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

Major Project Report –II

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UNDER THE SUPERVISION OF	**SUBMITTED BY-**
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CANDIDATE'S DECLARATION

I declare that the work presented in this thesis titled "***Thermodynamic Analysis of Combined Rankine and gas turbine Cycle Integrated with fuel cell***", submitted to Department of Mechanical Engineering, is an authentic record of my own work carried out under the supervision of Prof. Dr. R. S. MISHRA, Department of Mechanical Engineering, Delhi technological university, Delhi.

This report does not, to the best of my knowledge, contain part of my work which has been submitted for the award of any other degree either of this university or any other university without proper citation.

Date:

Place: DTU, Delhi Signature of candidate

CERTIFICATE

This is to certify that above statement made by ABHISHEK KUMAR is true and best of my knowledge and belief.

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First of all, I would like to express my gratitude to God & parents for giving me ideas, support and strengths to make my dreams true and accomplish this thesis.

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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 of 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.*

KEWWORDS: Gas turbine; Rankine cycle; Solid oxide fuel cell, integrated system; Thermodynamic analysis.

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Nomneclature

CH_4	Methane	NO_X	Nitrogen oxide emission
CO_2	Carbon dioxide	U_f	Fuel utilization coefficient
CO	Carbon monoxide	O_2	Oxygen gas
E_o	Open circuit voltage, *volt*	h	Enthalpy, *kJ/kg*
F	Faraday constant coulomb/mole	H_2O	Water vapour
GT	Gas turbine	p	Pressure,*bar*
H_2	Hydrogen	T	Temperature,*K*
$h_{fuel,in}$	Inlet fuel enthalpy, *kJ/kg*	NG	Natural gas
m_{air}	Required Air mass flow rate,*kg/s*	SOFC	Solid oxide fuel cell
m_{hyd}	Required hydrogen mass flow rate,*kg/s*	$\dot{m}$	Mass flow rate,*kg/s*
$\dot{m}_{fuel}$	Total input fuel flow rate,*kg/s*	TSOFC	Tubular SOFC
$\dot{m}_{fb}$	Combustor added fuel flow rate,*kg/s*	PSOFC	Planer SOFC
i_{den}	Current density, ma/cm^2		
$m_{hyd.cons.}$	Hydrogen mass flow rate reacted in fuel cell, *kg/s*		
$\dot{m}_{fa}$	Required fuel flow rate for solid oxide fuel cell stack,*kg/s*		
$P_{FC,AC}$	AC power output of the cell stack,*kW*		
Z	Number of elctron transferred for each molecule of the fuel		
$P_{FC,DC}$	DC power output of the cell stack, *kW*		
P_{GT}	Gas cycle net output power, *Kw*		
P_{heat}	Heating loss power, *kW*		
V_{cell}	Fuel cell voltage,*volts*		
SOFC-GT-ST	Solid oxide fuel cell and gas turbine with steam turbine Triple combined cycle		

Greek letters

Δg_f	Change in gibbs free energy of an electrochemical reaction, *kJ/mole*		
η	Efficiency	γ_{air}	Air specific heat ratio
η_{comb}	Combustor efficieny	η_{FC}	Fuel cell efficiency
η_{gen}	Generator efficiency	η_{GT}	Gas turbine cycle efficieny
η_{isen}	Isentropic efficiency	λ_{air}	Stoichiometric ratio of air
Δh_f	Change in enthalpy of an electrochemical reaction, kJ/kgmole		

CHAPTER 1

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 History of fuel cell

William Robert Grove, a British jurist with a hobby in science in, 1839 in Swansea, Wales, first discovered the principle of the fuel cell. Grove utilize four lage cell, each coating hydrogen and oxygen, to produce electric power which was then used to split the water in the smaller upper cell into hydrogen and oxygen. Fifty year later, Ludwig mond and charles langer, who first use the term “Fuel cell” in 1889, tried to build a power generating device using air and industrial coal gas. However it was not untill 1932 that Francic bacon developed the first successful fuel cell. It would take another 27 year to apply their invention to a practical application, a 5kwe sytem capable of poering welding machine. More recently, NASA used fuel cell during 1960 to power onboard electronics for the Gemni and Appolo spacecrafts. In fact, NASA still uses fuel cell to provide electricity and water for its space shuttle missions.

It is expected that fuel cell will break through the economic and technical barrier in wide range of application including among others: stationary power generation, portable devices, and hybrid vhicular applications. For energy providers, fuel cell offer a safe, efficient, and relible power solution that address critical issues such as deregulation, rising energy costs, increasing load factors, serve power outages, and increasing power consumption. For vehicle manufacturers, fuel cell represent the single gratest technology advancement in the last 100 year to replace the internal combustion engine and address growing environmental concern over issues such as global warming and air pollution.

1.2 Components of Fuel Cells

The main components of fuel cells are anode, cathode, electrolyte and interconnects. Interconnects are also called Current Collectors. Regardless of the type of fuel cell, two separate reactions occur in different sides of the fuel cell called Anode and Cathode. Each of the reactions is called half-cell reactions. They are even called an oxidation half reaction and a reduction half reaction respectively. These two reactions are normally slow when carried out at low temperature, which in return demands higher activation energy for the reactions to take place. This can be accomplished with a catalyst, which never participates in the reactions, but lowers the activation energy. In other words Catalysts facilitate reactions to proceed more quickly than before.

1.2.1 Anode

Anode is a negative electrode where the fuel is oxidized and splits into positively and negatively charged ions. The anode must meet certain requirements, so that efficient reactions can take place. These requirements are high electric and ionic conductivity, resistance to thermal cycling, chemical stability in contact with the two electrodes, optimized porous structure for the mass transport of the gas species, thermal expansion compatibility with other fuel cell components and high catalytic activity. Moreover the choice of low cost material and manufacturing process are required for realizing a low cost fuel cell. Anode must be stable in the reducing environment.

1.2.2 Cathode

Cathode is the positive electrode in a fuel cell where the reduction occurs. Cathode is a porous layer that facilitates the transport of oxygen to the reaction zone, conduct electrons and heat from the reaction zone. The doped Lanthanum strontium manganite is the commonly used cathode material**.** The variable x is a doping level that varies between 0 and 1. Electrons are released during oxidation process at the cathode. Cathodes must meet the same requirements as it is explained for the anode requirement except that they must be stable in an oxidizing environment. This is because reduction takes place only at the cathode where the reactant meets the supplied.

1.2.3 Electrolytes

Electrolytes are substances that separate different reactants, preventing electric conduction but allow ions to pass through them, causing a voltage difference between the anode and cathode when an electric current passes through an external load. Electrolytes can be liquid or solid with variable working temperature. The use of solid electrolyte in ceramic fuel cells eliminates the material corrosion and electrolyte management problem. The general requirements for an electrolyte are high ionic conductivity, low electric conductivity, stability in both oxidizing and reducing environments, good mechanical properties and long-term stability with respect to doping segregation. Additional requirements for electrolyte to meet are low cost, resistance to thermal cycling and chemical stability when they come in contact with the other two electrodes.

