Thermodynamic analysis of Gas Turbine Based Hybrid Power Cycle

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Abstract— In this paper a thermodynamic analysis of hybrid gas turbine has been performed on the basis of thermodynamic 1st and 2nd law. For making gas turbine cycle hybrid a Solid oxide fuel cell (SOFC) has been combined with recuperative gas turbine. For analysis a MATLAB code has been developed for examining the complete cycle performance. At each component of gas turbine hybrid cycle 2nd law performance in terms of entropy generation has been studied. The effect of various parameters has been studied on the cycle performance. The obtained results have been compared with result of previous researcher and showing good agreement. It has also been observed that in combustion chamber maximum entropy generation take place.

Key words: Hybrid Gas Turbine, SOFC, Energy, Entropy

I. INTRODUCTION

Fuel cell is an energy conversion unit that converts a gaseous fuel to electrical energy and heat by electrochemical combination of a fuel with an oxidant. Since it is operated electrochemically and is not limited by the Carnot cycle, lower emissions such as NOx or CO2 are produced from fuel cells compared to the cleanest combustion process. Due to its high conversion efficiency and environmental acceptability, the fuel cell is regarded as an effective process to produce electricity from chemical components. The application of fuel cell technologies to advanced power generation systems signifies the most significant advancement in energy conservation and environmental protection for the next decade [1].

This concept was first analyzed by Ide et al. [4] who compared the net plant efficiency of three types of fuel cell generation system. The efficiency losses of power generation processes are largely due to high irreversible fuel combustion. It can be improved by preventing the direct contact between air and fuel as it occurs in fuel cells. Theoretical studies of combined SOFC–GT cycles have attracted increasing attention worldwide by researchers. There are several other previous works in the literature involving thermodynamic analysis, design, modelling of SOFC–GT power system [2,3-20]. Massardo and Lubelli [2] developed a mathematical model that simulated the fuel cell steady-state operation of an integrated internal reforming SOFC–GT combined cycle.

Choudhary et al 2015 focuses on the thermodynamic analysis of Solid Oxide fuel cell (SOFC). In the present work the SOFC has been modeled to work with internal reforming of fuel which takes place at high temperature and direct energy conversion from chemical energy to electrical energy takes place.

Valerie et al. 2016 To improve on-site power generation capacity and efficiency in energy-intensive process plants, the indirect integration of a standard gas turbine cycle with an internal reforming solid oxide fuel cell (SOFC) system and bottoming organic Rankine cycle (ORC) is investigated thermodynamically and economically. Lv et al. 2016 use novel technique to determine safe zone for an intermediate-temperature solid oxide fuel cell and gas turbine hybrid system. The system is powered by biogas and a safe map is obtained to overcome from component malfunctioning. Results show that the hybrid system can achieve a high efficiency 60.78%, which is an interesting reference for distributed power stations.

Ramakrishnan and Edwards 2016 applied systematic irreversibility minimization approach in regenerative gas turbine engines to maximize the efficiency It considers engine architectures that employ two kinds of energy transfers: heat and work. It does not assume any cycle a priori (e.g., heat-recuperative reactive Brayton cycle).

Elwekeel and Antar 2016 investigate the addition mist to steam as coolant fluid in steam injected gas turbine for co generation purpose. The energy and exergy analysis has been carried out and the papramteric analysis has been carried out parameters such as steam coolant temperature, mist fraction, mist temperature, pressure ratio, turbine inlet temperature and blade temperature.

Khaljani et al. 2015 perform multi objective optimization to optimize cogeneration system consists of a gas turbine and an ORC (organic Rankine cycle) in which the two cycles are connected through a single-pressure HRSG (heat recovery steam generator). Optimization results indicate that exergy efficiency of the cycle increases from 51.4% at base case to 56.15% at the optimized condition while more than 12.98% reduction is achieved in the total cost rate of the system.

Choudhary and Sanjay 2017 developed a novel a novel SOFC-GT hybrid cycle with adoption f blade cooled gas turbine cycle. In their work first and second law analysis has been performed and efficiency of more than 70% has been achieved.

