MODELLING OF A HYBRID GAS TURBINE AND FUEL CELL SYSTEM FOR POWER GENERATION

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Modelling of a Hybrid Gas Turbine and Fuel Cell System for Power Generation

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Abstract

This paper presents the modelling of a hybrid cycle power generation with gas turbine and fuel cell technologies. The fuel cell used for the model is the Solid Oxide Fuel Cell (SOFC), with helium gas taken as the closed cycle fluid because of its high rate of heat transfer. Due to their ceramic constituent, SOFC can operate at high temperatures in the range of 800^{o}C - 1000^{o}C and requires no precious metal catalysts and is considered the most promising of all high temperature fuel cells.The fuel cell, gas turbine and heat exchanger were modelled and design calculations carried out show that the mass flow rate of hydrogen,the rate of heat exchange from the fuel cell and the gas turbine power output are respectively 0.225kg/s, 5931.46kW and 1087.65kW. A preliminary evaluation of the model was achieved by varying the stoichiometric constant λ and the turbine inlet temperature T_3 while the compressor inlet temperature T_1 and fuel cell voltage were kept constant at 375K and 0.65volts respectively. The hybrid efficiency increases with increase in turbine inlet temperature and attained 52% at 980K. The increase in stoichiometric constant from 1.25 to 2.0 led to a corresponding increase in the ac power output of the gas turbine from 1.65 to 2.0MW. The hybrid power output is 14MW.

Keywords: Hybrid Power cycle; Gas Turbine; Fuel Cell; Heat Exchanger; SOFC.

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1.Introduction

It is becoming increasingly important that any power plant using fossil fuel to generate electricity is both as efficient as possible and has very low emissions of pollutants. An alternative to the conventional energy conversion system is the use of fuel cell.Fuel cell when combined with either steam turbine or gas turbine produces a better power generation system. The combined cycle of fuel cell and a gas turbine is the most efficient way of power generation. The justification for this combination being that the fuel cell converts chemical energy directly to electrical power[1] hence lower losses and higher efficiencies compared with conventional heat engines, and the gases leaving the high temperature fuel cells have a relatively high enthalpy which can be utilized in a secondary cycle to generate more power[2]. The levels of pollutants in the gases leaving the fuel cell are also extremely low.

Fuel cells are classified as either high temperature or low temperature fuel cells. The low temperature fuel cells are the Proton Exchange Membrane Fuel Cell (PEMFC), the Alkaline Electrolyte Fuel Cell (AEFC) and the Direct Methanol Fuel Cell (DMFC). These fuel cells operate at a temperature that is below the temperature required to raise the temperature of the fluid to the inlet temperature of the gas turbine and as such cannot be used in combination with a gas turbine for optimized power production. The fuel cells operating at higher temperatures are the Phosphoric Acid Fuel Cell (PAFC), the Molten Carbonate Fuel Cell (MCFC) and the Solid Oxide fuel Cell (SOFC) [3,4]. The higher temperature increases the reaction rates at the electrodes, thereby decreasing losses [5]. Also, and critically for cycle operation, the gases leave the fuel cell with a relatively high value of enthalpy and therefore can be used as a heat source for a secondary cycle [6]. They are simply not ordinary fuel cells but an integral part of a complete fuel processing and heat generating system[3]. The high temperature of the MCFC gives high overall thermal efficiencies with the possibility of above 50% fuel conversion to electricity [7]. However, the excessive temperatures have anegative impact through electrolyte evaporation and electrode corrosion. As such, they are operated at temperatures not exceeding 650^{o}C. The Solid Oxide Fuel Cell (SOFC) is composed mainly of solid state materials, usually a ceramic as the electrolyte which acts as the ionic conductor. There is no liquid phase involved in this type of fuel cell. Due to their ceramic constituent, they can operate at high temperatures in the range of 800^{o}C - 1000^{o}C and require no precious metal catalysts. The SOFC can use both hydrogen and carbon monoxide as fuels [3], and is the most promising of all the high temperature fuel cells [4].

This paper focuses on a promising power plant system obtained by combining Solid Oxide Fuel Cell and Gas Turbine in closed cycle operation. Heat is exchanged from the topping cycle (fuel cell) to the bottoming cycle (gas turbine) via a high temperature heat exchanger. The combination of two or more thermodynamic power cycle from a thermodynamic point of view is to increase the efficiency over that of a single cycle. This combination gives very interesting and advantageous outcomes particularly when the cycles work with different working media, as they can then complement one another [8-10]. The heat is usually generated and supplied by the first cycle referred to as the "topping cycle" while the process which utilizes the heat that is not converted into work in the first cycle is called the "bottoming cycle". The heat exchanger recovers the waste heat from the exhaust of the fuel cell at a temperature of about 1000^{o}C and heats up the compressed gas from the compressor prior to entry to the turbine. With a careful selection of the working medium, optimum thermodynamic utilization of the waste heat is possible [8]. One such working medium, as stated previously, is helium.

