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A Hybrid Power-plant System To Reduce 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; however, it cannot provide answers to the complex problem of climatic change. A permanent solution would require combustion free technologies for converting the chemical energy of fuels directly into electricity. In this respect, devices such as fuel cells are highly efficient direct energy conversion devices which 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

$SOFC$	Solid oxide fuel cell
C_P	Specific heat at constant pressure
γ	Ratio of specific heat
$\dot{m}$	Mass flow rate
R	Universal gas constant, <u>Electrical resistance</u>
E	Potential energy
w	Specific work output
W	Work output
P	Pressure
T	Temperature
Q_r	Heat rejected
Q_a	Heat added
ε_{HE}	Effectiveness of the heat exchanger
η	Efficiency, <u>Overvoltage</u>
i	Current density
F	Faraday's constant
α	*Charge transfer coefficient*
n	*Number of transferred electrons per mole*

Subscripts

1	Compressor inlet
2	Compressor exit
3	Nozzle inlet
4	Nozzle exit
o	Stagnation, exchange current density
a	Air
c	Compressor, cathode, cell
j	Jet
$FCGT$	Combined fuel cell-gas turbine
FC	Fuel cell
HE	Heat Exchanger
$overall$	Over-all (Efficiency)
pt	Power turbine
gt	Gas turbine
act	Activation
con	Concentration
$ohmic$	Ohmic
int	Internal currents
H_2	Denotes partial pressure for Hydrogen
O_2	Denotes partial pressure for Oxygen

1. Introduction

Global public concern about the impact of the emissions of combustion gases on the environment is growing sharply as a consequence of disastrous flooding in various parts of the world. Hence, national quotas are being introduced for the emissions of carbon based combustion gases (CO and CO_2) as a political solution for a complex technical problem.

The permanent solution of the problems of energy conservation and protection of the environment would be

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the fuel cell; a highly efficient device that can convert the chemical energy of the fuel directly into electricity. However, as fuel cells of various types are under development to make them commercially viable, alternative solutions are needed in the short and the mid term to meet the ever increasing demand for clean energy.

Fuel cells and hybrid systems have emerged as advanced thermodynamic systems with great promise in achieving high energy/power efficiency with reduced environmental loads. In particular, due to the synergistic effect of using integrated solid oxide fuel cell (SOFC) and classical thermodynamic cycle technologies, the efficiency of the integrated system can be significantly improved (Zhang, Chan et al. 2010).

On account of the many advantages offered by the hybrid SOFC system, it is considered to be a key technology in improving power generation efficiency and reducing harmful emissions. First, there are no moving components in the fuel cell (except for balance of plant (BoP) components). Noise and vibrations associated with mechanical motion during operation are practically non-existent. This makes it possible to install the system in urban or suburban areas as a distributed power generation plant. Without moving parts, we would expect enhanced reliability and lower maintenance cost. Secondly, SOFCs (by virtue of high-temperature operation) can extract hydrogen from a variety of fuels. SOFC is the most sulfur-resistant (such as H_2S and COS) fuel cell. It can tolerate sulfur-containing compounds at concentrations higher than other types of fuel cells. In addition, it is not poisoned by carbon monoxide (CO); in fact, CO can be used as a fuel (Zhang, Chan et al. 2010).

Recently there have been various efforts to design and analyse the performance of pressurized SOFC hybrid systems considering various parameters and configurations. Park et al. (Park, Oh et al. 2007) simulated the design of a pressurized SOFC hybrid system using an existing (fixed) gas turbine and provided useful fundamental design characteristics as well as potential critical problems. Marko Santin et al. (Santin, Traversoa et al. 2009) presented a study of SOFC–GT hybrids for operation with liquid fuels. Thermodynamic and investment analysis performances were calculated based on zero-dimensional component models. The economic assessment was performed with a through-life cost analysis approach.

Bhinder et al (Bhinder, Ebaid et al. 2006) presented a parametric study of the fuel cell-gas turbine combined cycle power plant. They concluded that even when using a conservative figure of 55% for the fuel cell efficiency, the overall efficiency can be increased to approximately 65%; this increase in energy efficiency offers a solution to the two serious problems facing the power generation industry.

