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Thermodynamic Analysis of Solid Oxide Fuel Cell-Gas Turbine-Organic Rankine Cycle Combined System

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Abstract—*Energy availability concerns and depleting fossil fuel reserves have made it inevitable to explore environment friendly energy conversion options with reduced adverse impact on environment and energy crisis across the world. It necessitates for evolving the efficient energy conversion systems. Amongst the different energy conversion options, the fuel cells are considered as the potential direct energy conversion option and efforts are made for the energy efficient operation of solid oxide fuel cell systems integrated with other power generating systems. Performance enhancement of solid oxide fuel cell based systems depends upon the efficient utilization of energy. The present study investigates integration of solid oxide fuel cell with gas turbine cycle and organic Rankine cycle. The solid oxide fuel cell- gas turbine- organic Rankine cycle combined system is producing more power as compared to solid oxide fuel cell-gas turbine combined system. The study involves thermodynamic modeling and analysis of the combined power system. Here thermodynamic modelling of the considered combined cycle system has been carried out based on first law of thermodynamics. Based on the thermodynamic modelling, the computer simulation has been done for SOFC-GT-ORC combined cycle for studying the effect of different parameters on the cycle performance. Results show that the solid oxide fuel cell- gas turbine-organic Rankine cycle combined system yields increase in efficiency to 70.16% for cycle pressure ratio of 10, fuel utilization factor of 0.85 as compared to 60.38% in the solid oxide fuel cell- gas turbine combined system.*

Keywords: *SOFC, organic Rankine cycle, R1233zd(E), Gas turbine*

Nomenclature	
1, 2, 3....	Cycle states as shown in schematic
HRVG	Heat recovery vapour generator
m	Mass flow rate, kg/s
Cp	Specific heat, kJ/kg K
γ	Ratio of specific heat
h	Specific enthalpy, kJ/kg
GT	Gas turbine
ORC	Organic Rankine Cycle
SOFC	Solid oxide fuel cell
T	Temperature
U	Utilization factor
V	Voltage, V
i	Current density

Subscripts	
a	Air
comp	Compressor
comb	Combustion
DC	Direct current
f	fuel
tur	Turbine
sofc	Solid oxide fuel cell
inv	Inverter

1. INTRODUCTION

Among all fuel cells, the solid oxide fuel cell is emerging direct energy conversion technology to generate power and offers opportunity of using the high temperature exhaust for power augmentation through suitable energy conversion system. So its integration with the gas turbine and organic Rankine cycle for utilizing the heat carried by its' exhaust improves the system performance.

Brief literature review in this regard shows that the researchers studied the integration of SOFC with other power generating options such as SOFC-GT combined system [1-10] and SOFC-ORC combined system. Chan et al. [11] presented simple mathematical modelling of SOFC-GT combined system. Chinda et al. [12] studied two different SOFC-GT hybrid systems on energy basis to find the suitable SOFC-GT hybrid model for 300-passenger commercial aircraft. Zhao et al. [13] studied coal syngas fed an indirect SOFC-GT combined system and found that efficiency of the system decreases as the current density increases. Eveloy et al. [14] analyzed a SOFC-GT-ORC combined system and concluded that the efficiency of this combined system is 34% higher than gas turbine system.

In this paper, the integration of an organic Rankine cycle in SOFC-GT combined system is investigated for effective utilization of waste heat available with gas turbine exhaust from the SOFC-GT combined system. Thermodynamic modelling based on first law of thermodynamics has been carried out and the performance of the SOFC-GT-ORC system is analysed in respect to certain independent parameters. The results obtained are useful for power sector professionals.