1.1System layout

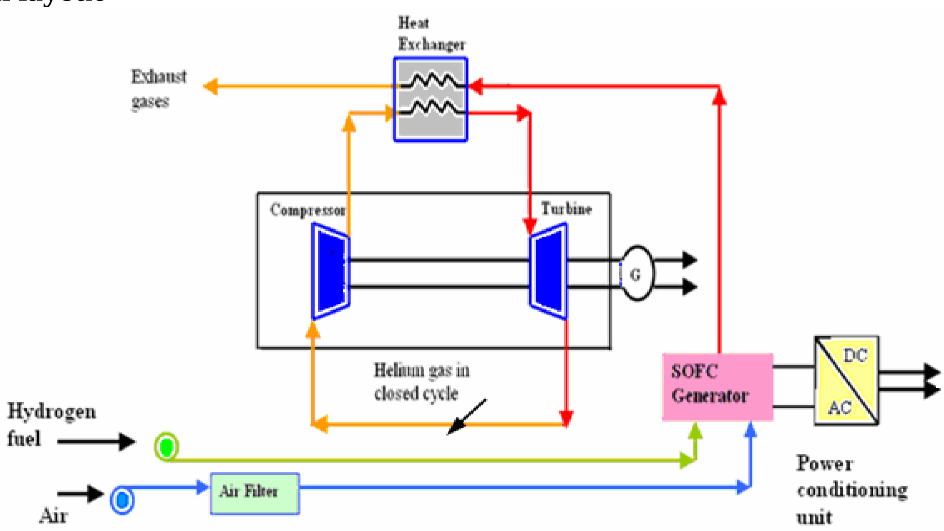

Figure1. A configuration of the SOFC/GT hybrid system[11].

The fuel cell operates just above ambient pressure with a blower circulating hot air to the fuel cell system having taken up heat via the heat exchanger. The fuel is also heated before it enters the fuel cell system. Thus the temperature of the air and fuel is raised to the minimum fuel cell operating temperature. The fuel and air reacts at the fuel cell to generate the DC power after which the hot gases from the fuel cell transfer their heat via a different heat exchanger to the compressed helium gas prior to its entry to the turbine, where it expands and generate additional power. The layout of the plant to be investigated is shown in figure 1.

2.Theory of modelling and calculations

The first step for the modelling is to acquire thermodynamic data and to use a reliable mathematical approach to simulate the steady-state operation of the fuel cell and the gas turbine. The key parameters at the design point of the hybrid system will be taken and assumed as: Fuel cell voltage is 0.65volts, excess air ratio is 1.25, Turbine inlet temperature is 1000K, Compressor inlet temperature is 375K, the fuel cell operates at a temperature is 1200K, compressor efficiency 88%, turbine efficiency 90%, fuel cell efficiency 45% and generator efficiency 93%,

2.1Modelling the fuel cell

The Nernst equation gives the connection between the potential chemical energy that can be converted into electrical energy and the operating parameters of temperature and pressure. The Nernst equation clearly shows the effect of high temperature on the fuel cell. Theoretically, the efficiency of the fuel cell decreases as the temperature increases because the change in Gibbs free energy of formation becomes more negative. However, in reality the reverse is the case as the activation and ohmic losses actually decrease with increasing temperature [3]. The parameters that determine the performance of any fuel cell are typically its temperature, pressure and the concentration of the gases.

The Nernst equation for the hydrogen fuel cell is express as;

$$\Delta g_f = \Delta g_f{}^o - RTln\left(\frac{P_{H_2}.P_{O_2}{}^{0.5}}{P_{H_2O}}\right)(1)$$

Note that these pressures are partial pressures of the operating pressure in the system, the pressures can be expressed in relation to the operating fuel pressure P, as $P_{H_2} = \alpha P$, $P_{O_2} = \beta P$ and $P_{H_2O} = \delta P$.

The final Nernst equation for the fuel cell is given as;

$$\Delta g_f = \Delta g_f{}^o - RTln\left(\frac{\alpha.\beta^{0.5}}{\delta}.P^{0.5}\right)(2)$$

Where R is the universal gas constant, T is the temperature of the fuel cell (K), P is the operating pressure of the fuel cell and α, β & δ are constants that depend on the molar masses and concentration of the gases.

For a fuel cell, the EMF or open circuit voltage (OCV) is given as;

$$E = \frac{-\Delta g_f}{ZF}(3)$$

Where E, F, Z and Δg_f is EMF or the open circuit voltage, Faraday constant, number of electrons transferred for each molecule of fuel consumed in the cell and Molar specific free Gibbs free energy of formation respectively.

The fuel cell is modelledwith the assumption that the reaction in the fuel cell uses purehydrogen as fuel as;

$$H_2 + \frac{1}{2}O_2 + \left(\frac{1}{2} * 3.76\right)N_2 \Longrightarrow H_2O + \left(\frac{1}{2} * 3.76\right)N_2 (4)$$

The operating efficiency of an ideal fuel cell can be written as;

$$\eta_{FC} = \frac{\dot{W}_{ACT}}{\dot{n}(-\Delta g)_f} (5)$$

The actual and Ideal Power ratio can be express in terms of their corresponding voltage ratios as[3].