1.2.4 Interconnects

The interconnection requires two interconnects which are often combined into a single material that makes contact with the anode on one side and the cathode on the other side. The choice of interconnection materials must meet some requirements. It must have high electronic conductivity, mechanical and chemical stability on either side of the electrodes, thermal expansion compatibility with other components of the cell. Either inexpensive perovskite structured oxide (ABO_3) layers or lanthanum chromite material can be used as an interconnector.

1.3 Classification of Fuel Cells

Fuel cells are classified in a variety of different ways, depending on the criteria used. Among these criteria, the area of application, operating temperature and pressure, direct or indirect use of primary fuels and oxidants, the nature of electrolyte fuel cells use, type of ion transferred through the electrolyte, type of reactants are very important ones to be mentioned. Based on the application, fuel cells are categorized a portable, stationary power and transportation fuel cells. Different application areas will be explained later. Depending on the operating temperature, fuel cells can be classified into five main groups. Fuel cells operating at a temperature below 200^0C are classified as low temperature fuel cells where as those operating above 600^0C are high temperature fuel cells. Fuel cells can also be categorized depending on electrolytes they use, which can either be liquid or solid. As mentioned below the first three are low temperature fuel cells with liquid electrolytes. The last two are high temperature fuel cells which use solid electrolytes. These five main categories of fuel cells with an overview can be listed below followed by figure 1 as follows:

- Proton Exchange Membrane Fuel Cell PEMFC)
- Alkaline Fuel Cell (AFC) -
- Phosphoric Acid Fuel Cell (PAFC)
- Molten Carbonate Fuel Cell (MCFC)
- Solid Oxide Fuel Cell (SOFC)

Since modern technology made it possible to lower the operating temperature of SOFC to around 300^0C - 600 ^{0}C, classification of fuel cells by the operating temperature has become more blurred. However, the present SOFC research focuses to lower the operating temperature to improve start-up time, cost and durability, while for PEMFC; the research is to increase the operating temperature up to more than 120^0C to improve waste heat management and water rejection. Low temperature fuel cells utilize hydrogen as a fuel, while high temperature fuel cells like SOFC are fuel flexible. It is even possible for high temperature fuel cells to use hydrogen rich fuels like methane. Hydrogen can be extracted through a reformation process either internally or externally.

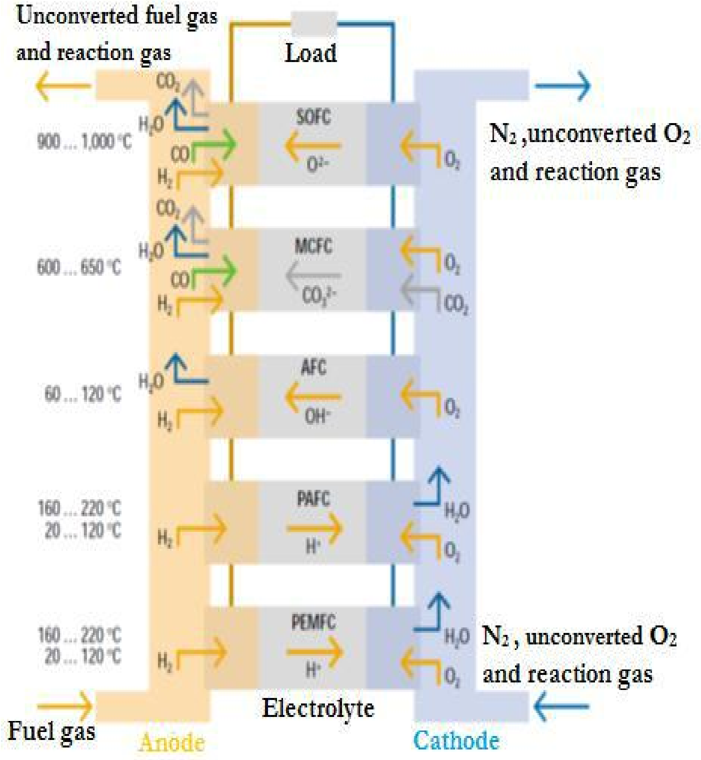

Figure 1 Overview of the chemical reaction in Fuel cell types **(Bewag, 2001)**

1.3.1 Proton Exchange Membrane Fuel Cells (PEMFC)

PEMFC are known even as ion exchange membrane fuel cells (IEMFC). In PEMFC platinum based catalyst is used at the anode to split hydrogen in to proton and electron. A proton conducting membrane cast in solid polymer form is used as an electrolyte. The ions pass through the membrane to the cathode to combine with oxygen and produce water and heat. It operates with pure hydrogen. PEMFC are considered to have a highest power density compared to other types of fuel cells. This is due to the quickest start up time of reactions. PEMFCs are also called solid polymer fuel cells. The operating temperature of the PEMFC is in the range of 20^0C to 120^0C and this allows the start-up time to be faster. Further this relatively low operating temperature makes them easier to contain and reduce thermal losses. PEMFC are smaller in volume and lighter in weight. Their size makes them perfect for automotive and portable applications. PEMFCs are particularly attractive for transportation applications, and also as a small or mid-size distributed electric power generator because it has a high power density, a solid electrolyte, a long stack life and low corrosion.

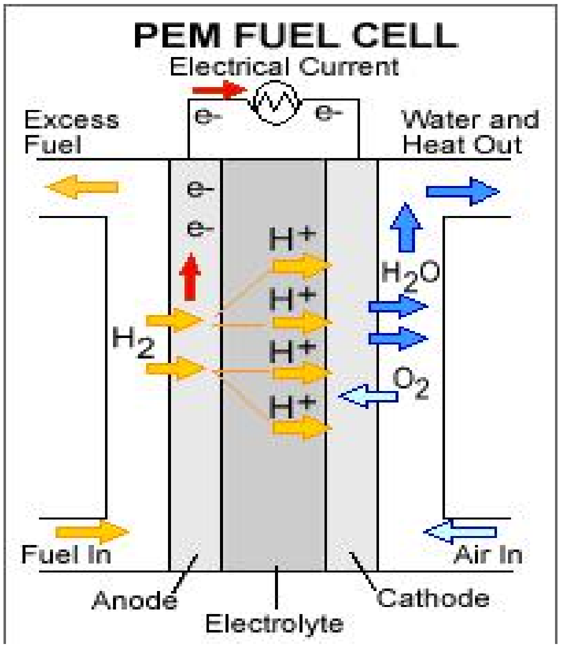

Figure 2 Schematics of Proton exchange membrane fuel cells **(Energy, 2011)**

1.3.2 Alkaline Electrolyte Fuel Cell (AFC)

AFCs are the first low temperature fuel cells which were put in practical service to generate electricity from the fuel hydrogen supplied. AFCs were even used in space application where they provided high energy conversion efficiency with high reliability. They operate at a range of 20^0C and 120^0C. The electrolyte used in AFCs is an alkaline solution of sodium hydroxide and potassium hydroxide. Low cost, high solubility and no excessive corrosion make these solutions good candidates as electrolyte. In most cases aqueous potassium hydroxide (KOH) is the used electrolyte, but even in stabilized matrix form. However KOH is liable to contamination of CO or reactions with CO_2. Because of this contamination, only pure hydrogen and oxygen are used as reactants.

