Thermodynamic Analysis of Combined Rankine and Gas turbine Cycle Integrated with Fuel Cell.

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Abstract - *High efficiency power system can be constructed by the combination of Rankine cycle, Gas turbine cycle and solid oxide fuel cell (SOFC). A solid oxide fuel cell is a fuel cell that can operate at high temperature. By applying its high temperature exhaust heat to gas combined power cycle generation. A triple combined cycle can be developed.*

In this paper, a triple combined cycle is proposed as an attractive option to high efficiency and limits the environmental impact. It include study of heat recovery system for 110 MW SOFC fuelled by natural gas. Two type of SOFC are considered, tubular and planer SOFC$_S$, operated either natural gas or hydrogen fuel. A detailed thermodynamic analysis for the triple combined cycle. Mass and energy balance are performed for each individual component and whole plant in order to evaluate performance and thermal efficiency, With the help of Energy Equation Solver (EES). It is found that a high overall efficiency approaching 70% may be achieved with an optimum configuration using SOFC. The integrated system would also reduce emission, fuel consumption and improve total fuel efficiency.

Key Words: *Steam Turbine, Gas turbine; Hydrogen fuel; Solid oxide fuel cell; integrated system, thermodynamic Analysis.*

1. INTRODUCTION

From long term perspective, thers is no doubt, that continuous growth of the world population present great challenge to energy resources and development.therefore it is evedent , that there is an ever growing need for sustainble and envirinmentally-benign energy supply as well as efficient power production system and distribution.

Fuel cell have been identified as promosing technology of the power production for stationary and mobile application due to their high efficiency and small environmental footprint. The fuel cell is an electrochemical device, which convert the chemical energy of a fuel into electric power directly, i.e, without any intermediate conversion process. Its benefit are that the electric power can be generated at high efficiency and with very low environmental emission both at full load and partial load. For the last thirt five years, federal and industrial support to develop fuel cell technologyies has been considerable. The use of fuel cell has been strongly promoted in the united state and japan for the medium scale cogeneration plants. Nowdays, this intrest has been extened to integrate the fuel cell with combined cycle plant(steam and gas turbine cycle). The current research work of this thesis is focussed on the use of this new technology for stationary cogenaration appllication, in particular triple combined cycle(SOFC-GT-ST) for the power production

1.1 SOLID OXIDE FUEL CELL

The first breakthrough for the solid oxide fuel cell(SOFC) came in the late 1890s when Walther Herman Nernst discovered various type of conductivity in doped zicronium oxide (singhal and kendall, 2003).[8] He also discovered that the material emitted white light when hot, and this led to patented light bulb. The patent was later sold to George westinghouse who produced light bulb until tungsten filament based lamps took over (singhal and kendall, 2003).[8] The research has continued until today, and siemens westinghouse power corporation is today considered to be the world leader in SOFC technology. Siemens westinghouse is also first company to demonstrate a SOFC-GT power cycle and working on SOFC-GT-ST power cycle. The SOFC has to compete with exsting heat engines that are currently used to produce electricity from hydrocarbon combustion. Such engine operate by burning fuel to heat a volume of gas, folloewd, for example, by the expansion of the hot gas in a piston or gas turbine device driving a dynamo. Although for many application conventional heat engine are theory less efficient and more polluting than fuel cells, they posses a significantly lower initial cost as aresult of regrous development, optimization, and mass manufacturing for almost century. Ostwald got it famously wrong in 1892 when he said " the next century will be one of electrochemical combustion "(singhaland kendall,2003).[8] Fuel cells are are significantly costly than conventioanal engine which can be manufactured for less than $50 per kwe (singhal and kendall, 2003).[8]

In the 1980s, it was envisaged that SOFCs could compete commercially wit other power generation systems, including large centralised power stations and smaller cogeneration units. This has not yet happened because costs have remaine high despite large injection of government funding for the SOFC development in the USA, Japan and Europe (Fuel cell handbook, 2004).[1]

One of the most promising application of SOFCs for the fture combination with gas turbine and steam turbine. The SOFC stack forms the combustor unit in gas turbine system. Compressed air is fed to the SOFC stack where the fuel is injected and electrical power drawn off. Operating at 50 plus conversion of fuel to electrical power, this SOFC then provide pressrized hot gases to turbine operating at 35 – 40 percent electrical efficiency. The overall conversion efficiency of this system can approch 65 plus percent, which can be further improved by adding a steam turbine cycle to drive the overall electrical efficiency into the mid seventies.