$$\frac{\dot{W}_{ACT}}{\dot{W}_{IDEAL}} = \frac{V_{ACT}}{V_{IDEAL}} (6)$$

$$V_{ACT} = E - A * \ln i - i * r - m * e^{(n*i)} (7)$$

Where A, r, m and n are constants for a particular fuel cell design.
The ideal voltage and power are given as;

$$V_{IDEAL} = \frac{(-\Delta g)_{H_2}}{2F} (8)$$

$$\dot{W}_{IDEAL} = \dot{n}_{H_2} * (-\Delta g)_{H_2} (9)$$

Where $(-\Delta g)_{H_2}$ is the change of Gibbs function for thereaction.
The expression for the ac power for the fuel cell is given as;

$$\dot{W}_{AC} = \dot{W}_{ACT} * \eta_{conv} (10)$$

The actual power from the fuel cell before conversion is given as;

$$\dot{W}_{ACT} = \frac{W_{AC}}{\eta_{conv}} (11)$$

The ideal power output can then be expressed as;

$$\dot{W}_{IDEAL} = \dot{W}_{ACT} * \frac{V_{IDEAL}}{V_{ACT}} (12)$$

$$\dot{n}_{H_2} = \frac{\dot{W}_{IDEAL}}{(-\Delta g)_{H_2}} (13)$$

The mass flow rate of the hydrogen gas in the fuel cell is defined as;

$$\dot{m}_{H_2} = \dot{n}_{H_2} * M_{H_2} (14)$$

Using the equations (1) to (14) above, the values obtained for the modelling of the fuel cell are V_{ACT} =0.65volt, V_{IDEAL} =0.963volt, $\dot{W}_{AC}$ =13MJ/s, $\dot{W}_{ACT}$ =13.98MJ/s, $\dot{W}_{IDEAL}$ =20.7MJ/s, $\dot{m}_{H_2}$ =0.225kg/s, and $\dot{n}_{H_2}$ =0.11146kmol/s.

2.2The mass flow rates of the gases in the fuel cell reactions

For an ideal fuel cell, the current flowing through the external can be express in terms of its charge and the circuit current per kmol of fuel as;

$$Q = I * t = n * Z * F (15)$$

$$n = \frac{I*t}{Z*F} (16)$$

Where n, t, and I is the amount of substance in moles, time in seconds and current respectively.

$$\dot{n} = \frac{I}{Z*F} \text{moles/s} (17)$$

Power is the product of voltage and current. Therefore current is expressed as;

$$I = \frac{\dot{W}_{ACT}}{V_{ACT}} (18)$$

From equations (17) and (18), the molar flow rate is expressed as;

$$\dot{n} = \frac{\dot{W}_{ACT}}{Z*F*V_{ACT}} (19)$$

The general expression for the mass flow rate is given as;

$$\dot{m} = \frac{M*\dot{W}_{ACT}}{Z*F*V_{ACT}} (20)$$

The molar flow rates of the gases entering the fuel cell taking the total composition of the air used into consideration can be expressed as follows;

$$\dot{n}_{H_2} + \dot{n}_{O_2} + \dot{n}_{N_2} (21)$$

For every half mole of oxygen there is a correspond amount of nitrogen in the air. Thegases exiting the fuel cell would be H_2O (steam) and the unused portion of the intakeair. At stoichiometric conditions the unused portion of the intake air would be nitrogenalone but when more air is supplied than is required for complete combustionoxidation, then oxygen would be a constituent of the exit gases. These gases can beexpressed in terms of their molar flow rates as;

$$\dot{n}_{H_2O} + \dot{n}_{N_2} (22)$$

The law of conservation, the mass flow rates must be conserved between incoming and outgoing streams.

$$\dot{m}_{H_2} + \dot{m}_{O_2} + \dot{m}_{N_2} = \dot{m}_{H_2O} + \dot{m}_{N_2} (23)$$

When the air supply is above the stoichiometric composition, then

$$\dot{m}_{H_2} + \dot{m}_{O_2} + \dot{m}_{N_2} = \dot{m}_{H_2O} + \dot{m}_{N_2} + x\dot{m}_{O_2} (24)$$

Where,x is the amount of excess oxygen gas in the reaction.
The required mass flow rate of hydrogen is express as;

$$\dot{m}_{H_2} = \frac{M_{H_2} * \dot{W}_{ACT}}{Z * F * V_{ACT}} (25)$$

The oxygen utilization from the air is computed as;

$$\dot{m}_{O_2} = \frac{M_{O_2} * \dot{W}_{ACT}}{Z * F * V_{ACT}} (26)$$

The total air utilization can be computed as;

$$\dot{m}_{air} = \frac{M_{air} * \dot{W}_{ACT}}{0.21 * Z * F * V_{ACT}} (27)$$

The above calculated air usage is for the stoichiometric condition. A stoichiometric constant, $\lambda$is introduce to account for situations above stoichiometric.

$$\dot{m}_{abv,stoic,air} = \lambda \dot{m}_{air} (28)$$

The air flow usage for stoichiometric conditions is expressed as;

$$\dot{m}_{stoic,air} = \dot{m}_{air} (29)$$

The molar flow rate of the nitrogen gas exiting the fuel cell is defined as;

$$\dot{n}_{N_2} = \dot{n}_{H_2} \left(0.5 * \frac{0.79}{0.21}\right) (30)$$

The mass flow rate of nitrogen is express as;

$$\dot{m}_{N_2} = \dot{n}_{N_2} * M_{N_2} (31)$$

The mass flow rate of the oxygen gas exiting the fuel cell is defined as;

$$\dot{m}_{air} - \dot{m}_{O_2} - \dot{m}_{N_2} = \dot{m}_{O_2(out)} (32)$$

The mass flow rate of the water vapour that is produced is given as;

$$\dot{m}_{H_2O} = \dot{n}_{H_2O} * M_{H_2O} (33)$$

Using equation (15) to (33) the values obtained from calculations are; $\dot{m}_{O_2}$=1.78kg/s, $\dot{m}_{air}$=7.7kg/s, $\dot{m}_{abv,stoic,air}$=9.625kg/s, $\dot{m}_{stoic,air}$=7.7kg/s, $\dot{m}_{N_2}$=7.364kg/s, $\dot{m}_{O_2(out)}$=0.481kg/s, and $\dot{m}_{H_2O}$= 2.01kg/s.