Choudhary and Saniay 2017 performed a entropy generation minimization in the field of gas turbine hybrid cycle. A novel configuration of Intercooled gas turbine cycle has been integrated with SOFC and minimizes the level of entropy generation by developed constrained based algorithm and 8.05W/K of entropy minimization has been achieved at optimum performance parameters.

II. MATHEMATICAL MODELING

A. Air Compressor (AC)

The pressure and temperature of air at the exit of air compressor are determined by the following equations. The isentropic efficiency of the compressor is defined as

$$\eta_c = \frac{W_{cs}}{W_{ca}} = \frac{h_{2s} - h_1}{h_2 - h_1} \qquad (1)$$

$$\frac{T_{2s}}{T_1}=\left(\frac{P_2}{P_1}\right)^{\left(\frac{\gamma-1}{\gamma}\right)} \qquad (2)$$

Entropy generation within the compressor is also written as follows:

$$S_{gen,c}=\left(c_{pa}\ln\frac{T_{2s}}{T_1}-R_a\ln\frac{p_2}{p_1}\right) \qquad (3)$$

B. Recuperator (Recup)

The effectiveness of the recuperator is described as

$$\varepsilon_{Recup}=\frac{T_3-T_2}{T_7-T_2} \qquad (3)$$

From mass conservation, $\dot m_2=\dot m_3$ and $\dot m_7=\dot m_8$. Thus, the entropy generation rate within the heat exchanger can be evaluated as follows.

$$S_{gen,Recup}=\dot m_2\left(s_3-s_2\right)-\dot m_7\left(s_7-s_8\right) \qquad (4)$$

C. Solid oxide fuel cell (SOFC)

The fuel utilized to supply the system is methane (CH4), with a lower heating value of 50,050 kJ/kg. the electrochemical research take place within fuel cell are as mention below:

Steam reforming Reaction

$$CH_4+H_2O \rightleftharpoons CO+3H_2 \qquad (5)$$

Water Gas Shift Reaction

$$CO+H_2O \rightleftharpoons H_2+CO_2 \qquad (6)$$

Overall Cell Reaction

$$H_2+\frac{1}{2}O_2\rightarrow H_2O \qquad (7)$$

$$E_{Nernst}=-\frac{\Delta\bar G_T^0}{n_eF}+\frac{RT}{n_eF}\ln\left(\frac{X_{H_2}X_{O_2}^{0.5}}{X_{H_2O}}\right)+\frac{1}{2}\frac{RT}{n_eF}\ln\left(\frac{P}{P^o}\right) \qquad (8)$$

$$\dot W_{FC,dc}=V_c\,jA_c \qquad (9)$$

$$V_c=E-\Delta V_{loss} \qquad (10)$$

$$\Delta V_{loss}=V_{act}+V_{ohm}+V_{conc} \qquad (11)$$

$$\dot Q_{gen,FC}=I\Delta V_{loss}=jA_c\left(E-V_c\right)\times10^{-6}\left[kW\right] \qquad (12)$$

$$\dot m_3h_3+\dot m_{fuel,FC}\times U_f\times LHV+\dot m_{fuel,FC}\times\left(1-U_f\right)h_{fuel,in} \qquad (13)$$
$$-\dot W_{FC,dc}-\dot m_4h_4=0$$

$$\dot S_{gen,FC}=\dot m_4h_4-\dot m_3h_3-\left(\dot m s\right)_{fuel,FC} \qquad (14)$$

D. Combustion Chamber (CC)

Natural gas has been taken as a fuel and is burnt in the presence of compressed air to raise its temperature. The combustion products at high temperature lead into the gas turbine where expansion of gases takes place.

$$\dot Q_{comb}=\left[\dot m_{fuel,FC}\times\left(1-U_f\right)+\dot m_{fuel,comb}\right]\times LHV \qquad (15)$$

$$\dot Q_{loss}=\left[\dot m_{fuel,FC}\times\left(1-U_f\right)+\dot m_{fuel,comb}\right]\times\left(1-\eta_{comb}\right)\times LHV \qquad (16)$$