Activation energy loss is the most important voltage loss in low temperature fuel cells. When compared to an acid electrolyte, the activation energy at the cathode is generally less in alkaline fuel cells. It makes them advantageous over acid electrolyte fuel cells. Besides the mentioned advantage, alkaline electrolytes do not need a noble metal electro catalyst and their performance is extremely good even with oxide catalysts, AFC became advantageous over the acid electrolytes. A working principle of AFCs can be simplified and illustrated in figure 3.

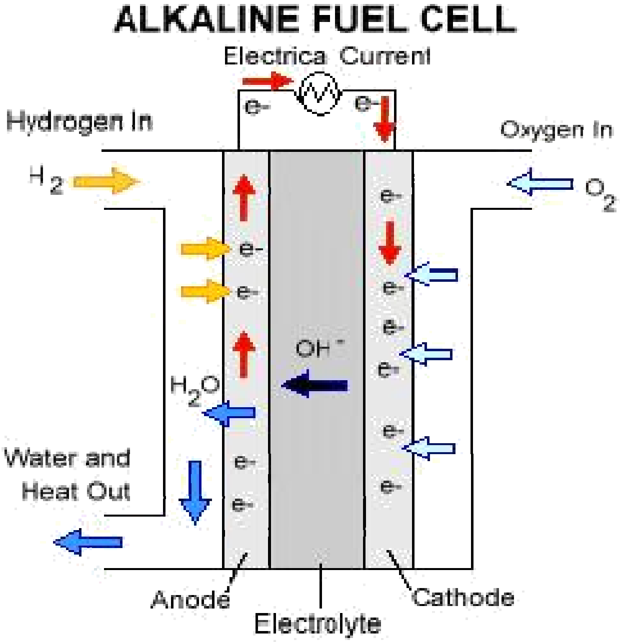

Figure 3 Simple schematics of alkaline fuel cells **(Energy, 2011)**

1.3.3 Phosphoric Acid Fuel Cells (PAFC)

PAFC are referred to as the first generation fuel cells with the operating temperature that lies in the range of 150^0C – 220^0C and 1-8 atmosphere pressure. Unlike AFC which is primarily developed for space application, PAFC was targeted for terrestrial commercial applications with the CO_2 – containing air as the oxidant gas and hydrocarbons as primary fuel for power generation **(Li, 2006)**. They are even called low temperature fuel cells .Platinum (Pt) or its alloy is used as catalyst in PAFCs function. The electrolytes in PAFC are aqueous solution of concentrated phosphoric acid and silicon carbide which dissociates into phosphate ions and hydrogen ions. The hydrogen ions act as the charge carrier. Water and waste heat are products of the electrochemical reactions which occur in any fuel cell.

Stable and continuous operation of PAFC can be assured by removing the byproducts of the reactions continuously. The removal of water is relatively easy because of the typical operating temperature of PAFC is above the boiling point of water. Thermal management and various cooling system can be achieved through removal of waste heat. The removal of waste heat can be achieved by heat transfer through convection method while cooling can be achieved through liquid coolant like water or dielectric liquid oil.

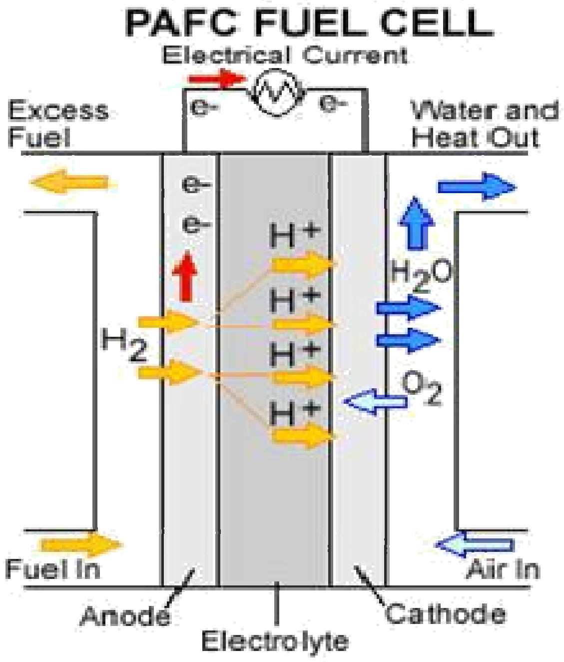

Figure 4 Schematics of Phosphoric Acid Fuel Cells **(Energy, 2011)**

1.3.4 Molten Carbonate Fuel Cells (MCFC)

Molten Carbonate Fuel Cells are called the second generation fuel cells operating at a temperature of about 600^0C – 700^0C.

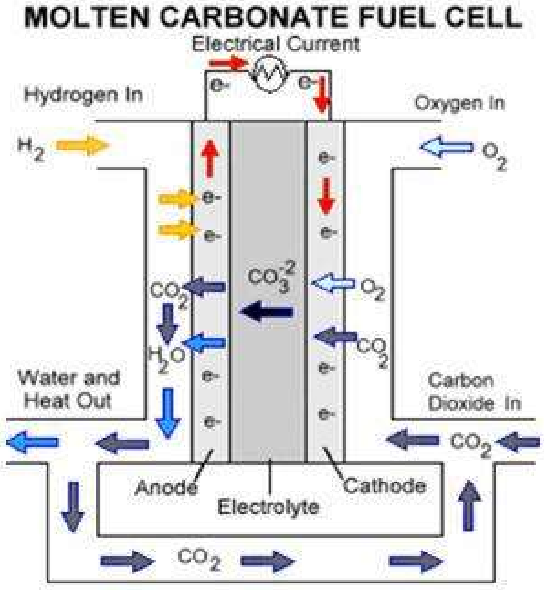

Figure5. Schematics of Molten Carbonate Fuel Cells **(Energy, 2011)**

Such a high temperature gives a possibility to use the high grade waste heat for use in fuel processing, CHP and getting higher efficiency the reduced activation, Ohmic and mass transfer polarization which in turn reduce the voltage loss can be reduced with this high temperature. Another advantage of this high temperature is that the external reformer is not necessary. MCFCs use highly conductive molten carbonate as an electrolyte which is a mixture of lithium carbonate and potassium carbonate contained in Lithium-Aluminum oxide matrix (**Varga, 2007).** MCFCs use methane or natural gas as fuel. With natural gas as a fuel and with the internal reforming of it, 50 – 60 % of efficiency can be achieved.