2. DESCRIPTION OF SYSTEM

In the schematic diagram of SOFC-GT-ORC, the air is compressed from state 1 to state 2 in air compressor. Before feeding air into cathode of SOFC, the compressed air is preheated to state 3 by the exhaust coming out from recuperator (R3) the state 15. The fuel is also compressed in fuel compressor from state 5 to state 6 and further preheated to state 7 before mixing into the mixer from the exhaust coming from recuperator (R2) at state 14 to get the desirable temperature. Hot fuel is mixed with steam generated from heat recovery steam generator into the mixer (M1). This mixed stream is fed into the SOFC anode where the electrochemical reactions take place. Unreacted gases and excess air of the SOFC are completely combusted into the after burner to generate high temperature exhaust gases at state 13. These exhaust gases coming out from the after burner are passed through three recuperator R1, R2, R3before getting expanded from state 16 to state 17. The exhaust leaving the gas turbine has sufficient amount of heat to superheat the refrigerant to run a organic Rankine cycle having refrigerant R1233zd(E). The ORC generates work due to expansion of the refrigerant upto condensing temperature. In condenser, the refrigerant is cooled down from state 21 to state 22. The exhaust gases leaving the heat recovery vapor generator possess less temperature as compared to the atmospheric condition.

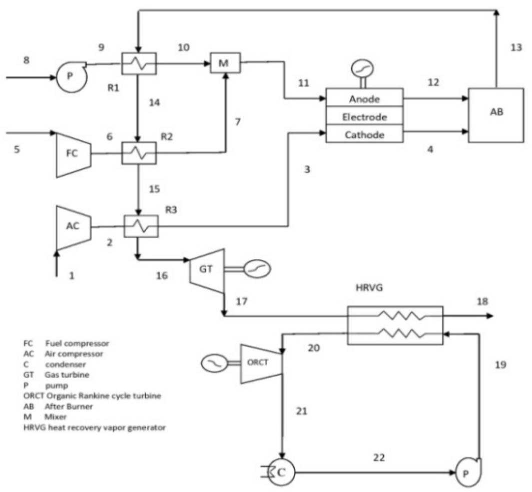

Figure 1: Schematic diagram of SOFC-GT-ORC combined system

3. THERMODYNAMIC MODELLING

Salient mathematical equations used in thermodynamic modelling are detailed ahead.

3.1 Gas properties model

The specific heat for air and natural gas (100%) is function of temperature and taken as given in reference [15]. The specific heat of the combust gases is temperature function and determined in excess air presence is given below as in kJ/kg K.

$$C_{pgas} = 28.9085-0.50322 \times 10^{-3} \times T+9.41292 \times 10^{-6} \times T^2-3.82388 \times 10^{-9} \times T^3/28.51 \quad (1)$$

3.2 Air compressor

The outlet temperature of air in compressor is calculated by

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma \times \eta_{poly,comp}}} \quad (2)$$

Where, $\eta_{poly,comp}$ is air compressor polytropic efficiency.

Work required for the air compressor is determined by in kJ/kg;

$$W_{a,comp} = h_2-h_1 \quad (3)$$

3.3 Fuel compressor

The outlet temperature of fuel in fuel compressor is obtained by

$$\frac{T_6}{T_5} = \left(\frac{P_6}{P_5}\right)^{\frac{\gamma-1}{\gamma \times \eta_{poly,comp}}} \quad (4)$$

Work required for the fuel compressor is obtained as;

$$W_{f,comp} = h_6-h_5 \quad (5)$$

3.4 Recuperator

Recuperator effectiveness (ε) is given as;

$$\varepsilon = \frac{T_{10}-T_9}{T_{13}-T_9} \quad \text{for R1} \quad (6)$$

$$\varepsilon = \frac{T_7-T_6}{T_{14}-T_6} \quad \text{for R2} \quad (7)$$

$$\varepsilon = \frac{T_3-T_2}{T_{15}-T_2} \quad \text{for R3} \quad (8)$$

Application of energy balance upon recuparators yields the following;

$$m_9(h_{10}-h_9) = m_{13}(h_{14}-h_{13}) \quad \text{for R1} \quad (9)$$

$$m_6(h_6-h_5) = m_{14}(h_{15}-h_{14}) \quad \text{for R2} \quad (10)$$

$$m_2(h_3-h_2) = m_{15}(h_{16}-h_{15}) \quad \text{for R3} \quad (11)$$

3.5 Mixer

The energy balance and mass balance for the mixer is given as;

$$m_7h_7+m_{10}h_{10}=m_{11}h_{11} \quad (12)$$

$$m_{10}+m_7=m_{11} \quad (13)$$

3.6 SOFC

Electrical power generated by the SOFC is given as,

$W_{sofc}=V_{cell} \times i_{cell}$ (14)