Calise et al (Calise, Accadia et al. 2007) presented an optimization method of a hybrid solid oxide fuel cell–gas turbine (SOFC–GT) power plant . The plant layout was based on an internal reforming SOFC stack; it also consisted of a radial gas turbine, centrifugal compressors and plate-fin heat exchangers. The results of their study showed that the design of a hybrid SOFC–GT power plant must focus an all its components, paying special attention to their coupling.

In the present work; a parametric study has been carried out to investigate the influence of the principal design variables of a hybrid power plant on its overall performance, in particular reduction of carbon based emissions (CO and CO_2), increase in energy utilisation efficiency and the impact of thermal loading on the environment. The plant comprises a closed cycle gas turbine and a high temperature fuel cell. This type of fuel cell is well developed and many plants have already been built around the world to meet the commercial and technical criteria (Zhang, Chan et al. 2010).

As the world is facing the challenges of rapidly depleting global reserves of fossil fuels and increasing impact of carbon based combustion gases on the environment, the paper should be of considerable interest to the Energy Industry and should lead to a stimulating discussion.

2. Theoretical Background of the Fuel Cell-Turbomachinery Propulsion Engine

A combined cycle power plant comprising a solid oxide fuel cell and a closed cycle gas turbine is shown in Figure 1. As the operating temperature of this type of fuel cell lies in the range from 800 °C to 1000 °C, it must be cooled in order to protect it from structural failure. On the other hand, low grade heat must be extracted form the hot air coming out from the gas 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. 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 CO_2.
iii. Significant drop in thermal loading on the environment.

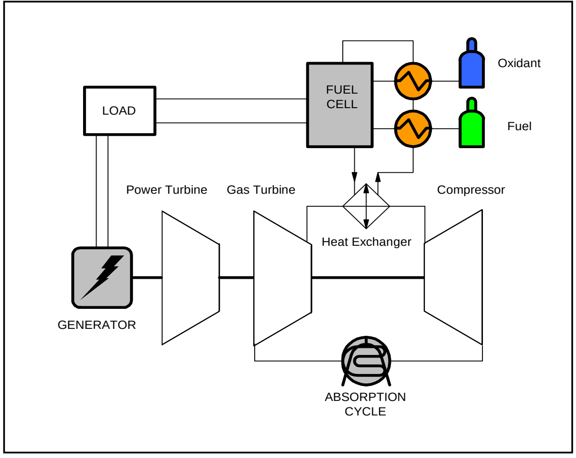

Figure 1. A Schematic Diagram of Hybrid Power Plant

3. The Solid Oxide Fuel Cell (SOFC)

Fuel cells are highly efficient electrochemical energy conversion devices that use the chemical energy of fuels to generate electricity. There are several types of fuel cells; in general, they all comprise four functional components: the anode, the cathode, the electrolyte and two chambers, one on each side, that allow the flows of fuel and 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 type of fuel cell under consideration is the Solid Oxide Fuel Cell which is shown schematically in Fig. 2. It operates at temperatures ranging from 800 ^{o}C to 1000 ^{o}C and offers many advantages such as:

1. The kinetics of the chemical reaction are improved due to the high temperatures, hence precious metal catalyst are not needed, which means a considerable reduction in fuel cell cost.
2. Pressurising the fuel cell does not have much significant effect on performance.
3. Both hydrogen and carbon monoxide can be used as fuels in the SOFC.
4. The anode of the SOFC is usually a zirconia cermet (ceramic and metal); the metallic component is nickel. Due to high conductivity and stability of nickel under chemically reducing conditions, it can be used as an internal reforming catalyst. This characteristic allows internal reforming in the SOFC directly on the anode.
5. The high operating temperature of the cell implies that the heat emitted is good grade thermal energy that can be used in the fuel cell-gas turbine or steam turbine combined cycle (Zhang, Chan et al. 2010).

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 cracking. 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.