2.3Modellingthe heat exchanger

The heat exchanger isassumed to use the counter flow arrangement where the cold and hot fluids enter atdifferent ends, flow in opposite directions and finally leave the heat exchanger atopposite ends. Using the effectiveness-NTU (number of transfer units) method, the effectiveness of the heatexchanger is expressed as follows

$$\varepsilon = \frac{C_{P(c)}(T_{c,o}-T_{c,i})}{C_{min}(T_{h,i}-T_{c,i})} \quad (34)$$

$$C_{P(c)} = C_{P(He)} * \dot{m}_{He} \quad (35)$$

$$C_{P(h)} = C_{P(H_2O)} * \dot{m}_{H_2O} + C_{P(N_2)} * \dot{m}_{N_2} + C_{P(O_2)} * \dot{m}_{O_2(out)} \quad (36)$$

Where ε is the heat exchanger effectiveness, $C_{P(c)}$ is the product of specific heat and mass flow rate for the cold fluid (Helium gas), $C_{P(h)}$ is the product of specific heat and mass flow for the hot fluid (fuel cell exit gases), C_{min} is the smaller of $C_{P(c)}$or$C_{P(h)}$, $T_{c,o}$ is the temperature of the cold fluid exiting the heat exchanger, $T_{c,i}$ is the temperature of the cold fluid entering the heat exchanger, $T_{h,i}$ is the temperature of the hot fluid entering the heat exchanger and $\dot{m}_{O_2(out)}$ is the mass flow rate of oxygen (for excess air condition).

The temperature of the helium gas exiting from the compressor can be calculated using the relationship for temperature and pressure in isentropic compression as shown below

$$\frac{T'_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \quad (37)$$

The cycle efficiencyη_c is express as;

$$\eta_c = \frac{T'_2-T_1}{T_2-T_1} \quad (38)$$

Under stoichiometric condition, the rate at which heat can be taken from the fuel cell gases via the heat exchanger is evaluated as;

$$\dot{Q}_{FC} = \dot{m}_{H_2O} * C_{P(H_2O)} * \Delta T + \dot{m}_{N_2} * C_{P(N_2)} * \Delta T \quad (39)$$

For conditions above stoichiometry, the above expression becomes;

$$\dot{Q}_{FC} = \dot{m}_{H_2O} * C_{P(H_2O)} * \Delta T + \dot{m}_{N_2} * C_{P(N_2)} * \Delta T + \dot{m}_{O_2(out)} * C_{P(O_2)} * \Delta T \quad (40)$$

Where $\Delta T = T_{h,i} - T_{h,o}$

The heat from the fuel cell would be transferred to the helium gas in the closed cycle gas turbine. Assuming no heat loss from the heat exchanger to the environment, $\dot{Q}_{FC}$will be equal to the rate at which heat is transferred to the helium as it exit from the heat exchanger

$\dot{Q}_{FC} = \dot{m}_{He} * C_{P(He)} * (T_{c,o} - T_{c,i})$(41)

Using equation (34) to (41), the values obtained from calculations are; $\dot{Q}_{FC}$=5931.46kW, T'_2=619.88K, T_2=653.3K, $\dot{m}_{He}$=3.29kg/s, η_c=88%, ε=90.73%.

2.4Modellingthe gas turbine

The gas turbine is modelled with the assumption that it is a single-shaft unit equippedwith an axial compressor and an axial turbine and the combination is required toproduce an output power of about *7MW*. The performance characteristics of thesemajor components will be used to simulate the operation of the gas turbine under thespecific conditions of the characteristics of the compressor and the turbine.
The cycle efficiency of the gas turbine is expressed as;

$\eta_{cy} = \frac{(\alpha-\rho_p)(\rho_p-1)}{(\beta-\rho_p)\rho_p}$(42)

Where, $\alpha = \eta_C\eta_T K,\ \beta = 1 + \eta_C(K-1), \rho_p = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$ and $K = \frac{T_3}{T_1}$.
Using the energy balance relation for a steady-flow system expressed as;

$\dot{Q} - \dot{W} = \dot{m}_{He}(\Delta h)$(43)

Consider schematic of a compressor in figure 2 below

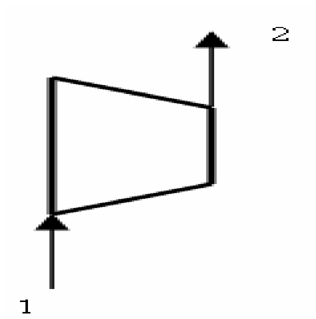

Figure 2.Schematic representation of the compressor

The compressor work is calculated as;

$\dot{W}_C = \dot{m}_{He} C_p T_1 \left[\frac{T_2}{T_1} - 1\right]$(44)

The isentropic power required by the compressor is expressed as;

$\dot{W}'_C = \dot{m}_{He} C_p T_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]$(45)