1.2 500 KW SOFC Model

The solid oxide fuel cell (SOFC) is considered as one of the most promising options for high temperature application applications SOFC can use Hydrogen gas directly as a fuel. For the near future, fuel cells can replace the diesel generator. The 110 *MW* SOFCPP model parameters and 85% fuel utilization coefficient. It consists of 220 internally reformed planar and tubular models of 500 *kW* connected in series and extrapolated for 110 *MW* SOFC. The 110 *MW* SOFCPP model main parameters are listed in Table1.(santin,et al.2010)[7]

Table 1 500KW SOFC model parameters.

Parameter	Value
Plant net power	110MW
SOFC inlet temperature	850 °*C*
SOFC outlet temperature	1000 °*C*
SOFC fuel utilization coefficient	85%
Component pressure loss	1-3%
Component heat loss	1-2%
Ambient pressure	1 *atm*
Ambient temperature	25 °*C*

2. SOFC-GT-ST HYBRID SYSTEM DESCRIPTION

In SOFC-GT combined cycle, the air flow to the SOFC is compressed with a gas turbine compressor. The flow then passes through an internal heat exchanger air and the fuel streams then pass into the cathode and anode compartments of the fuel cell. The air and fuel streams leaving the cell enter the combustor where they mix and the residual unused fuel burns. The combustion products enter the gas turbines, expand, and generate additional power. The low pressure turbine exhaust gases pass through gas to steam heat exchanger to generate steam to run the steam turbine. Gas turbine used as topping cycle and steam turbine used as bottoming cycle

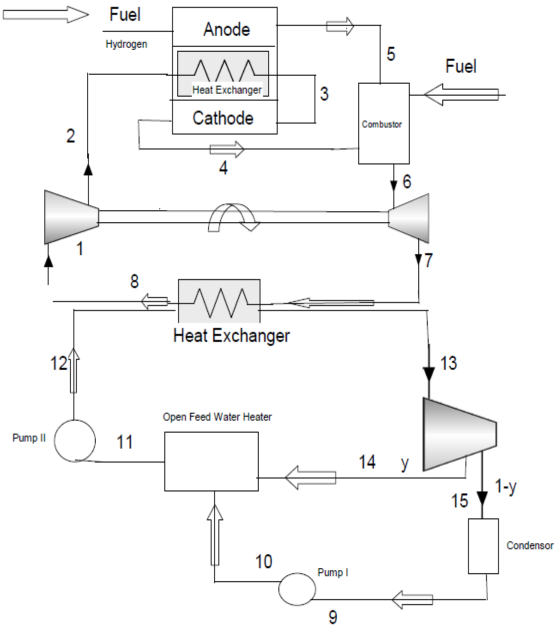

Figure 1 SOFC –GT-ST Integrated cycle

Steam turbine cycle composed of heat exchanger, the steam turbine, the pumps, the condenser, and the closed feedwater heater. The steam turbine is supplied with superheated steam, which is then expanded, producing mechanical power, which is converted to electric power by the electric generator (as with the gas turbine). After expansion, the steam is condensed and the water compressed, preheated, and deaerated in a vacuum deaerator before being fed to the HRSG by a feedwater pump. The main components of the steam turbine cycle model are:

- A steam turbine and an electric generator;
- A heat recovery steam generator (HRSG) which includes the following heat exchangers: economizer, evaporator, and superheater.
- A condenser which is dimensioned according to the turbine exit pressure and mass flow rate as well as ambient conditions;
- Two pump;
- one closed feedwater pumps

This study assumes 85% utilization coefficient of fuel in the cells. Table 2 summarizes the data of different auxiliary system components utilized in the combined SOFC-GT plant.

Component	Parameter	Value
Compressor efficiency (η_{com})	Isentropic efficiency (η_c)	86%
Gas turbine	Isentropic efficiency (η_{GT})	89%
Internal heat exchanger	Effectiveness ($\varepsilon_{HE.}$)	80%
Combustor	Combustion efficiency (η_{comb})	98%
AC generator	Electric efficiency (η_{gen})	95%
DC/AC Converter	Conversion efficiency	95%
Heatexchanger	Pressure loss	3%
SOFC stack	Pressure loss	3%
combustor	Pressure loss	2%

Table 2 Auxiliary system component data for SOFC-GT-ST plant.