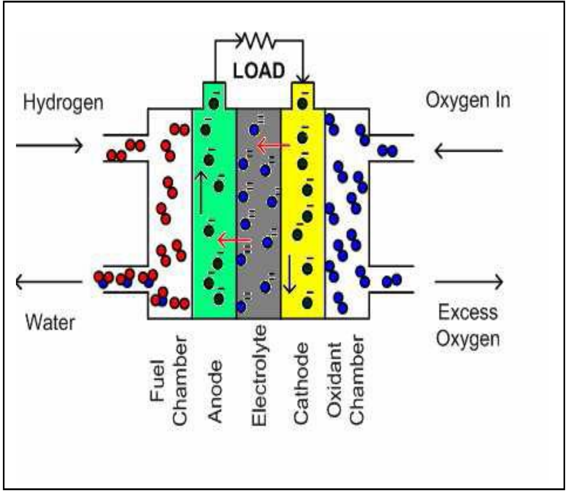

Figure 1. A schematic diagram of a single solid oxide fuel cell (not to scale).

The outputs of a High-Temperature Fuel Cell can be identified as follows:

1. Electric Power.
2. Heat Energy.
3. Hot gas emissions coming out of the electrode compartments as unused fuel and oxidant (air is used as an oxidant; so most of this gas will be Nitrogen with small amounts of Oxygen); in addition to water emissions which come out as superheated steam.

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:

4. Activation loss

Activation losses are caused by the slowness of the reaction taking place on the surface of the electrodes. A proportion of the voltage generated is lost in driving the chemical reaction that transfers the electrons to and from the electrode (J. Larmine 2003).

$$\eta_{act} = b\log\left(\frac{i_c}{i_o}\right) \qquad (1)$$

Where:

$$b = -\frac{RT}{\alpha nF}\ \alpha \qquad (2)$$

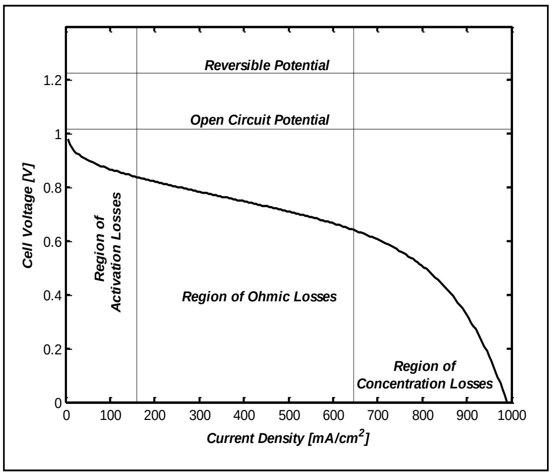

Figure 2. Typical power density and voltage versus current density curves

5. Ohmic loss

Ohmic losses are sometimes called ”resistive losses”, as they stem from the straightforward resistance to the flow of electrons in the various fuel cell components, as well as the resistance to the flow of ions in the electrolyte. This voltage drop is approximately linear and proportional to current density. Mathematically, the Ohmic resistance can be represented as(Mustafa 2009):

$$\eta_{ohmic} = R_i i \tag{3}$$

Where 'R_i'is the internal current resistance which comprises both electronic and protonic resistances caused by membrane and contact losses

6. Concentration loss

Concentration overvoltage or Mass transport losses result from the change in the concentration of one of the reactants at the surfaces of the electrolyte, which occurs when a chemical species participating in the reaction is in short supply due to obstruction in the pathway of this species. This type of loss is sometimes called "*Nernstian*" because of its connection with concentration effects which are modelled by the Nernst equation; the expression for this loss is given as follows (Mustafa 2009):

$$\eta_{con} = -\frac{RT}{nF}\ln\left\{1-\frac{i}{i_l}\right\} \tag{4}$$

Where '*n*' is the number of electrons transferred per molecule in the reaction (in the case of Hydrogen-Oxygen Fuel cell *n* = 2 for Hydrogen, and *n* = 4 for Oxygen), '*R*' is the universal gas constant (8.314 *KJ/kmol .K*), '*T*' is the temperature of operation in Kelvin, and '*F*' is Faraday's constant.

