A HYBRID POWER-PLANT TO MODERATE CARBON EMISSIONS

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ABSTRACT

Emissions of CO and CO_2 are understood to be the main cause of global warming, melting of glaciers, heavy rain fall in some areas resulting in catastrophic floods and severe draughts in others. Introduction of national quotas is a political solution to limit carbon emissions; it cannot provide answers to a complex problem of climatic change. A permanent solution would require combustion free technologies for converting chemical energy of fuels directly into electricity. Fuel cells are highly efficient direct energy conversion devices; they have the true potential to reduce carbon emissions. This paper describes a conceptual hybrid power plant comprising a solid oxide fuel cell (SOFC) and a closed cycle gas turbine. A simple analysis of the plant has been carried out to demonstrate that significant gains can be made in reducing carbon emissions, increasing energy utilisation efficiency and minimising the impact of thermal loading on the environment.

Keywords: *Fuel Cell, Combined power plant, Hydrogen energy, Energy conservation, Protection of the environment.*

NOMENCLATURE:

C_p	Specific heat at constant pressure (kJ/kg K)
E	Potential energy (kJ/kg)
m	Mass flow rate (kg/s)
R	Universal gas constant (kJ/kg K)
SOFC	Solid oxide fuel cell
w, W	Specific work output, work output
P	Pressure
T	Temperature
Q_a	Heat added
Γ	Ratio of specific heats
ε_{HE}	Effectiveness of the heat exchanger
η	Efficiency

SUBSCRIPTS:

1	Compressor inlet
2	Compressor exit
3	Gas Turbine inlet
4	Gas Turbine exit / Power turbine inlet
5	Power turbine exit
o	Stagnation
a	Air
c	Compressor
j	Jet
$FCGT$	Combined fuel cell-gas turbine
FC	Fuel cell
HE	Heat Exchanger
$overall$	Over-all (Efficiency)
p_t	Power turbine
g_t	gas turbine

1. INTRODUCTION

A combined cycle power plant comprising a solid oxide fuel cell and a closed cycle gas turbine is shown in fig. 1. As the operating temperature of this type of fuel cell lies in the range from 800 ^{o}c to 1000 ^{o}c, it must be cooled in order to protect it from structural failure. Low grade heat must be extracted also form the hot air coming out from the turbine before it enters the compressor. This cooling is achieved with the help of a regenerative heat exchanger. Cooling the air before it enters the compressor reduces compression work thereby improves the plant efficiency further with only a marginal increase in capital cost.

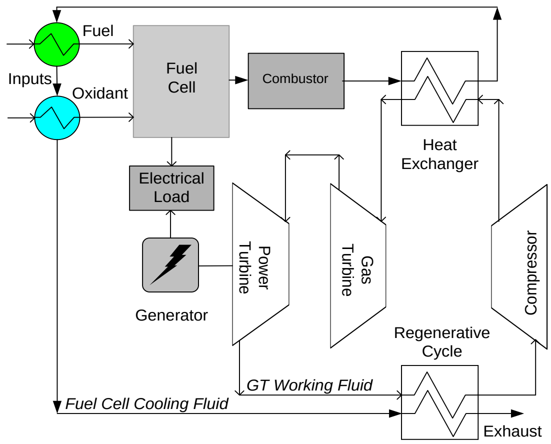

Fig.1. A Schematic Diagram of Hybrid Power Plant

The main feature of the proposed combined cycle plant is that it does not rely on burning the hydrocarbon fuel in order to use its chemical energy to generate electricity. Therefore, the combustion chamber of the gas turbine can be replaced by a heat exchanger to remove heat coming from the fuel cell and transfer it to the pressurised air that drives the closed cycle gas turbine. The aim of this paper is to show that the proposed hybrid plant can achieve: (i) substantial increase in the overall energy utilisation efficiency; (ii) reduction in emissions of CO and CO2 and (iii) significant drop in thermal loading on the environment.

2. THE SOLID OXIDE FUEL CELL

Fuel cells are highly efficient electrochemical energy conversion devices that use the chemical energy of fuels to generate electricity. There are six types of fuel cells; in general they comprise four functional components: the anode, the cathode, the electrolyte and two chambers, one on each side, that allow the flows of fuel and of oxidant. Since none of these components has any moving parts; fuel cells are simpler and quieter power generators than other devices such as steam turbines, gas turbines, reciprocating and rotary engines. The main components of a single solid oxide fuel cell are shown diagrammatically in Fig. 2.