The entropy balance equation for the combustor can be written as

$$\dot m_4s_4+\left(\dot m s\right)_{fuel,comb}+\frac{\dot Q_{comb}}{T_{comb}}+\dot S_{gen,comb}-\dot m_5s_5 \qquad (17)$$
$$-\frac{\dot Q_{loss}}{Tsurr}=0$$

$$\dot S_{gen,comb}=\dot m_5s_5-\dot m_4s_4-\left(\dot m s\right)_{fuel,comb}$$
$$+\frac{\dot Q_{comb}}{T_{comb}}-\frac{\dot Q_{loss}}{Tsurr}=0 \qquad (18)$$

E. Gas Turbine (GT)

This high pressure and temperature flue gases sequentially expand in the stages of axial flow gas turbine, thus power is developed by the continuous removal of energy content from the flue gases.

$$\eta_{GT}=\frac{\dot W_{GTa}}{\dot W_{GTs}}=\frac{h_5-h_6}{h_5-h_{6s}} \qquad (19)$$

the entropy generation rate during the expansion process is

$$\dot S_{gen,GT}=\dot m_5\left(s_6-s_5\right) \qquad (20)$$

F. Power Turbine (GT)

The relevant governing equations for the power turbine are similar to those presented in the previous section.

$$\eta_{PT}=\frac{\dot W_{PTa}}{\dot W_{PTs}}=\frac{h_6-h_7}{h_6-h_{7s}} \qquad (21)$$

$$T_{7s}=T_6\left(\frac{P_{6s}}{P_6}\right)^{\left(\frac{\gamma}{\gamma-1}\right)} \qquad (22)$$

The entropy generation rate during the expansion process is obtained as

$$\dot S_{gen,PT}=\dot m_6\left(s_7-s_6\right) \qquad (23)$$

G. Energy balance

The overall energy balance of the system gives

$$\dot m_1h_1+\dot m_{fuel,FC}\times U_f\times LHV+\dot Q_{comb}$$
$$-\dot m_8h_8-\dot Q_{loss}-\dot W_{PTs}-\dot W_{FC,dc}=0 \qquad (24)$$

Entropy balance

$$S_{gen}^{cyc}=\dot m_8s_8-\dot m_1s_1-\left(\dot m s\right)_{fuel}$$
$$-\frac{\dot Q_{comb}}{T_{comb}}+\frac{\dot Q_{loss}}{T_{sink}} \qquad (25)$$

III. METHODOLOGY

The governing equations for the hybrid gas turbine cycle has been discussed in mathematical modeling section and are solved by using MATLAB and cycle configuration has been shown in figure 1 and the operating conditions are mentioned in table 1

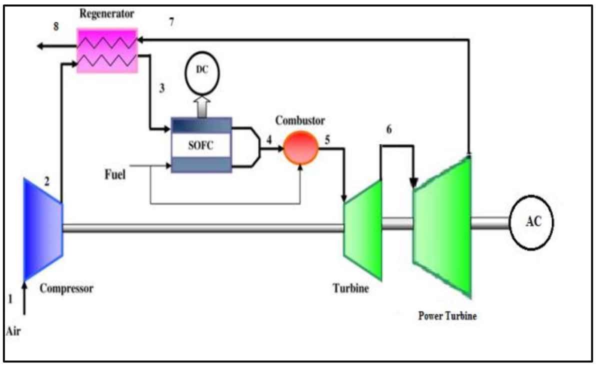

Fig. 1: Schematic of a combined Gas Turbine power plant with an SOFC

A. *Operating Condition*

Gas turbine cycle	
Compressor efficiency (ηcomp)	0.81
Turbine efficiency (ηGT)	0.85
Power turbine efficiency (ηPT)	0.89
Recuperator effectiveness (ηRecup)	0.8
Combustor efficiency (ηComb)	0.98
AC generator efficiency (ηGen)	0.98
Solid oxide fuel cell	
Air utilization factor (Ua)	0.25
Fuel utilization factor (Uf) 0	0.85
Steam-to-carbon ratio (STCR)	2.5
Stack temperature (Tstack) (K)	1273.15
Current density (A/cm2)	0.2
DC–AC inverter efficiency (ηinvert) 0	0.89
Cell area (cm2)	834
Pressure losses	
Recuperator gas/air sides (%)	4
Fuel cell stack (%)	4
Combustor (%)	5
Ambient conditions	
Temperature (K)	288
Pressure (atm)	1