1.3.5 Solid Oxide Fuel Cells (SOFC)

SOFCs are high temperature fuel cells with solid electrolyte and capable of generating power from any kind of fuel as natural gas, bio fuel, diesel, gasoline as well as hydrogen. The basic fuel used for SOFC is hydrogen gas. The potential to use hydrogen rich fuel directly gives an opportunity for SOFCs to bypass hydrogen source problem. Due to the fact that there are no infrastructures for storage of hydrogen, there may be a problem to use hydrogen as a fuel. But this problem can easily be tackled in SOFC with the help of reformation process from hydrogen rich fuels. The conventional operating temperature for SOFC is 650^0C – 1000^0C. This high temperature range has major advantages. Some of these advantages are:

- High efficient fuel utilization (80% - 90%),
- Efficient in converting fuel to electricity which is around 60%,
- High power density as high as 200 –800mW/cm^2
- Fuel flexibility and the possibility of internal reforming,

Internal Reforming means hydrogen is generated at the anode by reforming it from the hydrogen rich fuel. Methane can be a good example. The reformation process can be demonstrated in equation (1) and (2) as follows

$$CH_4 + H_2O \rightarrow CO + H_2O \qquad (1)$$

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad (2)$$

The operating principles of SOFC are very similar to the other types of fuel cell. Like other fuel cells, SOFC essentially consists of two porous electrodes separated by ion conducting electrolytes. These two electrodes are anode and cathode. Reformation of any hydrogen rich fuel like methane occurs at the anode. In the reformation process methane reacts with water to form carbon monoxide and further to carbon dioxide and pure hydrogen. This pure hydrogen is oxidized at the anode into hydrogen ion (H^+) and electron (e^-). Oxygen, which is supplied at the cathode, is reduced into oxygen ion (O^{2-}). The released ions are able to pass through the permeable electrolyte that separates the electrodes. Both hydrogen ions and oxygen ions react with each other and as a byproduct water is produced. The electrons liberated from the oxidation process are not able to move to the cathodes. Because of their inability to pass through the electrolytes, they have to be led through an external circuit to the protons. This flow of electrons from the anode to the cathode results in the production of electricity. The materials used in SOFC in figure 7 as anode, electrolyte and cathode are Nickel Oxide – Yttria Stabilized Zirconium (NiO -YSZ), YSZ and Strontium doped Lanthanum Manganite ($La_{1-x} Sr_xMnO_3$) respectively **(De Guire, 2003**). The operation in SOFC can be illustrated in figure 6.

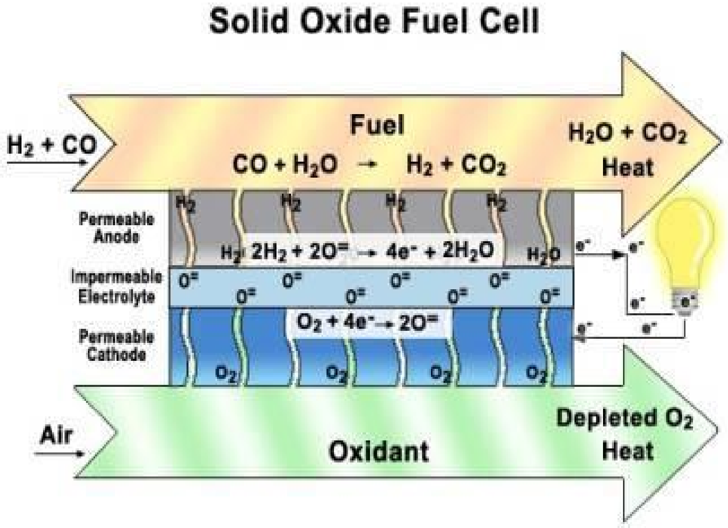

Figure 6 the operation principles of solid oxide fuel cell **(De Guire, 2003)**

Though High operating temperature has many advantages, it even has drawbacks like difficulty in sealing between cells in a flat plate, thermal expansion mismatch among materials which make the cost very high. High electrical resistivity in electrolyte used in SOFCs is caused by high operating temperature which reduces their performance even lower than MCFC. In order to tackle these kinds of problems, the operating temperature must be lowered without losing the mentioned advantages. Solid oxide Fuel Cells have emerged as serious alternative high-temperature fuel cells, and they have often been referred to as Third-Generation fuel cell technology because their commercialization is expected after PAFCs (The First Generation) and MCFCs (The Second Generation) **(Capehart, et al., 2007).**

SOFCs use solid state ceramic electrolyte. The utilization of solid electrolyte is advantageous over liquid electrolytes. This is because the problem of hardware corrosion occurred due to diffusion of droplets of liquid electrolyte can be avoided. The utilization of solid electrolyte even allows a flexible design shape, even if it is difficult to fabricate. Moreover the ceramics used in high temperature SOFC experience a relatively low conductivity that reduces the performance of SOFC.

Lowering operating temperature below the conventional temperature to a reasonable limitation affects the whole system when SOFCs are integrated with Gas Turbines in the hybrid system. The rate of electrochemical reactions, which occurs at the electrodes, decrease with the decrease in temperature. However, the decrease in operating temperature brings many advantages to the overall system. These advantages are mentioned as follows:

- Stainless steel can be used as current collector instead of very expensive ceramic interconnects
- Complexity and costs of the system can be reduced
- Individual components chemical stability can be improved
- Mismatching of thermal expansions of single components can be reduced as a consequence reduces the possibility of crack formation
- Startup and shutdown time can be reduced

The search for SOFCs, which operate at a lower temperature, could be realized either by reducing the thickness of the electrolyte to be used or through the development of new types of material for the electrolytes and the electrodes. Doped Cerium (CeO_2) and Doped Lanthanum Gallate ($LaGaO_3$) are two of the particularly attractive materials for the development of SOFC. This is because these materials have relatively high ionic conductivity in the low temperature range.For higher conductivity, cerium oxide (CeO_2) can be doped either with gadolinium [Ce_{1-x} Gd_xO_2 (CGO)] or with samarium [Ce_{1-x} Sm_xO_2 (CDO)] The recent development of nano-powder could help to reduce the thickness of CeO_2 based electrolytes to a small micron. The reduced thickness made good mechanical characteristics possible without reducing the performance like ionic conduction and mass transport through the cells. Developments achieved could make it possible to gradually decrease the operating temperatures from the conventional ones to about 400^0C - 500^0C. Based on this decrease in operating temperature, SOFCs can be categorized into the following:

- 800^0C - 1000^0C as High Temperature Solid Oxide Fuel Cell (HT-SOFC)
- 650^0C - 800^0C as Intermediate Temperature Solid Oxide Fuel Cell (IT-SOFC)
- Below 600^0C as Low Temperature Solid Oxide Fuel Cell (LT-SOFC)

1.3.6 500KW 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.

-

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

Table 1 500KW SOFC model parameters.

CHAPTER 2

Literature Review

2.1 Theoretical Background:-

The application of fuel cell in power generation system require drawing on knowledge across a broad range of discipline including thermal engineering, electrical engineering, electrochemistry, power plant engineering, chemical reaction, process dynamics and engineers. So variety of plant design and use of exhaust energy aimed at meeting the requirement of an application

2.2 Literature

EG&G Technical Services.**[1]** provided detailed information about the basic of fuel cell, classification of fuel cell, the role of Gibbs free energy and Nernst potential, ideal performance, cell energy balance, application, Advantage and disadvantage, cell efficiency, fuel cell performance variable, actual performance of fuel cell, fuel cell system, fuel cell system and design etc.