2.1 INPUT PARAMETERS

Parameter	Value
Air compressor inlet temperature	T_1= 27°C
Air compressor inlet pressure	P_1= 100 kPa
Pressure ratio of compressor	r_P= 11
SOFC inlet temperature	T_3= 850°C
SOFC exit temperature	T_4= 1000°C
Mass flow rate of air	m= 98.18 kg/s
Mass flow rate of hydrogen fuel	1.1555 kg/s
Isentropic efficiency of air compressor	η_C= 0.86
Inlet Temperature of gas turbine	T_3= 1277°C
Condenser pressure	P_{15}= 100 kPa
Extraction pressure of open feedwater heater	P_{14}= 800 kPa
Calorific value for hydrogen fuel	40MJ/kg
Calorific value for hydrocarbon fuel	120MJ/kg
Isentropic efficiency of Gas turbine	η_{GT}= 0.86
Inlet temperature of steam turbine	T_{13}= 350°C
Steam turbine inlet pressure	P_{13} =5000 kPa
Isentropic efficiency of steam turbine	η_{st}= 0.86
Fuel utilization factor	$_f$ = 0.85

The input parameters taken for computation of results are given below:

Table 3 input parameter for SOFC-GT-ST integrated cycle

3 THERMODYNAMIC ANALYSIS

The thermodynamic performance of each of the components introduced in the preceding section will be analyzed here. The mass and energy balance are employed under the assumption of steady flow for the entire cycle. The main stream of the working fluid, assumed as ideal gas, at different states of the cycle is shown in Fig. 1The required power for the compressor, gas turbine, and steam turbine & pump can be defined as:

3.1SOFC OPERATIONAL VOLTAGE

Solid oxide fuel cell voltage (V_{cell}) is the difference between cell voltage at no load, which can be called open circuit voltage and the specific fuel cell irreversibility or voltage drop. The following Eq. (1) shows the operating voltage of a fuel cell at a current density (i_{den}) (Larminie and Dicks, 2003; Maroju, 2002).[4,5]

$$V_{cell} = E_O - (i_{den} \times r) - A \times \ln(i_{den}) + m \times e^{n \times i_{den}} \qquad (1)$$

Where,

E_O is the open circuit voltage = 1.01V

A is the slope of Tafel curve = 0.002V

r is the specific resistance =2.0 × 10^{-3} $k\Omega cm^2$

m and n are constants =1.0 × 10^{-4} V and 8 × 10^{-3} cm^2 mA^{-1} respectively

3.2 AIR COMPRESSOR

$$W_c = \left[mc_p(T_2 - T_1)\right]_c \qquad (2)$$

Where W_c is the work of compressor.

$$\eta_c = \frac{h_{2s} - h_1}{h_2 - h_1} \qquad (3)$$

Where η_c is the efficiency of the compressor

$$(\eta_s)_c = \left[\frac{T_1}{T_2 - T_1}\left[\left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]\right]_c \qquad (4)$$

Where $(\eta_s)_c$ is the isentropic efficiency of the compressor.

3.3 INTERNAL HEAT EXCHANGER

$$q_{in} = (h_3 - h_2) \qquad (5)$$

3.4 GAS TURBINE

$$\eta_{GT} = \frac{h_6 - h_7}{h_7 - h_{7s}} \qquad (6)$$

Where η_{GT} is the efficieny of gas turbine.

$$W_{GT} = \left[mc_p(T_6 - T_7)\right]_{GT} \qquad (7)$$

Where W_{GT} is thework done by gas turbine.

$$(\eta_s)_{GT} = \frac{T_6 - T_7}{T_6\left[1 - \left(\frac{p_7}{p_6}\right)^{\frac{\gamma-1}{\gamma}}\right]_{GT}} \qquad (8)$$

Where $(\eta_s)_{GT}$ is the isentropic efficiency of gas turbine.Where the ideal temperatures of the working fluids at the outlet can be determined by the following equation

$$\frac{T_{2s}}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma_{air}-1}{\gamma_{air}}} \qquad (9)$$

$$\frac{T_{7s}}{T_6} = \left(\frac{p_7}{p_6}\right)^{\frac{\gamma_{air}-1}{\gamma_{air}}} \qquad (10)$$

3.5 SOFC

The fuel supplied to the system is hydrogen (H_2), with a lower heating value of 120 MJ/kg. The following electrochemical reactions expressed in Eqs. (11) to (15)