Apply energy balance and mass balance in the sofc by assuming an adiabatic process,

$m_4h_4+m_{11}U_fLHV+m_{11}(1-U_f)h_{11}= m_{12}h_{12}+m_4h_4+ W_{SOFCDC}$ (15)

where LHV is lower heating value of fuel

3.7 After Burner

Apply energy and mass balance upon after burner is expressed as;

$m_{12}U_fh_{12}+Q_{comb}+m_4h_4= m_{13}h_{13}$ (16)

$m_{12}+m_4=m_{13}$ (17)

where, $Q_{comb}= m_{12}(1-U_f)$ LHV

3.8 Gas turbine

The temperature of exhaust gases leaving the gas turbine at outlet is obtained by:

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

Where, $\eta_{poly,tur}$ is gas turbine polytropic efficiency

Work obtained by the gas turbine is given as in kJ/kg;

$W_{tur} = h_{17}-h_{16}$ (19)

3.9 ORC system modelling

Heat balance in HRVG is given as;

$\eta_{HRVG}(m_{17}Cp_{17}T_{17}-m_{18}Cp_{18}T_{18})=m_{ORC}(h_{20}-h_{19})$(20)

Work obtained from the ORC turbine can be expressed as

$W_{ORC}=m_{ORC}(h_{20}-h_{21})$ (21)

Heat rejected from condenser is given as;

$Q_c = m_{ORC}(h_{21}-h_{22})$ (22)

Work required for the pump is given as;

$W_P=m_{ORC}(h_{22}-h_{19})$ (23)

3.10 Efficiency

Efficiency of the SOFC-GT-ORC combined system is given as;

$\eta_{Overall} =W_{tot}/Q_{tot}$ (24)

Where, $W_{tot} = (W_{sofc,AC}+W_{tur}+W_{ORC})-(W_{comp} +W_{fuel})$

$Q_{tot} = m_f$ LHV

$W_{sofc,AC}= \eta_{inv} W_{sofc}$

4. RESULTS

Based on the first law of thermodynamic analysis, the computer simulation of the SOFC-GT-ORC combined system has been carried out. Thermophysical properties of refrigerant R1233zd(E) are taken from ethermo: Thermodynamic & Transport calculation platform [18]. The input parameters are shown in table 1.

Table 1: Input parameters [16,17]

Parameter	Value
Compressor polytropic efficiency, %	85
Inlet temperature, K	293, 298, 303
Cycle pressure ratio	4, 6, 8, 10
Turbine polytropic efficiency, %	95
Lower heating 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	1000
No. of cell, N	4100
DC-AC inverter efficiency, %	95
Combustor efficiency, %	100
Steam/natural gas ratio	2.5
HRVG exhaust temperature, K	310
Refrigerant in ORC	R1233zd(E)
ORC inlet temperature, K	423
ORC operating pressure, MPa	1

Figure 1 shows the variation of SOFC-GT and SOFC-GT-ORC combined system with the cycle pressure ratio. As the cycle pressure ratio increases, the efficiency of the SOFC-GT-ORC combined system decreases because of increment in the negative work is more as compared to increment in the positive work. Integration of the ORC in SOFC-GT system increases the overall work output of the SOFC-GT combined system. The overall efficiency of the SOFC-GT-ORC combined system is 70.16% for cycle pressure ratio of 10 and 0.85 fuel utilization factor.