7. Fuel Cross-Over and Internal Currents

Although the proton exchange membrane in the fuel cell is an electronic insulator, it will support very small amounts of electron cross-over. It will also allow some hydrogen to pass through diffusion from the anode to the cathode. This hydrogen will react with oxygen at the cathode in the presence of the catalyst to produce water and heat, but without producing electric current.

It is assumed here that the internal currents are equal to fuel cross-over. An empirical value for the internal currents suggested by (J. Larmine 2003) is *(3.00 mA/cm²)*. Substituting this value in equation (4) above, gives a value of fuel consumption due to fuel crossover equal to: (0.314×10^{-10} *kg/s.cm²)* of hydrogen.

The value of the internal current has to be added to the fuel cell current when measuring fuel cell performance.

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

$$V = E + (\vartheta \mathrm{act}{+}int + \vartheta \mathrm{ohmic}{+}int + \vartheta \mathrm{con}{+}int) \tag{5}$$

Where:

$$E = 1.229 - \beta_2\left(T - T^o\right) + \varphi T\left\{\ln\left(P^*_{H_2}\right) + \frac{1}{2}\ln\left(P^*_{O_2}\right)\right\}$$

This expression represents the *thermodynamic potential for a hydrogen/oxygen fuel cell on the basis of the Nernst equation* where the values of the constant terms $\beta_2 = 0.85\times10^{-3}$ [VK^{-1}] and $\varphi = 4.3085\times10^{-5}$ [VK^{-1}]. And P^* is the partial pressures of the reactant gases denoted by the respective subscript, 'T^o' is the standard state temperature (298.15 K).

Fuel cell voltage is plotted against the fuel cell current for various values of temperature in accordance with equation (5), the oxygen partial pressure ($P^*_{O_2}$) is considered constant at 1 atm. Different current densities [A] are plotted on the same graph to get an idea about the effect of this parameter on the fuel cell voltage under different operating temperatures.

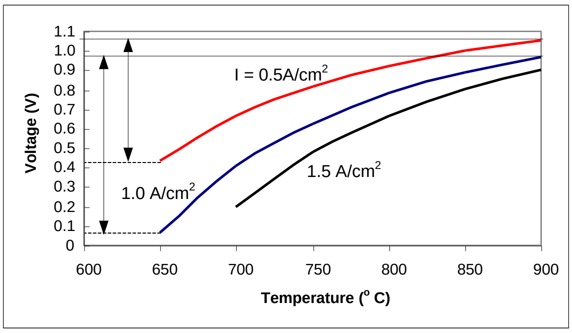

Figure 3. The effect of temperature on cell voltage

The effect of temperature on cell voltage [V] is obvious from the graph. It is noted that the influence of temperature is more prominent at higher current densities, however at temperatures higher than 750 °C the effect of temperature becomes small as can be seen from the graph.

8. Efficiency of the Fuel Cell

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.

The current generated by $\dot{m}_f$ (moles of fuel) can be written as follows: Since one mole of electrons contains the number of coulombs given by Faradays constant; definition of current is in coulombs/s, then:

$$I = \frac{\dot{m}_f}{M_f} nF \tag{6}$$

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:

$$\zeta_e = \frac{\dot{m}_f}{M_f} nF \times V \tag{7}$$

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:

$$\varepsilon_{fc} = \frac{\text{Electrical Power Output}}{\text{Rate of Energy Available}} \tag{8}$$

$$\varepsilon_{fc} = \frac{V_{cell} \times 2F}{M_{H_2} \times \text{Calorific value (HCV)}} \times 100\% \tag{9}$$