Reforming: $CH_4 + H_2O \rightarrow CO + 3H_2$ (11)

Shift gas reaction: $CO + H_2O \rightarrow CO_2 + H_2$ (12)

Electrochemical: $H_2 + 0.5O_2 \rightarrow H_2O$ (13)

occur within the anode and cathode of the fuel cell. As a 50 MJ/kg, is used for fueling the SOFC stack and combustor. Various reactions corresponding to the methane are listed below:The degree to which an anode supports comparing case, methane (CH_4), with a lower heating value of direct oxidation will then impact the degree of pre-reforming of the fuel that is required, which in turn typically impacts the balance of plant complexity and cost

(Subhash and Kevin, 2004; EG&G Technical Services, 2004). The net cell reaction is thus written as:

$$CH_{4,anode}+2O_{2,cathode}\rightarrow 2H_2O+CO_2 \qquad (14)$$

And the net cell reaction for hydrogen as a fuel is as follows:

$$H_{2,anode}+0.5O_{2,cathode}\rightarrow H_2O \qquad (15)$$

The maximum electrical work obtainable in a fuel cell operating at constant temperature and pressure is given by the change in Gibbs free energy (Δg_f) of the electrochemical reaction. If all the energy from the fuel was transformed into electrical energy, then the reversible open circuit voltage, E_0 , would be given by (Larminie and Dicks, 2003; Raja, et al., 2006):

$$E_0 = -\frac{\Delta g_f}{z\times F} \qquad (16)$$

So, the efficiency of fuel cell can be expressed as

$$\eta_{FC} = U_f\frac{V_{cell}}{E_0} \qquad (17)$$

where, U_f is the fuel utilization coefficient. Efficiency limit for heat engines such as steam and gas turbines can be calculated using Carnot efficiency limit which shows their maximum efficiency, but fuel cells are not subject to the Carnot efficiency limit. It is commonly supposed that if there are no 'irreversibility's', the efficiency could reach 100%.

The mass balance for SOFC system gives:

$$m_3 + m_{hyd} = m_4 + m_5 \qquad (18)$$

Where,

$$m_5 = m_{hyd}\times(1-U_f) \qquad (19)$$

The last term on the right hand side of the above equality represents the non-reacted mass flow rate that leaves the fuel cell downstream of the products. Applying the first law of thermodynam-ics to the SOFC and assuming an adiabatic process,

$$m_3\times h_3 + (m_{hyd}\times U_f\times CV) + (m_{hyd}\times(1-U_f)\times h_{fuel}) = P_{FC,DC} + (m_4\times h_4) \qquad (20)$$

3.6 INVERTER AND ELECTRIC GENERATOR

The electric power produced by the SOFC is dc current. The electric signal exerted by the SOFC is extremely unstable, since the current endures notable oscillations and in addition varies with operating conditions. Therefore, the electric signal needs to be conditioned before usage converted to ac current, and filtered from possible oscillations. This is done by a dc-ac inverter. The main parameter of interest is the inverter's efficiency

Similarly, the mechanical energy produced by the gas turbine must be converted to electric power. This conversion is accomplished by an electric generator. Again, the main parameter of interest is the efficiency, or in other words, the relationship between the mechanical power output to the ac electric power output. The efficiency for both components is defined as:

$$\eta_{inv} = \frac{W_{AC}}{W_{DC}} \qquad (21)$$

Where η_{inv} is the inverter efficiency, W_{AC} is the AC power, W_{DC} is the DC power.

$$\eta_{gen} = \frac{W_{mech}}{W_{elec}} \qquad (22)$$

Where η_{gen} is the generator efficiency, W_{mec} is the mechanical power, and W_{el} is the electrical power.

3.7 COMBUSTOR

The working fluid of the cycle, with products from the fuel cell, is further heated within the combustor. Considering that non-reacted flow of fuel from the SOFC is burnt in the combustor in addition to the small amount of fuel added (m_{fb}) and applying the mass balance for combustor gives:

$$m_5 + m_{fb} + m_4 = m_6 \qquad (23)$$

Applying the first law of thermodynamics for the combustor we get:

$$(m_5 + m_{fb})\times(CV\times\eta_{comb}) + (m_4\times h_4) = m_6\times h_6 \qquad (24)$$

where, $\eta_{comb.}$ represents the efficiency of the combustor.