Holland, B.J. and Zhu, J.G.[2] describes the design of a 500W PEM fuel cell test system which can be used for both validating fuel cell models and for measuring the fuel cell model parameters. The software controllable operation and wide operating range of the fuel cell test system is such that a variety of control strategies tested. The major difficulties in the design of the PEM fuel cell test system are presented and options for further development work are discussed.

Kumm, W.H.[3] Presented, the parameters which affect fuel cell performance, the number of cells, cell voltage, open cell voltage, fuel cell efficiency, and fuel utilization coefficient. The actual PEM cell voltage is 0.868 volt and the open cell voltage is 1.031 volt. These two values affect the efficiency and performance of the fuel cell. Also, fuel utilization coefficient determines the amount of hydrogen consumption in fuel cell and also affects the cell efficiency.

Larminie, James and Dicks, Andrew.[4] Analyzed hydrogen fuel cell, fuel cell system, energy and EMF of hydrogen fuel cell, efficiency and efficiency limit, operational fuel cell voltage, activation loss, ohmic loss, fuel cell irreversibility, tafel curve etc.

Yousri M. A. Welaya, et al[5] utilizing the exhaust energy of fuel cell analyzed variant of the combined cycle includes a SOFC and a steam turbine with a single pressure waste heat boiler. Yousri, demonstrated that high overall efficiency approaching 60% may be achieved with optimum configuration using SOFC system.

Brian Tarroja et al[6]. A systems-level analysis and design iteration of a liquid hydrogen fuelled 50 kW class solid oxide fuel cell gas turbine (SOFC/GT) hybrid auxiliary power unit for high-altitude unmanned aerial vehicles is performed with the intention of investigating system configuration, system parameters and system design constraints on system efficiency. The analysis is performed using thermodynamic models where the sizing of components is allowed to vary. Effects of system pressure ratio, oxygen utilization, and current density on the system design are examined.

Mitsubishi Heavy Industries Ltd.[7] Presently working on Triple combined cycle i.e. (solid oxide fuell cell integrated with gas and steam turbine) low power application as well as high power application up to (700 – 800 MW) and would be completed on 2016 and 2020 respectively.

Robert J.Barun et al. [8] Using modeling and simulation, presented optimal system design and operation strategies for stationary solid oxide fuel cell systems applied to single-family detached dwellings.

Alexandros Arsalis et al.[9] Developed thermodynamic, kinetic, geometric, and cost models are validated for the synthesis/design and operational analysis of hybrid solid oxide fuel cell (SOFC) – gas turbine (GT) – steam turbine (ST) systems ranging in size from 1.5 MW to 10 MW. A parametric study is used to determine the most viable system/component syntheses/designs based on maximizing total system efficiency or minimizing total system life cycle cost.

Singhal, Subhash C and Kendall, Kevin.[10] They explained the operating principle, cell component materials, cell and stack designs and fabrication processes, cell and stack performance, and applications of SOFCs. Also provided a comprehensive discussion on high temperature Solid Oxide Fuel Cells, Fundamentals, Design and Applications of solid oxide fuel cells (SOFCs). SOFCs are the most efficient devices for the electrochemical conversion of chemical energy of hydrocarbon fuels into electricity, and have been gaining increasing attention for clean and efficient distributed power generation.

Sjöstedt and chen,[11] presented Virtual component testing for PEM fuel cell system: An efficient, high quality and safe approach for supplier and OEM's.

Siemens Westinghouse Power Company,[12]. Presented A high efficiency PSOFC/ATS-gas turbine power system, the first 220 kW all electric cycle demonstration plant with integrated micro gas turbine has successfully tested. They show the combined efficiency of micro gas turbine with different type of fuel cell

Kakac, et al.[13] Presented a systematic approach to heat exchangers, focusing on fundamentals and applications. Provided realistic design and Basic design methods for sizing and rating of heat exchangers.

Energy, US Department [14] Provided detailed information cost, performance, and durability of fuel cell, classification of fuel cell, and operating principle of different type of fuel cell.

Raja, A.K., Srivastava, A.P. and Dwivedi, M.,[15] presented overview of hybrid power system, more ever different kind of fuel cell as non fossil based energy generation system and their generation mechanism. And described possible combination of hybrid power system and their operation strategies.

Maroju,**P.[16]** Developed a simple model for the proton exchange membrane hydrogen-oxygen fuel cell, and deals with the theory behind the fuel cell from electrochemical, thermodynamic and mathematical point of view. And documents the simple model of the fuel cell developed using Simulink. This is followed by a detailed analysis of this model and comparison with the practical fuel cell.

Santin et al[17] studied SOFC-GT hybrid operation with liquid fuel. Two liquid fuel methanol and kerosene were investigated. A 500KW hybrid system was analyzed. WTEMP software were used for thermodynamic and investment analysis. In comparison methanol –fuelled system showed lower efficiency, but attractive economic performance where kerosene fuelled system poor economic performance.

2.3Motivation & Objective

This study is motivated by the continuous quest for the higher therma efficiencies of the conventional power plant. From the era of the rankine cycle with steam turbine(ST)(single engine) and through the peak year of the Brayton – Rankine combined with gas turbine(GT) and steam turbine (ST) has been striving to maximize the power generation efficiency by continuously increasing operating temperature and pressure. The situation can be improved by using regeneration bottoming cycle, but imrovement is limited.

It makes engineering sense to take advantage of the very desirable charecterstics of the solid oxide fuell cell at high temperature and use of high temperature exhaust gase as the energy source for the efficient combustion, and increase the turbine inlet temperature. This result the triple cmbined cycle SOFC-GT-ST (Rankine cycle, Brayton cycle and solide oxide fuel cell).

Objective:-

The specific objective of this study is to make through investigation of the thermodynamic analysis and performance charecterstics of integrated power system configuration consisting of a solid oxide fuel cell, gas turbine, and steam turbine for statinary power application. To model and then analyze the integrated system configuration as realastically as possible, detailed system and component thermodynamic, kinetics, and geometric model will be developed, implemented, and validated and the used to parametric analysis of the key system and component parameter.

(a) Develop a Triple Combine cycle, i.e, Gast turbine, Steam turbine integrated with solid oxide fuel cell.
(b) Thermodynamic analysis of individual component and whole plant.
(c) Investigate the thermal efficiency.
(d) Charectrize the performance of the power plant.
(e) Study the thermodynamic performance by integrating SOFC with steam cycle and rankine cycle and perform the parmetric studies to identify the sources of enegy.