Where $V = E + (\vartheta_{act+\text{int}} + \vartheta_{ohmic+\text{int}} + \vartheta_{con+\text{int}})$, HCV is the higher calorific value of the fuel used in the fuel cell, typically hydrogen. Substituting the values for Faraday's constant, molar mass of hydrogen and the interpolated calorific value for hydrogen, the efficiency of the fuel cell becomes:

$$\varepsilon_{fc} = \frac{V_{cell}}{1.38} \times 100\% \tag{10}$$

Following the same lines, the electrical efficiency is the ratio of measured electrical output to actual electrical input, which can be written as:

$$\varepsilon_e = \frac{iV_{cell}}{(i + i_{\text{int}})E^o} \tag{11}$$

Where 'i'is the current density, 'i_{int}' is the cross over current which is assumed to be equivalent to internal currents; both are considered as currents defining the input power together with the theoretical reversible voltage of the fuel cell. From equations (6 - 11) and the definition of maximum thermal efficiency, the efficiency of the fuel cell becomes:

$$\varepsilon = \frac{0.87 \times iV_{cell}}{(i + i_{\text{int}})E^o} \tag{12}$$

Calculated Efficiency vs. Power Output for one MW fuel cell is plotted in Fig. 5 based on equation (12). The relationship with T is embedded in the expression for the standard cell voltage E_o.

It should be noted from the graph 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. IN the case of combustion engines, the efficiency increases as temperature increases, which clearly indicates the dependence of efficiency on temperature.

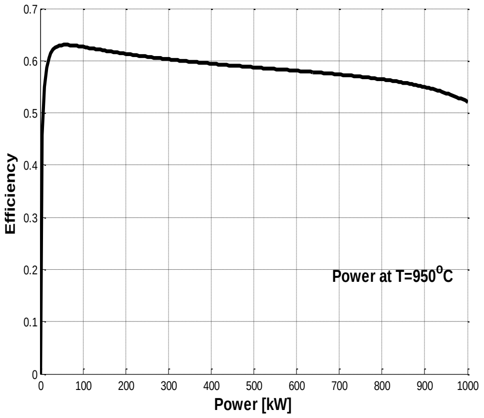

Figure 4. Fuel cell efficiency vs. power output

9. Efficiency vs. Fuel Type

The ratio of the mass of hydrogen and the total mass of a specific fuel depends on the chemical formula of the fuel (C_mH_n) where m and n are constants for a hydrogen fuel. Since hydrogen is very light compared with carbon, the ratio decreases as carbon atoms 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 which is plotted on the bases of equation (9) and the calorific values of the relevant fuels from standard tables of material properties.

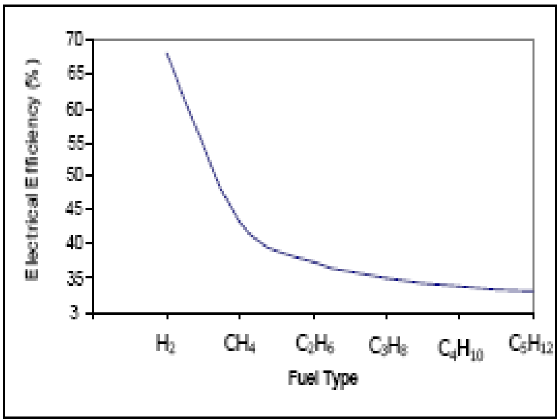

Figure 5. The effect of fuels on the efficiency of the fuel cell

10. Closed Cycle Gas Turbine

The gas turbine cycle is shown 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.

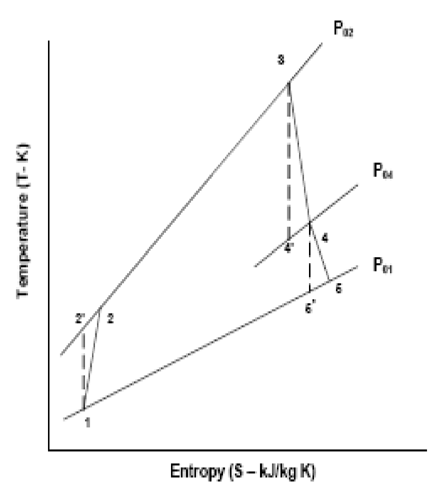

Figure 6. T-S Diagram of the gas turbine cycle

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:

$$\frac{P_{04}}{P_{05}}=\frac{P_{02}}{P_{01}}\left\{1-\frac{\left(\frac{P_{02}}{P_{01}}\right)^{\frac{\gamma-1}{\gamma}}-1}{\frac{T_{03}}{T_{01}}\eta_c\eta_t}\right\}^{\frac{\gamma}{\gamma-1}} \qquad (13)$$