3.8 STEAM TURBINE

$$W_{st} = \dot{m}_{st}(h_{13} - h_{15s}) \tag{25}$$

We have steam turbine efficiency as,

$$\eta_{st} = \frac{h_{13}-h_{15}}{h_{13}-h_{15s}} \tag{26}$$

$$W_{net,steam} = m_{steam}(W_{steam,turb} - W_{steam,pump}) \tag{27}$$

3.9 PUMP

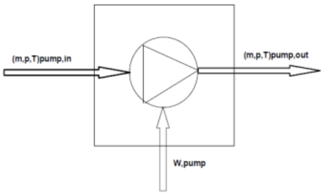

Figure 2 Schematic of pump

$$m_{in} = m_{out} \tag{28}$$

$$w_{pump1} = m_{in}(h_{10} - h_9) \tag{29}$$

$$w_{pump2} = m_{in}(h_{12} - h_{11}) \tag{30}$$

3.10 OPEN FEED WATER HEATER

$$y(h_{14} - h_{10}) = (h_{11} - h_{10}) \tag{31}$$

3.11 CONDENSER

$$q_{out} = (1 - y)(h_{15} - h_9) \tag{32}$$

3.12 GAS TO STEAM HEAT EXCHANGER

$$m_{steam}(h_{12} - h_{13}) = m_7(h_8 - h_7) \tag{33}$$

3.13 OVERALL BALANCE EQUATIONS OF INTEGRATED CYCLE

The integrated gas turbine power plant with SOFC in Fig. 1 may be analyzed as a lumped control volume. In the following, mass balance as well as the first and second laws of thermodynamics can be derived from the above mentioned control volume.

The mass balance for the total system can be written as:

$$m_1 + m_{fuel} = m_7 \tag{34}$$

$$m_1 = m_2 = m_3 \tag{35}$$

$$m_6 = m_7 = m_8 \tag{36}$$

$$m_{fuel} = m_{hyd} + m_{fb} \tag{37}$$

Overall energy balance can be expressed as

$$(m_1 \times h_1) + (m_{hyd} \times U_f \times CV) + (m_5 + m_{fb}) \times (CV \times \eta_{comb}) = (m_7 \times h_7) + P_{FC,DC} + P_{GT} \tag{38}$$

Where

$$P_{GT} = m_7 \times (h_7 - h_8) \tag{39}$$

Combined cycle efficiency can be expressed as:

$$\eta_{combined} = \frac{P_{FC,AC}+P_{GT}}{m_{fuel}\times CV} \tag{40}$$

$$\eta_{integrated} = \frac{P_{FC,AC}+P_{GT}+P_{ST}}{m_{fuel}\times CV} \tag{41}$$

The gas turbine cycle efficiency can be expressed as

$$\eta_{GT} = \frac{P_{GT}}{m_{fuel}\times CV} \tag{42}$$

$$\eta_{ST} = \frac{P_{ST}}{m_{fuel}\times CV} \tag{43}$$

The required mass flow rates of hydrogen and air in *kg/s* are expressed in Eqs. (44) and (45) respectively, and the value of utilization coefficient U_f in Eq. (46) refers to the ratio of hydrogen reacted in the fuel cell (Holland and Zhu, 2007; Kumm, 1990).[2,3]The required hydrogen mass flow rate can be expressed as:

$$m_{hyd} = \frac{1.05\times P_{FC,AC}}{10^5\times V_{cell}} \tag{44}$$

The required air mass flow rate can be written as:

$$m_{air} = \frac{3.57\times\lambda_{air}\times P_{FC,AC}}{10^4\times V_{cell}} \tag{45}$$

In addition, the hydrogen mass flow rate reacted in fuel cell can be written as:

$$m_{hyd,cons} = m_{hyd} \times U_f \tag{46}$$

The hydrogen formula in Eq. (44) applies only to a hydrogen-fed fuel cell. In the case of a hydrogen/carbon monoxide mixture derived from a reformed hydrocarbon, it will be different. Eq. (47) shows the relationship between the efficiency of the fuel cell, the calorific value (CV) in kJ/kg of fuel and the resulting fuel rate in kg/s (Sjöstedt and chen,2005),[9]

$$Fuel\ flow\ rate = \frac{P_{FC,AC}}{\eta_{FC} \times CV} \tag{47}$$

$$P_{heat} = P_{FC,AC} \times \left(\frac{1.25}{V_{cell}} - 1\right) \tag{48}$$

4 RESULT AND DISCUSSION

The performance of a solid oxide fuel cell stack is usually described by the polarization curve, which relates the cell voltage to its current density. This polarization curve is affected by the losses of the fuel cell.