2.4 Conclusion and gap

Combined cycle power plant is used for producing power by coupling Gas turbine cycle (Top cycle) and Rankine cycle (bottom cycle). By incorporation of fuel cell in combined cycle plant the output of plant can be increased. From literature survey of fuel cell integrated combined cycle plant, it is found that detailed thermodynamic analysis of Gas-turbine power plant with fuel cell, and Rankine cycle plant with fuel cell are done earlier. From literature survey it is found that thermodynamic analysis of Rankine cycle combined with Gas-turbine cycle integrated with fuel cell is done by some author for small power application. For large application not done yet. Solid oxide fuel cell exhaust energy is used for gas turbine and the gas turbine exhaust is used run the steam turbine.

2.5 Problem Formulation

In the present study thermodynamic analysis of combined Rankine cycle and gas turbine cycle integrated with fuel cell is investigated and comparison of various organic fluids is carried out to find best organic fluid which will give maximum efficiency. The effect of regeneration and reheating are also evaluated on performance of combined cycle plant.

It is proposed to examine the effect of following parameters on the efficiency of integrated cycle and evaluation of better thermal efficiency.

- Effect of different compression ratio on thermal efficiency
- Effect of different air mass flow rate on thermal efficiency
- Required mass flow rate of hydrogen for different MW plant.
- Heat loss at different SOFC operational cell voltage.
- Current density at different cell voltage.

CHAPTER 3

INTEGRATED SYSTEM DESCRIPTION

3.1Details of Component:-

Symbol	***Component***	***Description***
SOFC	Solid oxide fuel cell	A fuel cell of the solid oxide type that perform the shift and steam reforming reaction by converting the fuel into hydrogen the electrochemical reaction convert the chemical energy of the fuel to electric power
PR	Pre-reformer	A typical catalytic reactor where hydrogen and carbon dioxide are produced from natural gas and steam
HEC	Counter-flow heat exchanger air injection pipe	A heat exchanger of the counter flow type that reheat tha air before enering the cathode
CB	Catalytic combustor	A combustor that burns the non-oxidized part of anode exhaust with air flow inside by an air compressor
INV	Invertor	The inverter converts the DC current produced by the fuel cells into the more suitable AC current
GT	Gas Turbine	A gas turbine of the radial-type that uses the exhaust gases from the SOFC to produce mechanical energy, part of which is used to operate the air compressor (which is connected with the same shaft) as well as produce electric power in the electric generator.
AC	Air compressor	A compressor of the centrifugal-type used to suck air at ambient pressure and compress it up to the fuel cell operating pressure before it is brought into the cathode compartment of the stack.
EG	Electric generator	A generator used to convert the mechanical energy produced from the gas turbine or the steam turbine into electric power.

DR	Drum	The drum separates the liquid water from the saturated steam.
FP	Feedwater pump	A pump that receives the preheated water from the deaerator and pumps it to the HRSG (in particular the economizer).
ST	Steam Turbine	The superheated steam produced by the superheater is supplied to the steam turbine where during expansion mechanical power is produced. A small fraction of the superheated steam at low pressure is extracted to the deaerator to be used later on for deaerating and feedwater preheating.
CON	Condenser	A shell and tube heat exchanger that condenses the wet steam coming from the steam turbine exhaust.
CP	Condensate pump	A pump that receives the condensate from the condenser and pumps it to the deaerator.

Table 2 Integrated power plant component description

3.2 Integrated fuel cell Combined cycle

Fuel Cells appear to be very attractive power generation systems, promising highly efficient electricity generation with very low negative effects to the environment. These efficiencies can be further increased by integration of high temperature fuel cells (SOFCs, MCFCs) into hybrid cycles. While a wide variety of potential bottoming technologies for the exploitation of the high temperature exhaust gases waste heat is available, a lot of research effort is needed to determine the optimal integration of well established technologies with these very novel conversion devices.

Integrated fuel cell systems are combinations of conventional heat engines (e.g., gas turbines, steam turbines, etc.) and different types of fuel cells (e.g., SOFC, MCFC) or even combinations of two different types of fuel cells (e.g., a SOFC and a PEMFC).

These aforementioned systems are extremely efficient. They have the potential of achieving efficiencies near or even higher than 70 percent. This also means that they can be environmentally friendly due to their reduced emissions. With such capabilities these engines are better than any other known engines today. They are a perfect match for stationary applications (centralized or distributed) while there are still significant difficulties in utilizing them in mobile and vehicular applications due to issues primarily of cost. Fortunately, however, during the last few years, this cost has dropped significantly with the use of cheaper materials and is expected to drop even lower with the expected mass manufacture and commercialization of these systems. Also, due to the high full and part load efficiency potential, the operating cost is already lower compared to conventional power generating systems.

3.3 Integrated Solid Oxide fuel cell – Gas turbine – Steam Turbine Cycle

In this integrated cycle, shown in Figure 7 (Fuel Cell Handbook, 2004), a SOFC, a gas turbine, and a steam turbine are combined. In this system, the gas turbine has a dual role: it is the bottoming cycle with respect to the fuel cell, but it is also a topping cycle with respect to the steam turbine. Air and fuel streams enter the cathode and anode compartments of the SOFC. The separate streams leaving the cell enter the combustor and then the gas turbine. The gas turbine exhaust flows into the heat recovery steam generator and then to the stack. The steam produced drives the steam turbine. It is then condensed and pumped back to the steam generator.

The air/fuel ratio entering the fuel cell and the fraction of the fuel consumed in the cell are selected to achieve the desired fuel cell operating temperature range and gas turbine operating temperature and pressure ratio. Performance results for this hybrid cycle are given below and are based on the idealized gas and steam turbine cycles illustrated in the T-s diagrams shown in Figure 8. The heating of the air and fuel, the operation of the fuel cell, and the burning of the residual fuel are assumed to occur at constant pressure. The expansion of the combustion product gases in the gas turbine is represented as an adiabatic, reversible (constant entropy) process. Energy is recovered from these gases at nearly constant pressure in the heat recovery steam generator after which they pass out of the system via the stack.