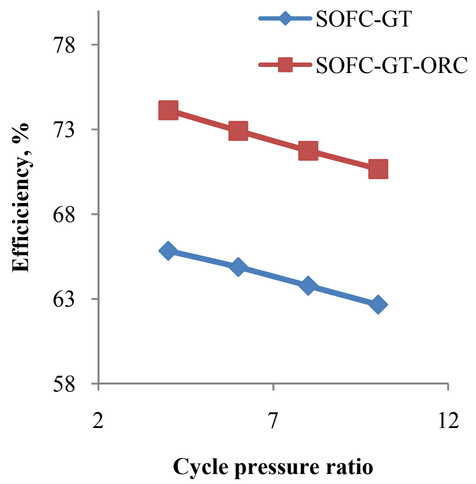

Figure 2.Variation of the efficiency with cycle pressure ratio

Figure 3 shows the variation of the specific work output of the SOFC-GT combined system and SOFC-GT-ORC combined system with the cycle pressure ratio. As the cycle pressure ratio increases, the efficiency of the SOFC-GT-ORC combined system decreases because the increment in negative work is more as compared to increment in the positive work. Integration of the ORC in SOFC-GT system increases the overall work output of the SOFC-GT combined system. The specific work output of the SOFC-GT combined system is found as 435.67 kJ/kg for cycle pressure ratio of 10 and 0.85 fuel utilization factor.

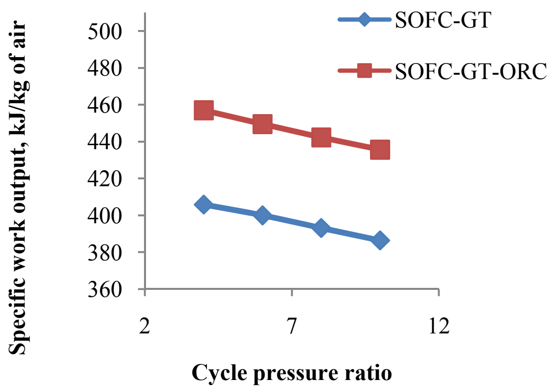

Figure 3.Variation of the specific work output with cycle pressure ratio

Figure 4 shows the variation of the efficiency of the SOFC-GT combined system and SOFC-GT-ORC combined system with ambient temperature. As the ambient temperature increases, the efficiency of the SOFC-GT-ORC combined system decreases because of the increment in the negative work is more as compared to increment in the positive work.

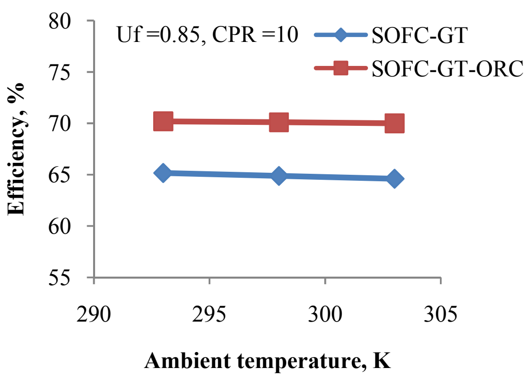

Figure 4. Variation of efficiency with ambient temperature

5. CONCLUSION

Based on the thermodynamic analysis of SOFC-GT-ORC combined system, following conclusions have been obtained.

1. Integration of the organic Rankine cycle in SOFC-GT system increases the overall specific work output of the combined system. The overall specific work output of the SOFC-GT-ORC combined system is obtained as 432.16kJ/kg air at inlet for 10 cycle pressure ratio and 0.85 fuel utilization factor.
2. The efficiency of the SOFC-GT-ORC combined system is obtained as 70.16% for cycle pressure ratio of 10 and fuel utilization factor of 0.85.
3. The efficiency of SOFC-GT-ORC combined system decreases with the increase in ambient temperature because of the fact that there is more increment in negative work as compared to positive work from turbines.

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