Fig.3 shows the polarization curve of the SOFC case study. As the cell current increases from zero, there will be a drop of the output voltage of the SOFC. This drop of the cell voltage is due to activation voltage loss. Then, almost a linear decrease of the cell voltage is seen as the cell current increases beyond certain values, as shown in Fig. 3, which is a result of the ohmic loss. Finally, the cell voltage drops sharply to zero as the load current approaches the maximum current density that can be generated by the fuel cell. The sharp voltage drop is the effect of the concentration loss in the fuel cell.

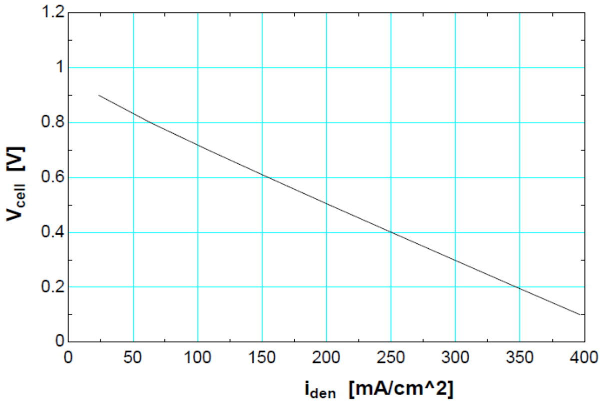

Fig.3 Current density at different SOFC voltage.

Prediction of the maximum available voltage from cell process involves evaluation of energy differences between the initial states of reactants in the fuel cell process. Open circuit voltage of SOFC plays an important role in the cell performance. The effect of changing open circuit voltage on SOFC operational voltage and efficiency. As the open circuit voltage increases, the SOFC operational voltage will be increased which improves the cell efficiency.

The value of fuel mass flow depends on fuel utilization coefficient and cell voltage for the SOFC. Figs. 4 and show the effect of fuel consumption of hydrogen for different SOFC power plants. The higher voltage of the SOFC will correspond to higher SOFC efficiency. So, hydrogen and natural gas mass flow rates decrease as the SOFC voltage increases.

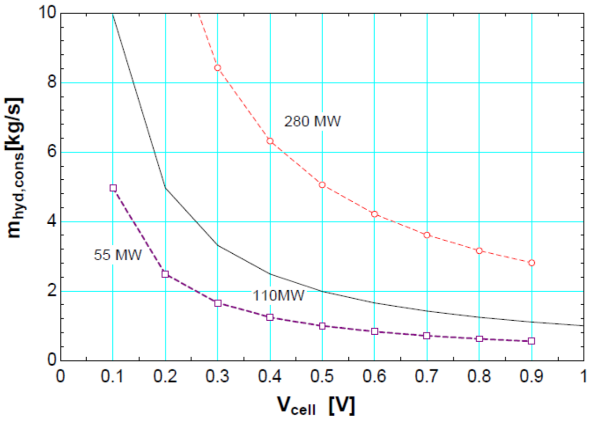

Fig. 4 Hydrogen fuel consumption for SOFC a different electric powers.

An essential aspect of SOFC design and application is the heat produced by the electrochemical reaction. Heat is inevitably generated in the SOFC by ohmic losses, electrode over potentials, etc. These losses are present in all designs and cannot be eliminated but must be integrated into a heat management system. Indeed, the heat is necessary to maintain the operating temperature of the cells. The benefit of the SOFC over competing fuel cells is the higher temperature of the exhaust heat which makes its control and utilization simple and economic. SOFC heating power in kW can be calculated from Eq. (48) (Larminie and Dicks, 2003):

4.1 SOFC-GT-ST power plant results

One of the great benefits of the SOFC is its capability to utilize a wide range of fuels. The fastest reaction at the nickel anode is that of hydrogen. But other fuels can also react directly on the anode, depending on catalyst composition. In this study two types of fuel are included, hydrogen and natural gas. Four layouts have been studied. They include tubular SOFC (TSOFC), and planar SOFC (PSOFC) using natural gas internal reforming and pure hydrogen fuels.