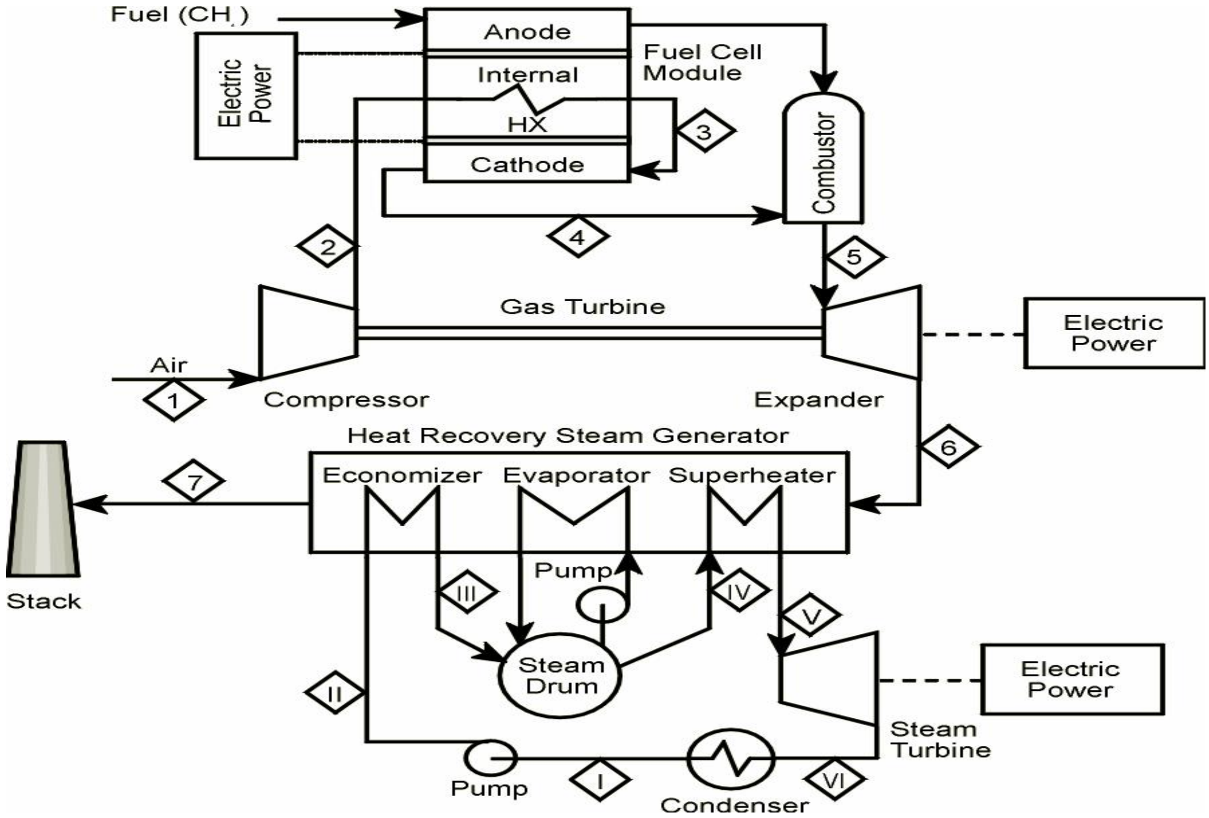

Figure 7 Integrated SOFC – Gas turbine – Steam turbine cycle (Fuel cell Handbook, 2004)

The main thermodynamic advantage of the steam turbine bottoming cycle, is the lowered temperature of heat rejection to the environment. Performance results for this hybrid cycle assume gas turbine compressor and expander efficiencies of 83 percent and 89 percent and a steam turbine efficiency of 90 percent. The principal result is that the efficiency of the overall system is 75 percent for the overall system.

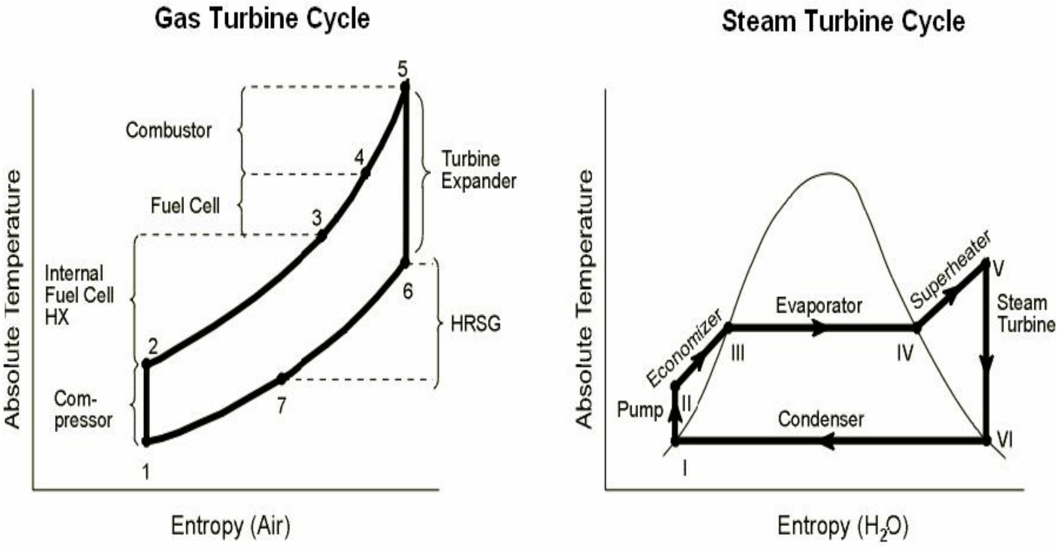

Figure 8 A T-S diagram of the integrated SOFC – Gas Turbine – Steam Turbine cycle.(Fuel cell Handbook, 2004)

The key component between the gas turbine cycle and the steam turbine cycle is the heat recovery steam generator. In general, the heat transfer in an HRSG entails losses associated with three main factors:

1. The physical properties of the water, steam and exhaust gases do not match causing exergetic and energetic losses.
2. The heat transfer surface cannot be infinitely large.
3. The temperature of the feed water must be high enough to prevent corrosive acids forming in the exhaust gas where it comes into contact with the cold tubes. This limits the energy utilization by limiting the temperature to which the exhaust gas can be cooled.

The extent to which these losses can be minimized (and the heat utilization maximized) depends on the concept and on the main parameters of the cycle. In a more complex cycle, the heat will generally be used more efficiently, improving the performance but also increasing the cost. In practice, a compromise between performance and cost must always be made (Kehlhofer, 1999).

3.4 SOFC-GT-ST Integrated Description

In SOFC-GT-ST combined cycle, the air flow to the SOFC is compressed with a gas turbine compressor. The flow then passes through a 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 high pressure turbine exhaust gases pass through gas to steam heat exchanger to generate steam to run the steam turbine. Gas turbine as topping cycle and steam turbine used as bottoming 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

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 with presnt layouts have been studied. They include tubular SOFC (TSOFC), and planar SOFC (PSOFC) using natural gas internal reforming and pure hydrogen fuels.

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 additions, 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. (51), 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.

3.5 Methodology

In order to fulfill the objectives mentioned above, a thorough literature review will be carried out on Gas Turbines Steam Turbine and Solid Oxide Fuel Cells. For *GT* part, focus will be on the operating conditions as temperature, pressure, fuel gas flow and their effect on the performance. The impacts of different variables as temperature, pressure, gas components involved in different reactions occurring in the system must be understood to optimize the performances, to design and integrate Gas Turbine and Steam Turbine with Solid Oxide Fuel Cell successfully. Consequently the improvement of the performance of the whole integrated system will be easier. For the Solid Oxide Fuel Cell part, the focus will be on the following aspects:

- The electrodes to be used
- Materials for interconnect,
- the cost of material for fabrication,
- Compatibility of the SOFC to be fabricated with the Gas Turbine and steam Turbine

For the Steam Turbine, the focus will be on the following aspects:

- Layout of the steam turbine cycle.