The efficiency of the compressor is therefore expressed as;

$\eta_C = \frac{\dot{W}'_C}{\dot{W}_C}$(46)

Consider schematic of a turbine in figure 3 below

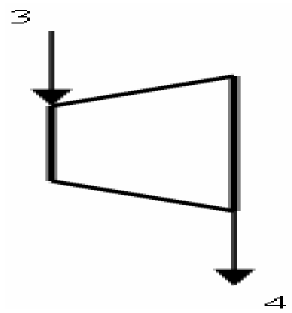

Figure 3.Schematic representation of the turbine

The turbine work is calculated as;

$\dot{W}_T = \dot{m}_{He} C_p T_4 \left[\frac{T_3}{T_4} - 1\right]$(47)

The isentropic power performed by the turbine is expressed as;

$\dot{W}'_T = \dot{m}_{He} C_p T_4 \left[\left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]$(48)

The efficiency of the turbine is expressed as;

$\eta_T = \frac{T_3 - T_4}{T_3 - T'_4} = \frac{\dot{W}_T}{\dot{W}'_T}$(49)

The turbine isentropic output temperature is evaluated as;

$T'_4 = T_3 \left(\frac{P_4}{P_3}\right)^{\frac{\gamma-1}{\gamma}}$ (50)

The actual total ac power that the gas turbine would finally generate is expressed as;

$\dot{W}_{GT,ac} = (\dot{W}_T * \eta_m - \dot{W}_C)\eta_{gen}$ (51)

Using equation (42) to (51) the values obtained from calculation for compressor work, turbine work and the total power of the gas turbine are respectively 4638.63kW, 5926.68kW and 1087.65kW.

2.5Modelling thehybrid system

The total power output of the hybrid system is the summation of the power output of the fuel cell and the gas turbine given as;

$\dot{W}_{HS} = \dot{W}_{AC} + \dot{W}_{GT,ac}$(52)

The efficiency of the hybrid system is

$$\eta_{HS} = \frac{\dot{W}_{HS}}{\dot{m}_{H_2}(LHV)_{H_2}} (53)$$

The values obtained from calculations using equations (52) and (53) for $\dot{W}_{HS}$ and η_{HS} are 14087.65kW and 52.13% respectively.

2.6The heat released by thehot gases exiting thefuel cell

One important aspect of the operation of the hybrid plant that needs to be considered is whether or not external heat needs to be supplied to the plant to heat the gases supplied to the fuel. Heat is rejected in the fuel cell reaction and this can be used to heat the incoming gases. The following equations allow the calculations to be made, which shows that excess heat is released in the reaction which will allow the fuel cell to be operated with excess air (λ>1) which in turn will allow more heat to be transferred to the gas turbine.

$$\dot{Q}_{out} - \dot{W}_{ACT} = \dot{m}_{H_2O} C_{P(H_2O)}(T_{hi} - T_{amb}) + \dot{m}_{N_2} C_{P(N_2)}(T_{hi} - T_{amb}) + \dot{m}_{O_2(out)} C_{P(O_2)}(T_{hi} - T_{amb}) + \dot{m}_{H_2} \Delta h_{H_2O(T_{amb})} (54)$$

Where $\dot{Q}_{out}$ is the heat release to the atmosphere by the fuel cell exiting gases.
At stoichiometric conditions $\dot{m}_{O_2(out)}$=0, but for conditions above stoichiometry, $\dot{m}_{O_2(out)}$>0.
Therefore, using design point values, $\dot{Q}_{out}$ of the hybrid system is -2456kJ/s.

3.Results

The evaluation of the model was carried out and the results are shown below.