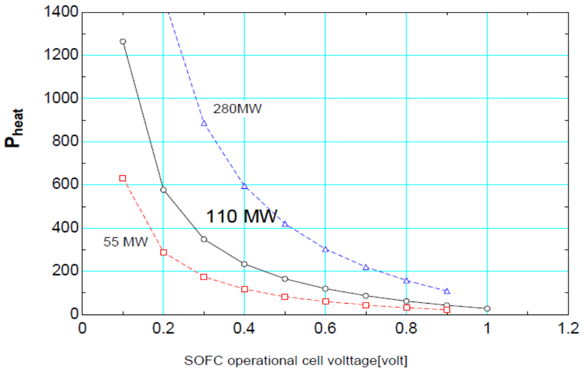

Fig 5 Heat losses from SOFC at different electric powers

The selected operating point for the combined SOFC-GT-ST cycle is at cell output current density of 250 mA/cm^2, cell voltage of 0.4997 *volts*, and fuel utilization coefficient of 85%. At this operating point the mass flow of fuel consumption is 1.1555 *kg/s* and 1.323 *kg/s* for hydrogen and natural gas respectively. The combustor fuel flow rate is assumed to be 0.01 *kg/s* for both hydrogen and natural gas fuels. The inlet fuel temperature is assumed to be 50 ^oC. In addition, the mass flow rate of the air used for SOFC-GT cycle depends on the type of fuel used. Air consumption for hydrogen fuel is 98.18 *kg/s* calculated using Eq. (44), which is nearly half the assumed value if natural gas fuel is used. Also, the value of the inlet and outlet temperatures of SOFC depends on the type of SOFC modules. For TSOFC the temperatures are 1073 *k* and 1273 *k* for the inlet and outlet flows respectively. PSOFC has a higher inlet temperature of 1123 *k* and a lower outlet temperature of 1223 *k* compared with TSOFC modules. These values will affect T_3 and T_4

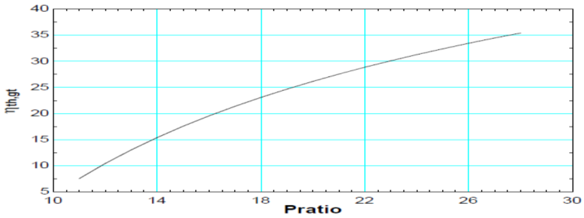

Figure 6 Gas Turbine efficiency at different compression ratio

Fig 6 Shows the effect of compression ratio of gas turbine on gas cycle efficiency. The cases include planar and tubular SOFCs operated with natural gas incorporating internal reforming at the anode or hydrogen. Hydrogen operated SOFC has the maximum efficiency. Also, tubular SOFC has a higher efficiency than planar SOFC.

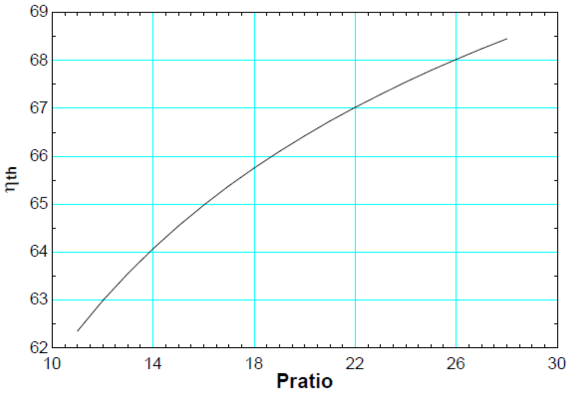

Figure 7 Integrated cycle efficiency at different compression ratio

The combined cycle efficiency is affected by the type of fuel used. Hydrogen fuel has the highest hybrid efficiency over different compression ratios.

The mass flow rate of air used plays an important role in determining the efficiency of the SOFC-GT hybrid cycle. In addition, gas cycle efficiency decreases as inlet flow rate increases, A gas cycle associated with TSOFC has higher efficiency at different inlet air flow rates than PSOFC gas cycle. Therefore, the TSOFC hybrid system with internal reforming achieves higher efficiency than PSOFC hybrid system Fuel utilization coefficient not only affects SOFC performance, but also affects SOFC-GT hybrid system efficiency. At higher fuel utilization coefficients, the hybrid efficiency will be reduced for both TSOFC and PSOFC.

SOFC voltage determines the main characteristics of the cell. It also affects both the total integrated system power and output power from the gas turbine and required power for the compressor. Fig 7 shows the variation of integrated cycle efficiency at different compression ratio.

In addition, the variation of SOFC voltage affects the total integrated cycle efficiency as the efficiency of SOFC will be changed. On the other hand, the SOFC voltage variations have nearly no effect on the gas cycle efficiency.