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

$$\frac{w}{m}=\eta_{t2}c_pT_{04}\left\{1-\left(\frac{P_{04}}{P_{05}}\right)^{-\left(\frac{\gamma-1}{\gamma}\right)}\right\} \qquad (14)$$

From equations (13) and (14) an expression for specific work output can be written as:

$$Specific\ work=C_pT_{01}\left[\eta_t\frac{T_{03}}{T_{01}}\left(1-\left(\frac{P_{01}}{P_{02}}\right)^{\frac{\gamma-1}{\gamma}}\right)-\frac{1}{\eta_c}\left(\left(\frac{P_{02}}{P_{01}}\right)^{\frac{\gamma-1}{\gamma}}-1\right)\right] \qquad (15)$$

The thermal efficiency of the system can be defined in the substituting for the thermal efficiency from the following equation involving the air to fuel ratio (A/F) as follows:

$$\eta_{th}=\frac{(A/F)C_p\Delta T_{02-03}}{C.V.} \qquad (16)$$

This equation can be used to find a relationship between turbine inlet temperature and compressor inlet temperature in terms of air to fuel ratio as follows:

$$\frac{T_{03}}{T_{01}}=\frac{C.V.}{(A/F)C_pT_{01}}+\frac{1}{\eta_c}\left\{\left(\frac{P_{02}}{P_{01}}\right)^{\frac{\gamma-1}{\gamma}}-1\right\}+1 \qquad (17)$$

Substituting the temperature ratios in the equation for specific work output (15) a graph for Specific work output vs. compression ratio can be plotted. The result is given in **Fig. 8** which it shows 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.

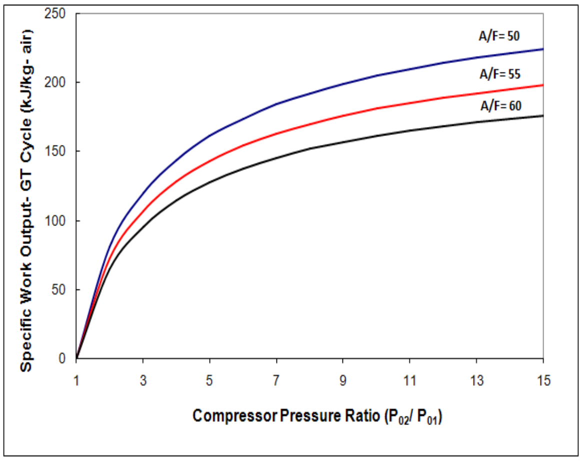

Figure 7. Specific Work Output vs. Cycle Pressure Ratio proposed

11. 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 (Kuchonthara, Bhattacharya et al. 2003). 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.

12. Flow of mass and heat in an internally reformed SOFC

So as to derive a relationship to relate the work output of the power turbine to the fuel input of the fuel cell, the fuel cell- reformer arrangement is considered. The following reactions take place in the reformer-fuel cell system; this is tackled in a general form below and is applicable to any hydrocarbon.

Steam reforming of fuel in the reformer is an endothermic reaction (energy consuming reaction):

$$C_mH_n+mH_2O\underset{Catalyst}{\overset{Heat}{\rightleftarrows}}mCO+(m+\frac{n}{2})H_2 \qquad (18)$$

The Gas shift reaction, this is an exothermic reaction (energy producing reaction):

$$mCO+mH_2O\longrightarrow mCO_2+mH_2 \qquad (19)$$

Fuel cell reaction:

$$(2m+\frac{n}{2})H_2+(m+\frac{n}{4})O_2\longrightarrow(2m+\frac{n}{2})H_2O \qquad (20)$$

It is noted that the amount of steam generated by the fuel cell is sufficient for the reformation of the hydrocarbon. It is assumed that the heat enquired for the steam reformer (SR) is provided by the preheating of the fuel and steam input to the reformer and through the heat generated in the water gas shift (WGS) reaction.