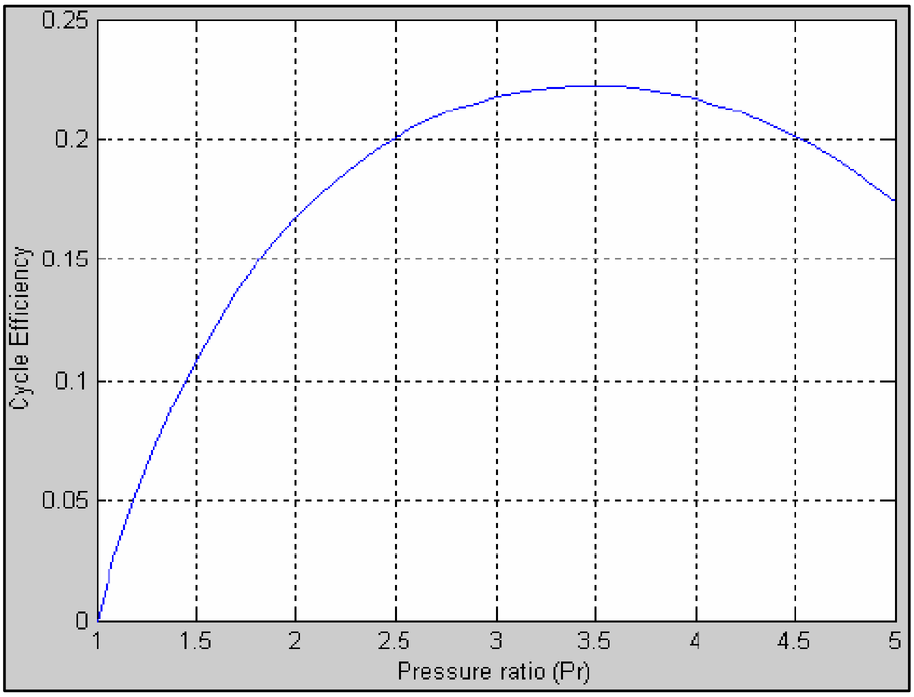

Figure 4. Performance of a gas turbine

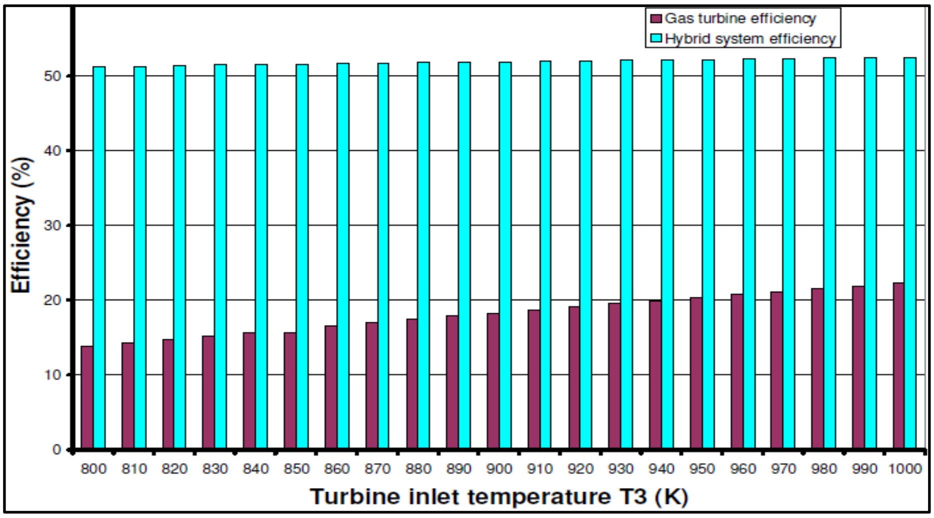

Figure 5.The efficiencies of gas turbine and hybrid system.

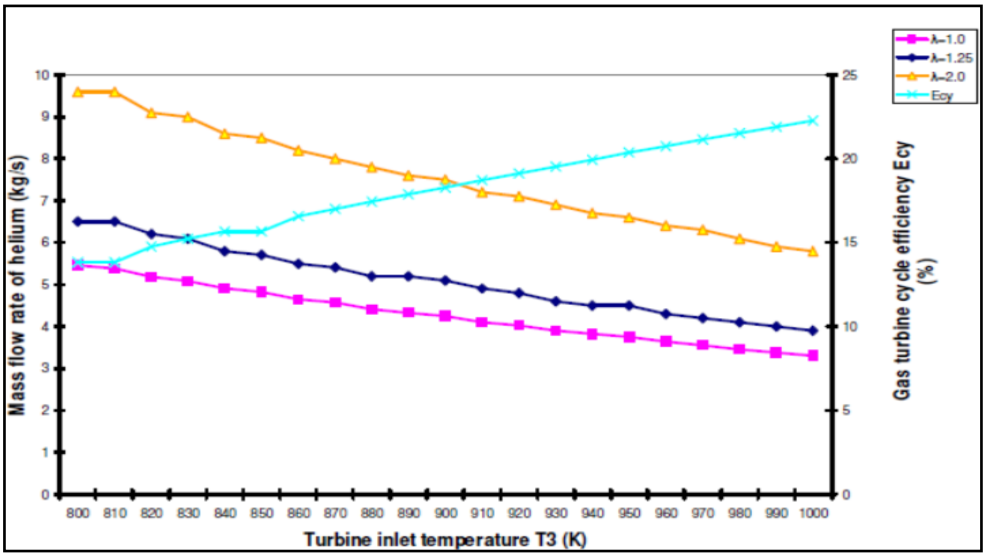

Figure 6. Mass flow rate of helium and turbine cycle efficiency.

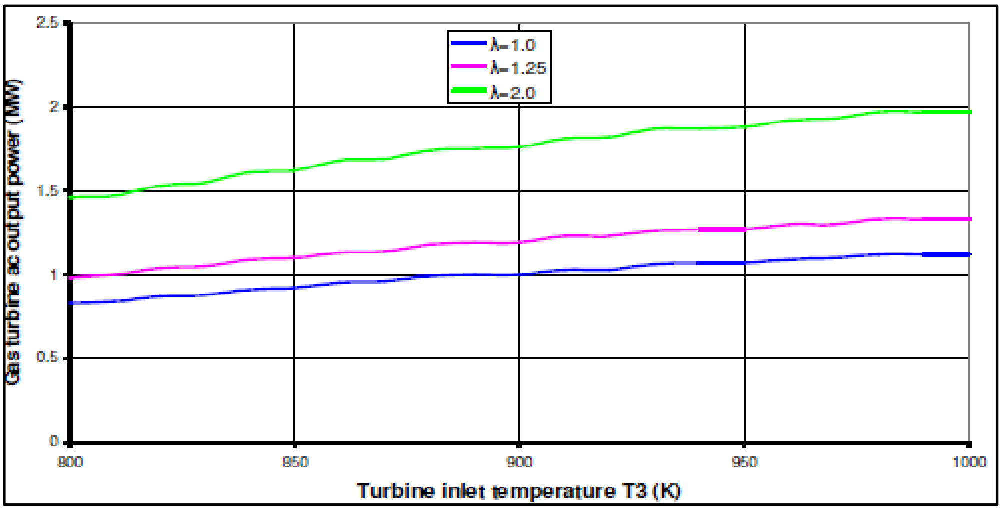

Figure 7. Gas turbine ac output at varying temperatures.