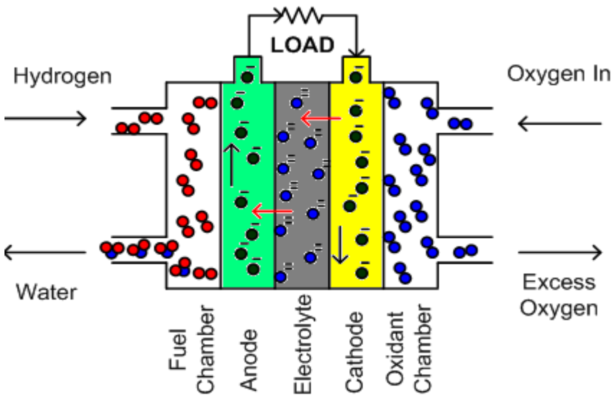

Fig. 2 A schematic diagram of a single solid oxide fuel cell (not to scale).

The primary fuel for fuel cells is hydrogen; a light and combustible gas which is present in water, hydrocarbon fuels and bio fuels. Hydrogen may be derived from water with the help of electrolysis and from hydro carbon and bio fuels by reforming or thermal racking. In the case of a solid oxide fuel cell reforming can be performed internally because of its high operating temperatures. Heat rejected by the fuel cell can be used in the closed cycle gas turbine to generate additional electricity.
The performance of a fuel cell is given usually by the Current Density vs Voltage curve, known as the **polarisation curve** shown in Fig. 3. The theoretical curve, which represents open circuit voltage, is a straight line parallel to the X axis. The difference between the actual curve and the theoretical curve is due to four main sources of losses defined as follows:

<u>Activation loss</u> This loss is given by the following expression

$$\vartheta_{act+\text{int}} = -0.9514 + 0.00312T + 7.4\times10^{-5}T\ln(C^*_{O_2}) - 0.000187 \quad (1)$$

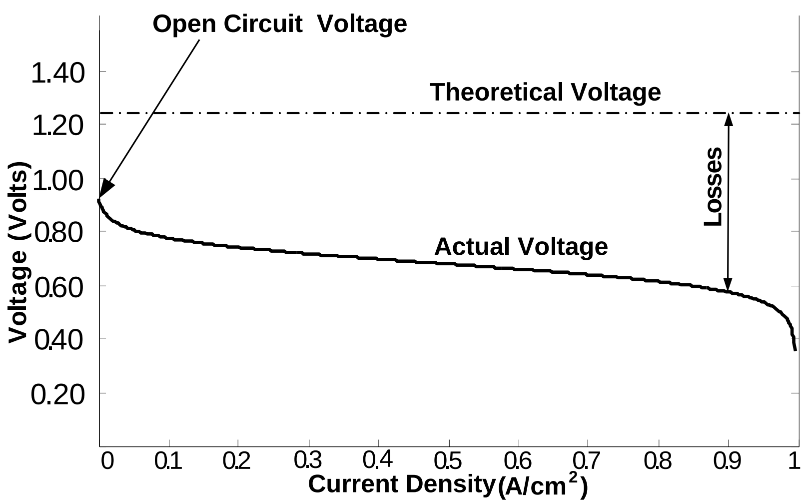

Fig. 3 Typical power density and voltage versus current density curves [1]

<u>Ohmic loss</u> The expression for this loss is given below:

$$\vartheta_{ohmic+\text{int}} = -(i+i_n)\Omega_{total} = -(i+i_n)(K_1 + K_2T) \quad (2)$$

where: K_1, K_2 are empirical constants.

<u>Concentration loss</u> This loss is given by the following equation

$$\vartheta_{con+\text{int}} = -\frac{RT}{nF}\ln\left[1-\frac{i+i_n}{i_l}\right] \quad (3)$$

The total output voltage of a fuel cell, taking these losses into account, is given by the following expression [2]:

$$V = E + (\vartheta_{act+\text{int}} + \vartheta_{ohmic+\text{int}} + \vartheta_{con+\text{int}}) \quad (4)$$

The cell voltage V is affected also by the temperature; however at temperatures higher than 750 ^{o}C the effect of temperature becomes small as can be seen from Fig. 4.

