go to the SOFC. Here exothermic

Figure1. Layout of SOFC-GT integrated system

electrochemical reactions take place in both electrodes and anode & cathode streams get heated up. A converter converts the DC current from SOFC into AC current.

Some fuel does not get oxidised in SOFC and the same is used in, the combustor located down below for burning. Products coming out at the state 16 help in realizing prescribed TIT at state 25 and state 19.

3. Thermodynamic Modelling

Governing equations used for thermodynamic modelling of SOFC-GT integrated system are given ahead. Some of the major assumptions considered for the thermodynamic modelling of constituents of the integrated systems are as following.

- I. Thermodynamic modelling considers the system to be operating under steady state.
- II. Fuel cell anode and cathode have identical temperatures at inlet and outlet respectively.
- III. Polytropic efficiency of compressor and turbine has been considered to take care of deviations from ideal performance.
- IV. Pressure loss across the system is neglected.

3.1 Gas properties

The specific heat values have been considered as function of temperature and the same is used for estimating the energy interaction. The specific heat for air and (100% methane) as fuels are taken from reference [9]. The specific heat of the combustion products in the presence of excess air is given as;

$$C_{pgas}(T) = 28.9085 - 0.50322 \times 10^{-3} \times T + 9.41292 \times 10^{-6} \times T^2 - 3.82388 \times 10^{-9} \times T^3 / 28.51, \text{ kJ/kg.K}$$

3.2 Air compressor

The outlet temperature of stream leaving compressor is obtained considering the polytropic efficiency of compressor as;

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma \times \eta_{poly,comp}}} \quad (1)$$

The compression process is assumed to be carried out with perfect intercooling so,

$$T_1 = T_3 \quad (2)$$

$$T_2 = T_4 \quad (3)$$

Work required in compressor is,

$$W_{comp} = (h_2 - h_1) + (h_4 - h_3) \quad (4)$$

3.3 Fuel compressor

Temperature of fuel at exit compressor is obtained through:

$$\frac{T_{12}}{T_{11}} = \left(\frac{P_{12}}{P_{11}} \right)^{\frac{\gamma-1}{\gamma \times \eta_{poly,fcomp}}} \quad (5)$$

Work required for the fuel compressor is determined by applying energy balance equation as,

$$W_{fcomp} = (h_{12} - h_{11}) \quad (6)$$

3.4 Gas turbine

Outlet temperature of stream leaving GT is determined by:

$$\frac{T_{18}}{T_{25}} = \left(\frac{P_{18}}{P_{25}} \right)^{\frac{(\gamma-1) \times \eta_{poly,tur}}{\gamma}} \quad (7)$$

Reheating in the gas turbine is considered with the assumption detailed below;

$$T_{19} = T_{25} \quad (8)$$

$$T_{20} = T_{18} \quad (9)$$

Work produced by the gas turbine is determined by applying energy balance equation as,

$$W_{tur} = (h_{18} - h_{25}) + (h_{20} - h_{19}) \quad (10)$$

3.5 Solid oxide fuel cell

Electrical output from SOFC are obtained by,

$$W_{sofc} = V_{cell} \times i_{cell} \quad (11)$$

The mass conservation in SOFC system yields:

$$m_5 + m_{15} = m_6 + m_{16} \quad (12)$$

The energy balance equation for SOFC by assuming adiabatic process as:

$$m_5 h_5 + m_{21} U_f LHV + m_{15} (1 - U_f) = m_6 h_6 + m_{16} h_{16} + W_{SOFC,DC} \quad (13)$$

3.6 Recuperator

Recuperator's effectiveness is obtained by;

$$\varepsilon = \frac{T_5 - T_4}{T_{20} - T_4} \quad (14)$$

Energy conservation in recuperators is given as:

$$m_4 (h_5 - h_4) = m_{20} (h_{20} - h_{21}) \quad \text{for R1} \quad (15)$$

$$m_{12} (h_{13} - h_{12}) = m_{21} (h_{21} - h_{22}) \quad \text{for R2} \quad (16)$$

3.7 Mixers

Energy conservation in respective mixers is written as under:

$$m_{13} h_{13} + m_{30} h_{30} = m_{14} h_{14} \quad \text{for M1} \quad (17)$$

$$m_6 h_6 + m_8 h_8 = m_{10} h_{10} \quad \text{for M2} \quad (18)$$

3.8 Separators

The energy balance equation for separator is:

$$m_{16} h_{16} + m_8 h_8 = m_9 h_9 \quad \text{for S2} \quad (19)$$

3.9 Combustor

Mass conservation in combustor yields;

$$m_{10} + m_{31} = m_{25} \quad (20)$$

Energy conservation in combustor is given by

$$m_{10} U_{fh_{10}} + Q_{comb} = m_{25} (h_{25} - h_{18} + h_{19}) \quad (21)$$

where

$$Q_{comb} = (m_{15} (1 - U_f) + m_{31}) LHV \quad (22)$$

Overall thermal efficiency can be estimated by:

$$\eta_{SOFC-GT} = W_{SOFC-GT} / Q_{tot} \quad (23)$$

$$\text{where } W_{SOFC-GT} = W_{SOFC,AC} + W_{tur} - W_{comp} - W_{fcomp} \quad (24)$$

$$Q_{tot} = m_f U_f LHV + Q_{comb} \quad (25)$$

A detailed computer program in C language is written based on thermodynamic modelling of the constituent components of SOFC-GT integrated system and used for performance assessment with various input parameters.