The variation of the output current density of SOFC changes the performance of both systems SOFC and the SOFC-GT-ST. As the current density increases, integrated cycle efficiency increases. On the other hand, current density has nearly no effect on gas turbine efficiency like cell voltage variation. It only affects SOFC efficiency. At high current density, SOFC voltage reduces highly and this reduction in voltage is converted into heat energy.

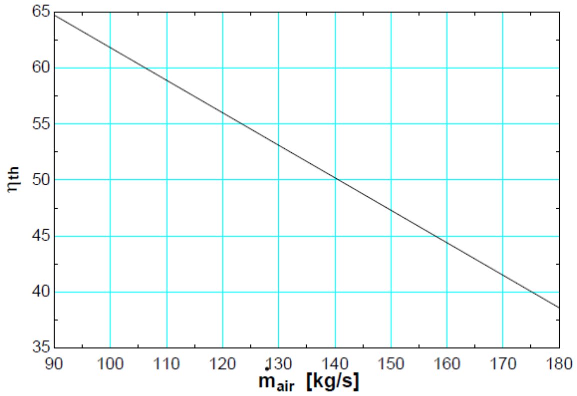

Figure 8 Integrated cycle efficiency at different mass flow rate of air

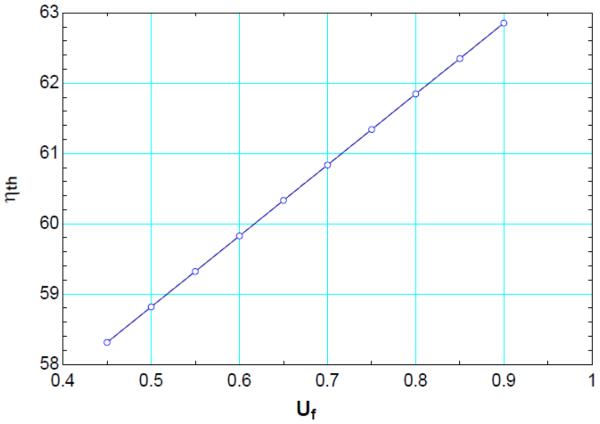

Figure 9 integrated cycle efficiency at different SOFC fuel utilization coefficient

3. CONCLUSIONS

The thermodynamic analysis of natural gas and hydrogen-fuelled SOFC was presented as a proposed solution to achieve high efficiency and satisfy the requirements of international regulations. Both TSOFC and PSOFC are integrated with gas turbine cycle to make use of the waste heat of the SOFC. Layout shown in figure 1 were studied, combining SOFC modules with gas turbine operated either by natural gas, through internal reforming, or hydrogen. Thermodynamic principles are used to under-stand the process of energy conversion in SOFCs. The reversible work of a fuel cell is defined by the free or Gibbs enthalpy of the reaction. The mass flow of the consumed fuel is proportional to the electric current and the reversible work is proportional to the reversible voltage.

The parameters, which affect fuel cell performance, include the cell voltage, open cell voltage, fuel cell efficiency, and fuel utilization coefficient. The actual SOFC cell voltage can be taken as 0.801 *volt* at $100 mA/cm^2$ output current density with cell efficiency of 43.62%, and the open cell voltage is 1.01 *volt*. These values affect the hybrid efficiency and the performance of the SOFC. The proposed model of 110 *MW* SOFC power plant shows that the power lost in heating for the fuel cell power plant is 20.089 *MW* which is 24.4 % of the total input for SOFC at 100 mA/cm^2 output current density.

The combination of a SOFC with GT and ST has a high electric efficiency. The main parameters which affect SOFC-GT-ST power plant are gas cycle compression ratio, inlet air mass flow rate, SOFC fuel utilization coefficient, cell voltage, and cell output cur-rent density. The SOFC-GT-ST system is very suitable for high-efficiency power generation. At the operating point of $250 mA/cm^2$ the total integrated cycle efficiency is 63%. So, the integrated SOFC-GT-ST exceeds the GT plant by 27.2% with respect to thermal efficiency, and in addition, produces fewer emissions. Finally, TSOFC has a higher output temperature of exhaust gases and total thermal efficiency than PSOFCs.

The thesis only presents the thermodynamic analysis of the integrated gas turbine and steam turbine with SOFC power plant system. It should be complemented by additional technical and economic analysis to fully justify the use of such integrated systems in power plant.

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