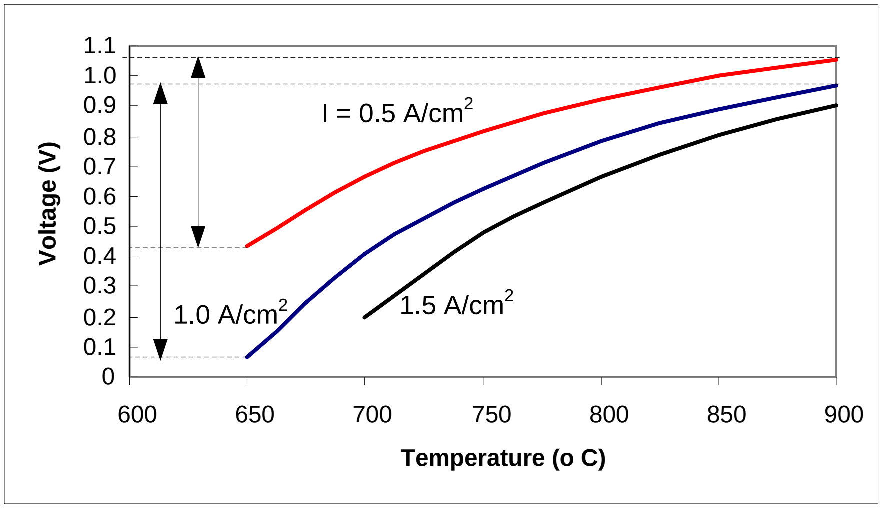

Fig. 4 The affect of temperature on cell voltage

The current generated by a fuel cell that uses hydrocarbon fuel depends on the number of electrons contained in a given mass of that fuel. Current is the rate of flow of charge. Since one mole of electrons contains the number of coulombs given by Faradays constant; the current generated by $\dot{m}_f$ moles of fuel of molar mass M_f kg-mole can be written as follows:

$$I = \frac{\dot{m}_f}{M_f} nF \qquad (5)$$

where M_f is the molecular weight of the fuel (kg-mole); I is the fuel cell current (Amp) and F = 96495 is the Faraday constant (C/mol).

The electrical power output ζ_e of the fuel cell can be written as follows

$$\zeta_e = \frac{\dot{m}_f}{M_f} nF \times V \qquad (6)$$

In this expression n is the number of hydrogen atoms in a molecule of the fuel.

The electrical efficiency of the cell is given be the following expression:

$$\eta_e = \frac{\text{Electrical Power Output}}{\text{Rate of Energy Available}} = \frac{nF \times V}{M_f \times HCV} \qquad (7)$$

Calculated efficiency vs power output graph for one MW fuel cell is shown in Fig. 5. It should be noted that a very attractive feature of the fuel cell is that its part load performance is superior compared with combustion engines. This can be seen from the rising efficiency curve as power output is reduced.