Table 1:

IV. RESULT AND DISCUSSION

A. *Validation*

On solving the governing equation of hybrid cycle exclusive comparison has been made on the basis of operating condition which is detailed in table 2

Parameters	Haseli [14]	Tse [15]	Present
Thermal efficiency of the plant, %	60.55	59.4	59.75
Specific power to drive compressor, kJ/kg	175.7	174	174.7168
Specific power from generator, kJ/kg	146.4	158	143.4771
Specific power from SOFC, kJ/kg	437.5	440	435.5323
Total specific power produced, kJ/kg	583.9	598	579.020
Net power, kW	2419.3	2457.4	2387.3
Air mass flow rate, kg/s	4.123	4.11	4.123
Mass flow rate of fuel to the combustor, kg/h	62.1	64	62.1
Mass flow rate of fuel to the fuel cell, kg/h	225.3	232.4	225.3

Table 2: Validation and compression of performance of hybrid gas turbine cycle

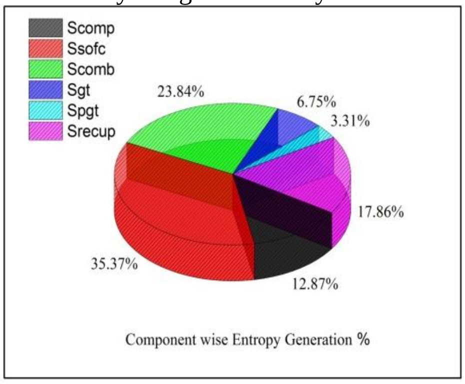

Fig. 2: Component wise entropy generation rate.

Figure 2 shows the component wise entropy generation rate within the SOFC-GT based cycle. It has been observed that the maximum entropy generation takes place with SOFC i.e. 35.37% at 4 compression ratio (rp), secondly, in combustion chamber the rate of entropy generation is 23.84%. Thirdly, in the recuperater the generation rate is 17.86%. Fourthly, in compressor it is 12.87%. Fifthly in gas turbine it is 6.75% and lastly, at the power turbine it is 3.31%.

Figure 3 illustrates the variation of specific power and thermal efficiency with respect to turbine inlet temperature. TIT has been observed that increasing TIT thermal efficiency decreases, while specific power increases significantly. This is because of further heating of working fluid, subsequent to fuel cell in combustion chamber is ineffectual. On the other hand, the un-reacted fuel from SOFC can be utilized for developing additional heat. Therefore specific power increases.

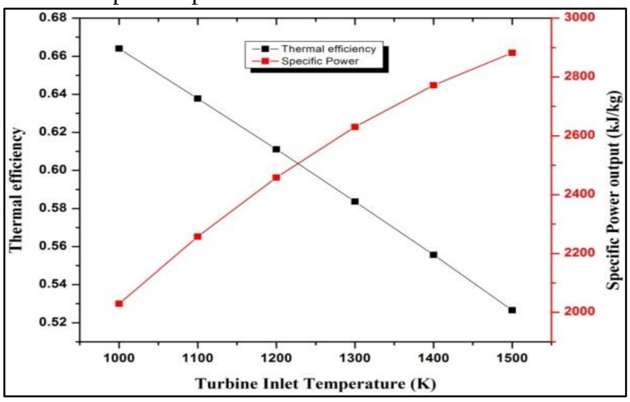

Fig. 3: Variation of Specifc power and thermal efficiency with respect to turbine inlet temperature

V. CONCLUSIONS

On the basis of developed hybrid gas turbine following conclusions has been drawn:

– Increasing in turbine inlet temperature the thermal efficiency of hybrid cycle decreases linearly

- The specific power of hybrid cycle increases linearly as turbine inlet temperature.
- Maximum entropy generation takes place with combustion chamber and minimum in power gas turbine.
- The fuel cell produces major portion of power of hybrid has turbine as it utilizes waste heat from the gas turbine exhaust
- Performance of hybrid cycle can be improved by adopting chemical loop combustion which helps in minimizing entropy in combustion chamber.

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