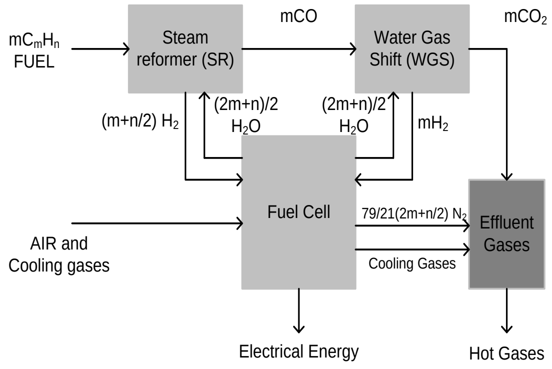

Figure 8. flow chart of the flow of gases in a self reforming fuel cell system

A flow chart of the flow of gases in an internally reforming fuel cell system. The molar weight of the fuel is: $M = 12m + n$ (g/mole), while the molar weight of Carbon dioxide is 28 g/mole. (Larmine and Dicks 2003)

The electrical current can be calculated on the bases of the number of electrons available which is (n) electrons. This is based on the assumption that all the hydrogen in the fuel has been extracted.

The proposed solid oxide fuel cell (SOFC) uses methane (CH4) (molar weight = 16 g/mole) as the fuel. The steam reforming reaction (SR) for this fuel is given below (Larmine and Dicks 2003):

$$CH_4 + H_2O \rightarrow CO + 3H_2 \tag{21}$$

Gas shift reaction (GS)

$$CO + H_2O \rightarrow CO_2 + H_2 \tag{22}$$

From this reaction; hydrogen is utilised in the fuel cell and carbon dioxide is emitted to the environment. Summation of equations (21) and (22) yields:

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2 \tag{23}$$

Hydrogen is utilised in the fuel cell to produce water and electricity as well as heat output:

$$4H_2 + 2O_2 \rightarrow 4H_2O \tag{24}$$

Which means that for each mole of methane, one mole of carbon dioxide is produced, in terms of mass: for each 16 g of methane an amount of 28 g of carbon dioxide is produced. The amount of carbon dioxide emissions is a direct factor of efficiency of the system.

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;

Table 1. Efficiency calculation for the plant

Calculated parameter	Value	Unit or Justification
Electrical output of the fuel cell	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	Ratio
Heat available to the gas turbine	450	kJ/s
Cycle pressure ratio	12:1	Ratio
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	71 %	(550 + 160)/1000

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.

Using the calculated value of the efficiency of the hybrid system, and a value of 35% for the IC engine, the information presented above in equation (23) is used to calculate CO$_2$ emissions for both systems.

Carbon dioxide emissions vs. power output are shown in Fig. 9 for the proposed hybrid power plant and for conventional 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.

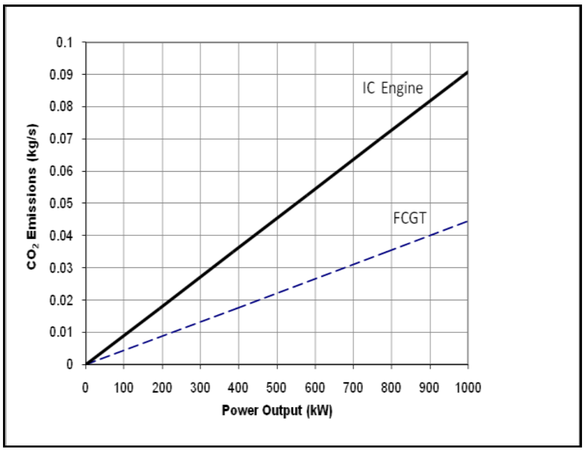

Figure 9. Emission of CO2 vs. power output (kg/kW. s)

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 CO2) 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.

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