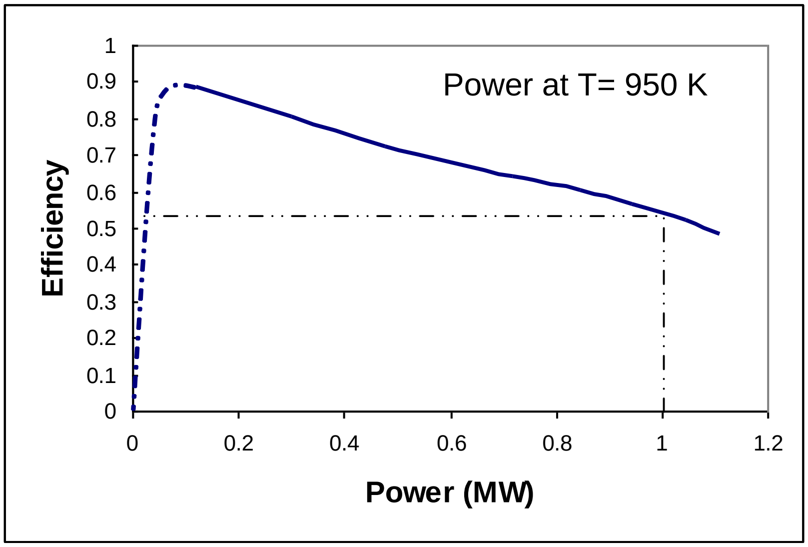

Fig. 5. Fuel cell efficiency vs power output

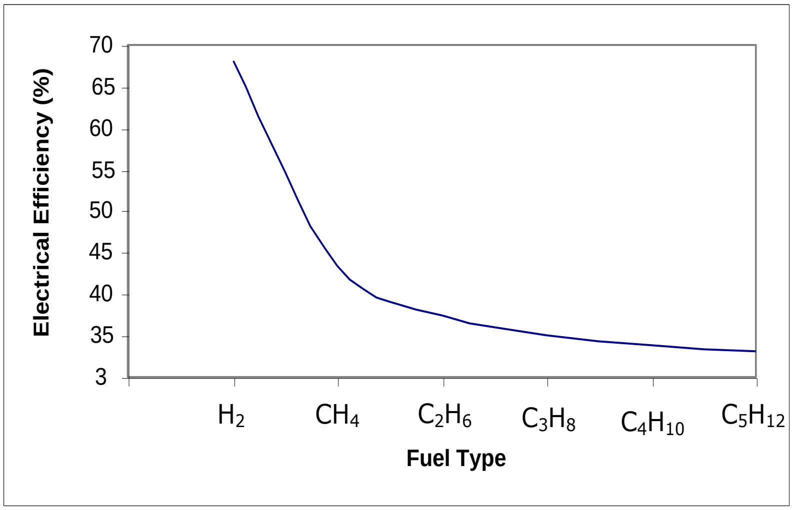

Fig. 6. The effect of fuels on the efficiency of the fuel cell

The ratio of the mass of hydrogen and the total mass of a fuel depends on the chemical formula of the fuel ($C_m H_n$). Since hydrogen is very light compared with carbon, the ratio decreases as carbon increases, hence electrons which can be separated from hydrogen decrease. Since flow of electrons is the source of flow of electrical energy, the available electrical energy compared with thermal energy (i.e. calorific value) reduces. The effect of this ratio on the efficiency of the fuel cell is shown in Fig. 6

3. CLOSED CYCLE GAS TURBINE

The gas turbine cycle is sown on T-S diagram, Fig. 7. Air at Temperature T_{01} and pressure P_{01} the working fluid is compressed by the compressor to pressure P_{02}; the corresponding temperature of air is T_{02}. While flowing through the heat exchanger air is heated to Temperature $T_{03.}$ From point 3, compressed hot air expands through the gasifier turbine to point 4 while its pressure and temperature drop to P_{04} and T_{04} respectively. Hot gasifier turbine exhaust flows through the free power turbine down to P_{05} and $T_{05,}$ point 5.