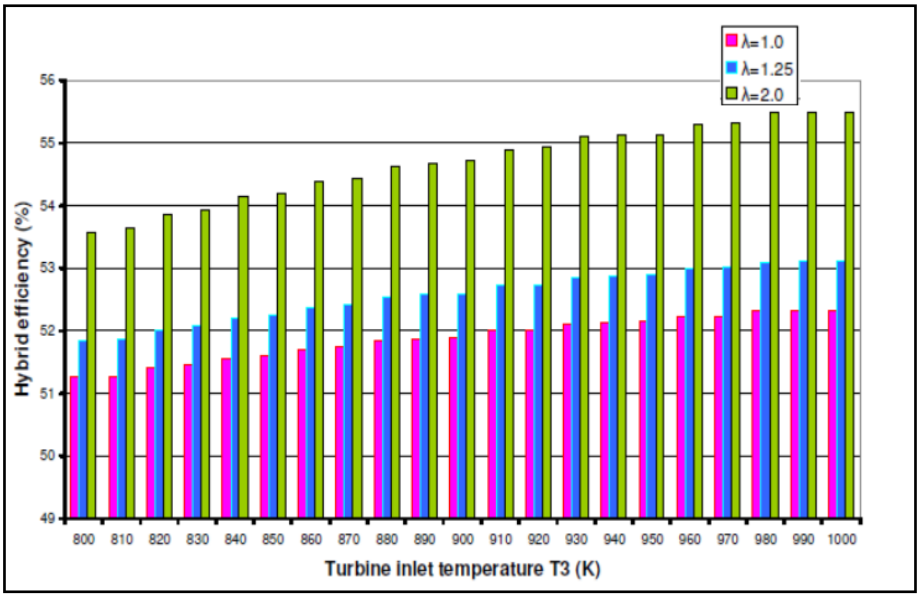

Figure 8.Hybrid efficiency of stoichiometric constants.

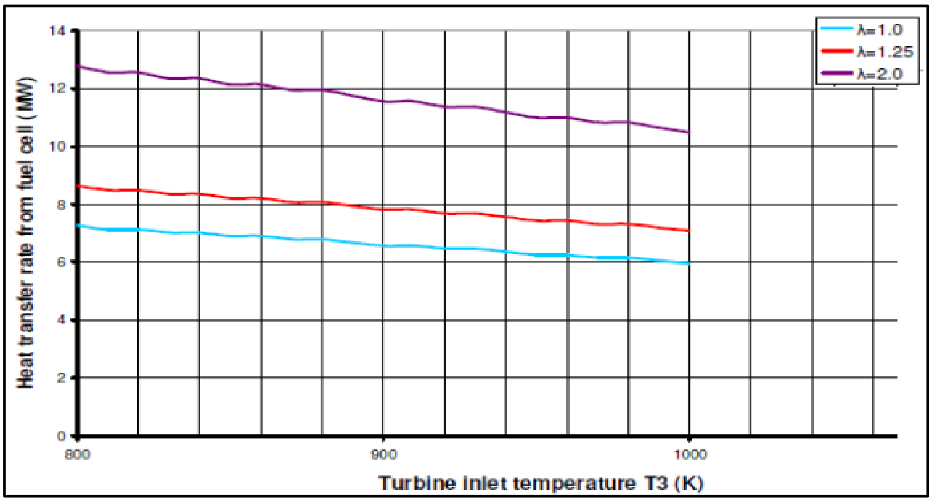

Figure 9.Fuel cell heat transfer rate of stoichiometric constants.

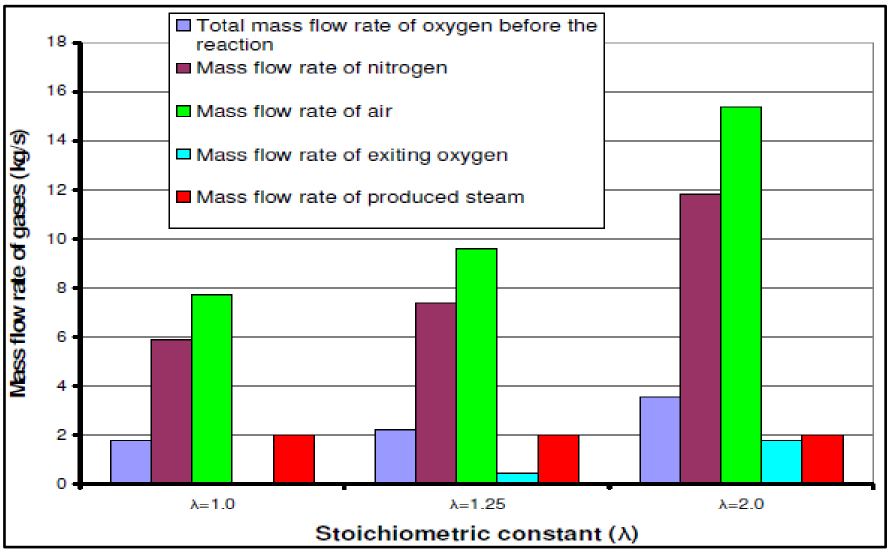

Figure 10.The mass flow rate of fuel cell gases of stoichiometric constants.