4. Result and discussion

The results obtained for SOFC-GT integrated system have been graphically presented in the figures presented ahead. Table 1 gives the input parameters used for performance evaluation.

Figure 2 shows the changes in overall cycle work output with varying cycle pressure ratio for different fuel utilization factors of 0.65, 0.75 and 0.85. It depicts that the overall cycle work output gradually increases with increase in fuel utilization factor in solid oxide fuel cell. It is also seen that the increase in fuel utilization factor yields increase in gas turbine work output. The cycle work output increases with increase in cycle pressure ratio at any fuel utilization factor and constant turbine inlet temperature 1473K. The increase in cycle pressure ratio is accompanied by the increase in compression work and increase in turbine work both; however the increase in turbine work is more than the increase in compressor work requirement. Thus, it results increase in overall work output. At cycle pressure ratio of 10 and fuel utilization factor of 0.85 at 1473 K the overall work output is obtained as 966.84 kJ/kg air. Overall work output is seen to increase with increase in TIT due to higher work potential of expanding gases at higher turbine inlet temperatures.

Table 1 Input parameter of SOFC-GT combined cycle [1, 10, 11]

Parameter	Value
Compressor polytropic efficiency, %	90
Inlet temp, K	298
Cycle pressure ratio	10
Turbine polytropic efficiency, %	92
Turbine inlet temp, K	1473
Lower calorific value of fuel, kJ/kg	50000
Fuel utilization factor	0.85
Current density, A m ⁻²	4000
Area of cell, m ²	0.04
Cell voltage, V	0.7
Operating temp, K	1073
No. of cell, N	4100
DC-AC inverter efficiency, %	95
Combustor efficiency, %	95
Steam/natural gas ratio	2.5
Pre-reformer operating temperature, K	873
Air composition by mass	O ₂ : 21%, N ₂ =79%
Fuel composition by mass	100% CH ₄

Figure 2. Variation of overall cycle work output with cycle pressure ratio for fuel utilization factors in solid oxide fuel cell

Figure 3 presents the changes in overall cycle work output with changing cycle pressure ratio at different TIT of 1473K, 1573K and 1673K for 0.85 fuel utilization factor. The results depict that the work output increases with increase in turbine inlet temperature for fixed

Figure 3. Variation of overall cycle work output with cycle pressure ratio for different turbine inlet temperatures at fuel utilization factor of 0.85

utilization factor due to increase in gas turbine work output. Graphical result shows that the overall work output is 966.84 kJ/kg air for TIT 1473 K & cycle pressure ratio of 10 at 0.85 fuel utilization factor.

Figure 4 depicts that the efficiency of the SOFC-GT integrated system is higher as compared to gas turbine cycle due to increase in overall work output due to availability of additional gas turbine work output after SOFC. The overall efficiency of the system decreases with increase in cycle pressure ratio due to the increase in requirement of additional fuel supply at stage 31. SOFC-GT integrated system offers gain in thermal efficiency by 67.87% as compared to the GT system alone. The highest efficiency of the SOFC-GT integrated system is calculated as 60.42% at cycle pressure ratio of 10, TIT 1473 K, & fuel utilization factor of 0.85.

Figure 4. Variation of efficiency with cycle pressure ratio for turbine inlet temperature of 1473 K and fuel utilization factor of 0.85

Figure 5 shows the changes in gas turbine efficiency with the varying cycle pressure ratio at 0.85 fuel utilization factor. At any TIT value the increase in cycle pressure ratio results in higher work output, which eventually results in increase in efficiency. It is seen that the gas turbine efficiency improves with the increase in the TIT due to increase in the gas turbine work output. The gas turbine efficiency is found to be 35.99% for 10 cycle pressure ratio and 1473 K TIT. As the TIT changes from 1473 K to 1673 K, the GT efficiency increases from 35.99% to 41.03%.

Figure 5. Variation of gas turbine efficiency with cycle pressure ratio at constant fuel utilization factor of 0.85

Figure 6 shows the validation of present thermodynamic modelling of SOFC-GT integrated system with reported results of Haseli et al. [4] in respect to efficiency. For the same operating parameters, at 10 cycle pressure ratio and 1250 K TIT, the efficiency obtained in this study is 58.3% for considered SOFC-GT integrated system. Haseli reported 58% efficiency for the SOFC-GT integrated system without intercooling & reheating in the gas turbine. Result obtained from the present study is nearly similar to the results available in the published work; however, slight deviation is due to the difference in basic modelling assumptions as the same is not available in the published work and slight change in cycle arrangement due to reheating and intercooling.

Figure 6. Validation of present studied SOFC-GT system efficiency with Haseli et al. [4] reported in their study

5. Conclusions

The integration of SOFC and GT cycle from the better energy utilization perspective yields the following conclusions.

1. SOFC-GT integrated system is having highest efficiency of 60.42 % as compared to the gas turbine power plant with efficiency of 35.99% while operating in isolation.
2. SOFC-GT integrated system has 966.84 kJ/kg maximum work output at 10 cycle pressure ratio, 1473 K TIT & 0.85 fuel utilization factor.
3. Integration of SOFC with GT having intercooling and reheating offers effective utilization of available heat and better thermal efficiency.

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