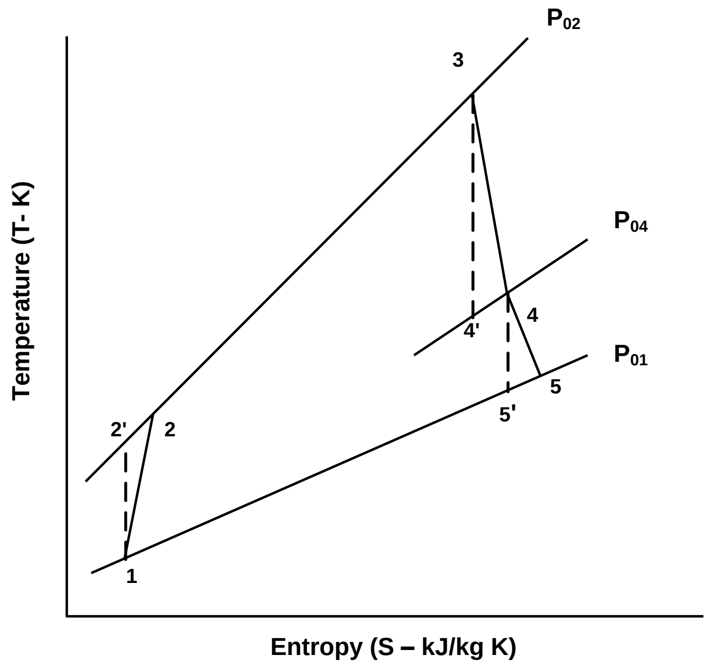

Fig. 7 T-S Diagram of the gas turbine cycle

In order to calculate the shaft work produced by the free power turbine, it is necessary to carry out thermodynamic analysis of the cycle. The analysis is based on the assumptions that C_p = constant over the range of temperatures considered and pressure drop from point 2 to point 3, is negligible. Thus expansion ratio across the free power turbine (P_{04}/P_{05}) can be written in terms of cycle pressure ratio, maximum to minimum temperature ratio and isentropic efficiencies of the gasifier compressor and turbine.

The final expression (P_{04}/P_{05}) is given below:

$$\frac{P_{04}}{P_{05}} = \frac{P_{02}}{P_{01}} \left\{ 1 - \frac{\left(\frac{P_{02}}{P_{01}}\right)^{\frac{\gamma-1}{\gamma}} - 1}{\frac{T_{03}}{T_{01}} \eta_c \eta_t} \right\}^{\frac{\gamma}{\gamma-1}} \quad (8)$$

Finally the specific work output (i.e. work output per unit mass of air) of the free power turbine vs it expansion ratio is given by the following expression:

$$\frac{w}{m} = \eta_{t2} c_p T_{04} \left\{ 1 - \left(\frac{P_{04}}{P_{05}}\right)^{-\left(\frac{\gamma-1}{\gamma}\right)} \right\} \triangleright \quad (9)$$

This expression can now be plotted by combining these two equations. The results given in Fig. 8 show that for maximum specific work output, the cycle pressure ratio higher than 13:1 is needed. At this pressure ratio and Air/Fuel ratio *(A/F*) of 55 the specific work output is approximately 175 kJ/kg.

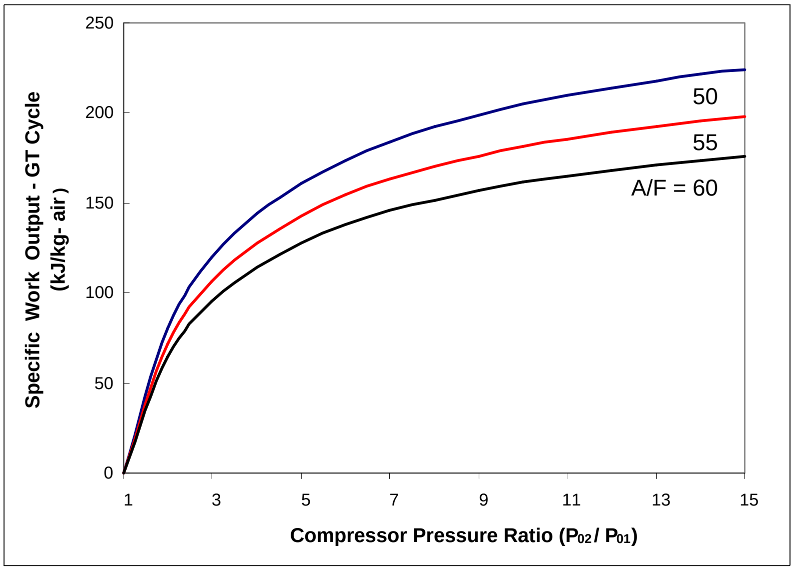

Fig. 8. Specific Work Output vs Cycle Pressure Ratio

4. THE COMBINED CYCLE HYBRID PLANT

The proposed hybrid plant was shown diagrammatically in Fig. 1 and it was claimed that carbon emissions could be reduced significantly by combining a solid oxide fuel cell and a closed cycle gas turbine. In addition the proposed hybrid plant would also achieve higher energy utilisation efficiency and minimise the impact of thermal loading on the environment. Those claims have been quantified by calculations. The results of the calculation are summarised in this section.