4. Discussions

The hybrid system was analysed by considering two conditions; stoichiometry and above stoichiometry. The stoichiometric constant λ and the turbine inlet temperature T_3 were varied while the compressor inlet temperature T_1 and fuel cell voltage were kept constant at 375K and 0.65volts respectively. Figure 4 show that the optimum value of gas turbine pressure ratio for the design point has a maximum cycle efficiency of 22.28% at a pressure ratio of 3.5 and these values were adopted for the calculation.

With the compressor inlet temperature and fuel cell voltage fixed at 375K and 0.65volts respectively, the turbine inlet temperature was varied for a range of temperatures (800K-1000K). The best performance of the hybrid system was found to occur at a temperature range of 980K-1000K. All output characteristics, including the hybrid efficiency increases as the turbine inlet temperature increases as shown in figure 5. The maximum turbine efficiency is 22.28%, while that of the hybrid is 52% (figure 5).

As the mass flow rate of helium at stoichiometric (λ=1) reduces with increasing turbine inlet temperature, the increases (figure 6). The increases in air supply above stoichiometric (λ=1.25 & 2.0), led to the corresponding decrease in mass flow rate of helium with no effect on the maximum pressure ratio and hence gas turbine cycle efficiency. This is due to the cycle efficiency being dependent on pressure ratio, T_1 and T_3 which are constant. However, as the helium temperature at entry to the turbine is raised, there is an increase in the gas turbine cycle efficiency, as shown in the figure 6.

Figures 7 shows that the gas turbine power output increases as the air supply to the fuel cell system increases and further increment is observed for each operating turbine inlet temperature. A value of 2MW was attained at a temperature of 1000K using a stoichiometric constant of 2.0. The hybrid efficiency increases to a maximum of 55.5% as the air supply increases (λ=2.0) as shown in figure 8. The effect of increasing air supply is to increase the mass flow rate of the gases exiting from the fuel cell, thereby increasing the amount of heat that can be transferred to the gas turbine cycle. This heat transfer rate reduces with increase in turbine inlet temperature as shown in figure 9. The mass flow rates of gases exiting the fuel cell increases with increase in air supply except for steam which remains constant as the stoichiometric constants increases from 1 to 2 (figure 10). The power output of the hybrid system is 14MW.

5. Conclusion

The modelling of a hybrid gas turbine and fuel cell power generation plant is presented. The hybrid system used Solid Oxide Fuel Cell with hydrogen gas as it fuel and working in closed cycle gas turbine system. The hybrid system was analysed by considering two conditions; stoichiometry and *above* stoichiometry. The stoichiometric constant λ and the turbine inlet temperature were varied while the compressor inlet temperature and fuel cell voltage were kept constant at 375K and 0.65volts respectively. Higher turbine inlet temperatures increase the efficiency of gas turbine. The mass flow rate of helium at stoichiometric ratio (λ=1) reduces with increasing turbine inlet temperature. A power output of 14MW is achievable for the hybrid system.

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References

[1] Sanchez D., Chacartegui R., Munoz A. and Santez T. On the effect of methane internal reforming modelling in Solid Oxide Fuel Cells. International Journal of Hydrogen Energy2008, 33(7), 1834-1844.

[2] Rory R., Jack B., Faryar J., Tobias J. and Hossein G. Control design of an atmospheric solid oxide fuel cell/gas turbine hybrid system: Variable versus fixed speed gas turbine operation. Journal of Power Sources.2006, 161(1), 484-491.

[3] Larminie J. and Dicks A. Fuel Cell Systems Explained. 3rd Ed. England: John Wiley& Sons Ltd, 2003.

[4] Yang W.J., Park S.K., Kim T.S., Kim J.H., Sohn J.L and Ro S.T. Design performance analysis of pressurized solid oxide fuel cell/gas turbine hybrid systems considering temperature constraints. Journal of Power Sources 2006, 160(1), 462-473.

[5] Appleby A.J. and Foulkes F.R. Fuel Cell Handbook. USA: Van Nostrand Reinhold, New York, 1989.

[6] Peters R., Dahl R., Kluttgen U., Palm C. and Stolten D. Internal reforming of methane in solid oxide fuel cell systems. Journal of Power Sources 2002, 106(1-2), 238-244.

[7] Manfred B.Molten Carbonate Fuel Cells: A high temperature fuel cell on the edge of commercialization. Journal of Power Sources 2006, 160(2), 842-845.

[8] Kehlhofer Rolf. Combined-cycle Gas and Steam Turbine Power Plants [The Fairmount Press, INC] Lilburn Georgia Editors: Prentice Hall Int., UK. 1991.

[9] Park S.K., Oh K.S. and Kim T.S. Analysis of the design of a pressurized SOFC hybrid system using a fixed gas turbine design. Journal of Power Sources 2007, 170, 130–139.

[10] Chan S.H., Ho H.K. and Tian Y. Modelling of simple hybrid solid oxide fuel cell and gas turbine power plant. Journal of Power Sources 2002, 109, 111–120

[11] Daibo J.D. Combined Cycles for Power Generation: Using Fuel Cell and Gas Turbine. MSc. Thesis, University College London, 2008.