The proposed solid oxide fuel cell (SOFC) uses methane (CH_4) as the fuel. The steam reforming reaction (SR) for this fuel is given below [3]:

$$CH_4 + H_2O \rightarrow CO + 3H_2 \tag{10}$$

Gas shift reaction (GS)

$$CO + H_2O \rightarrow CO_2 + H_2 \tag{11}$$

From this reaction hydrogen is utilised in the fuel cell and carbon dioxide is emitted to the environment

$$4H_2 + 2O_2 \rightarrow 4H_2O \tag{12}$$

The two reactions together yield 4 moles of hydrogen and 4 moles of water which goes back to the fuel to take part in the reforming process.

Methane is supplied as fuel to the fuel cell with energy content of 1000 kJ/s (1 MW). The fuel has the design point efficiency of 55%. Hence,

Electrical output of the fuel is	= 550 kJ/s
Heat rejected to the cooling fluid	= 450 kJ/s
The working temperature of cell	= 1173 K
The heat exchanger effectiveness	= 0.8
Heat available to the gas turbine	= 450 kJ/s
Cycle pressure ratio	= 12:1
Turbine entry temperature	= 1173 K
The mass flow rate of air in the closed cycle	= 0.7 kg/s
The output of the gas turbine	= 160 kJ/s
Total output	= 710 kJ/s
The overall energy utilisation efficiency	= (550 + 160)/100
	= 71 %

It should be noted that the effectiveness of the heat exchanger was used for calculating the mass flow of air in the closed cycle gas turbine.

Carbon dioxide emission vs power output is shown in Fig. 9 for the proposed hybrid power plant and for the combustion. It should be remembered that for a given power output, the amount of fuel used depends on the efficiency of the energy conversion process. The hybrid plant proposed in this paper has reached energy utilisation efficiency of 71%. The combustion engine, at best, may reach an efficiency of 45%. Hence, the hybrid can reduce emissions almost to half the level of combustion engines.

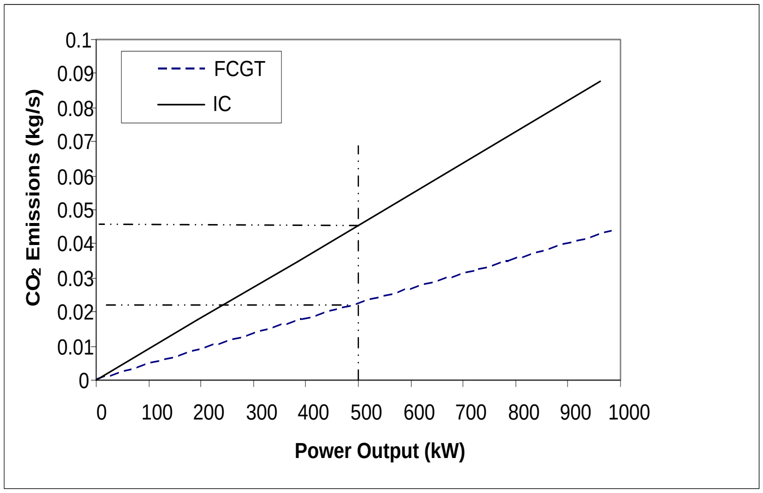

Fig. 9. Emission of CO_2 vs power output (kg/kW. s)

5. CONCLUSIONS

1. The potential of a hybrid power plant comprising a solid oxide fuel cell and a closed cycle gas turbine has been studied. The results show that the combined plant efficiency can be raised to 71%.

2. The emission of greenhouse gases (CO and CO_2) from any plant depends primarily on the mass of fuel consumed per kW which, in turn, depends on the efficiency of converting the chemical energy (kJ/kg) of the fuel into electricity. Therefore, reduction in emissions would be directly proportional to the increase in efficiency. The results of this study confirm this hypothesis.

3. Since the energy utilisation efficiency is defined as the (energy converted to electricity/energy available in the fuel). The unavailable energy is converted to heat; rejection of that heat creates thermal loading on the environment. Therefore, thermal loading would reduce as efficiency increases. Since the efficiency of the hybrid plant has risen to 71%, there would be corresponding reduction in thermal loading.

4. At long last, the disastrous consequences of carbon emission are being taken seriously. Urgent steps are needed to bring carbon emissions under control in order to meet the targets set by the United Nations. This paper has shown the technical feasibility of a hybrid plant which can achieve drastic reduction in carbon emissions.

6. REFERENCES

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