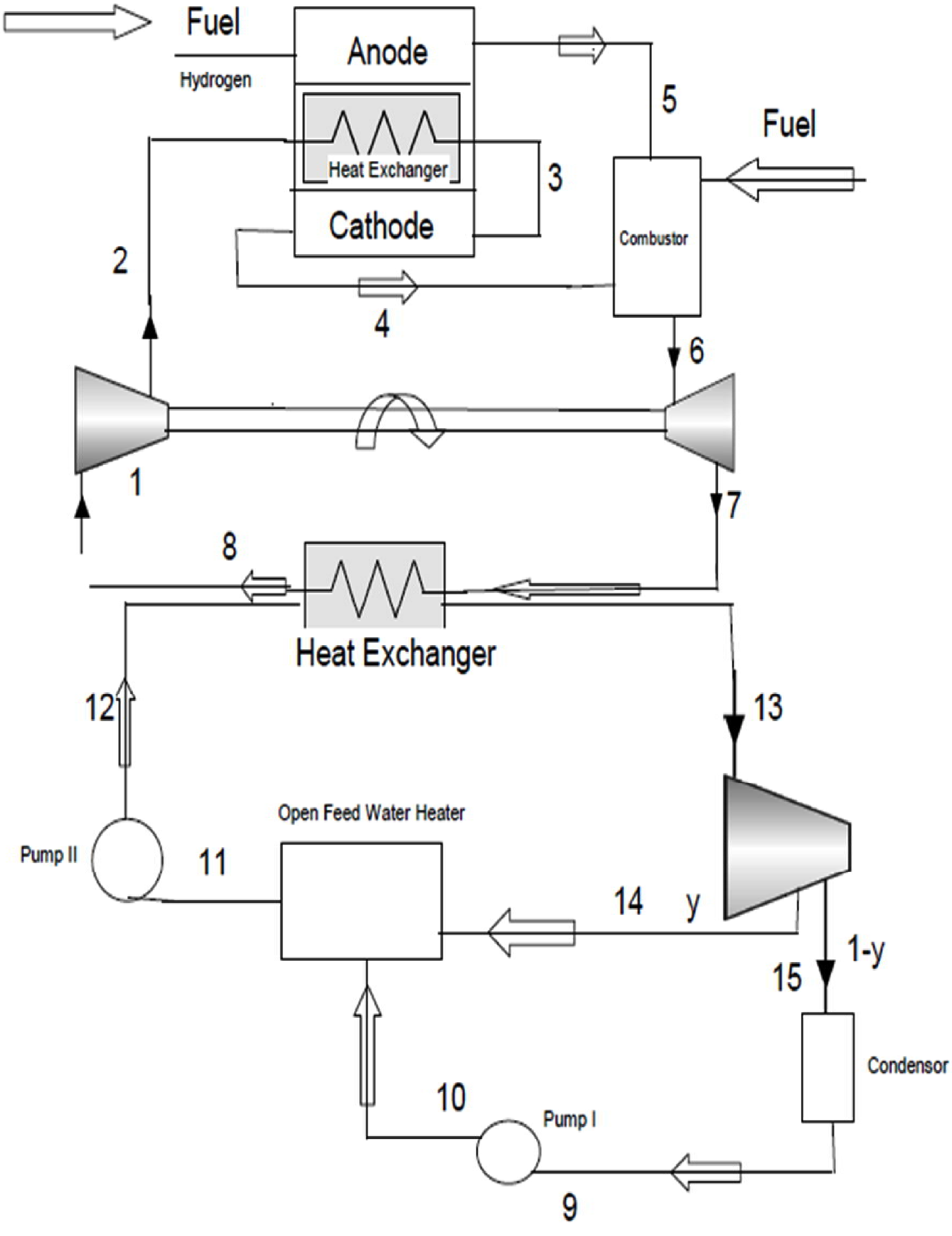

Figure 9 SOFC – GT-ST Integrated cycle

3.6 Input Parameters:

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

Sr. No	**Parameter**	**Value**
1	Air compressor inlet temperature	T_1= 27˚C
2	Air compressor inlet pressure	P_1= 100 kPa
3	Pressure ratio of compressor	r_P= 11
4	SOFC inlet temperature	T_3= 850˚C
5	SOFC exit temperature	T_4= 1000˚C
6	Mass flow rate of air	m = 98.18 kg/s
7	Mass flow rate of hydrogen fuel	1.1555 kg/s
8	Isentropic efficiency of air compressor	η_C= 0.86
9	Inlet Temperature of gas turbine	T_3= 1277˚C
10	Condenser pressure	P_{15}= 100 kPa
11	Extraction pressure of open feedwater heater	P_{14}= 800 kPa
12	Calorific value for hydrogen fuel	40MJ/kg
13	Calorific value for hydrocarbon fuel	120MJ/kg
14	Isentropic efficiency of Gas turbine	η_{GT}= 0.86
15	Inlet temperature of steam turbine	T_{13}= 350˚C
16	Steam turbine inlet pressure	P_{13} =5000 kPa
17	Isentropic efficiency of steam turbine	η_{st}= 0.86
18	Fuel utilization factor	U_f = 0.85

Table 3 parameter for integrated cycle

The computer program for the analysis is developed in EES has been given in Appendix along with its flow diagram for computation procedure.

Table 4 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 (ε_{HE})	80%
Combustor	Combustion efficiency (η_{com})	98%
AC generator	Electric efficiency (η_{gen})	95%
DC/AC Converter	Conversion efficiency	95%
Gas to steam heat exchanger	Pressure loss	3%
SOFC stack	Pressure loss	3%
combustor	Pressure loss	2%

Table 4 Auxiliary system component data for SOFC-GT-ST plant.

CHAPTER 4

Thermodynamic analysis

4.1 SOFC 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. (3) shows the operating voltage of a fuel cell at a current density (i_{den}) (Larminie and Dicks, 2003; Maroju, 2002).

$$V_{cell} = E_O - (i_{den} \times r) - A \times \ln(i_{den}) + m \times e^{n \times i_{den}} \tag{3}$$

Where,

E_O is the open circuit voltage = 1.01 V

A is the slope of Tafel curve = 0.002 V

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

4.2 Energy Formulation Of components

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 above figure.

The required power for the compressor, gas turbine, steam turbine, pump & The isentropic efficiencies of the compressor, gas turbine can be defined as:

4.2.1 Air Compressor

$$W_c = \left[mc_p(T_2 - T_1)\right]_c \tag{4}$$

Where W_c is the work of compressor.

$$\eta_c = \frac{h_{2s}-h_1}{h_2-h_1} \tag{5}$$

Where η_c is the efficiency of the compressor

$$(\eta_s)_c = \left[\frac{T_1}{T_2-T_1}\left[\left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]\right]_c \tag{6}$$

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

4.2.2 Internal heat exchanger

$$q_{in} = (h_3 - h_2) \tag{7}$$

4.2.3 Gas Turbine

$$\eta_{GT} = \frac{h_6-h_7}{h_7-h_{7s}} \tag{8}$$

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

$$W_{GT} = \left[mc_p(T_6 - T_7)\right]_{GT} \tag{9}$$

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

$$(\eta_s)_{GT} = \frac{T_6-T_7}{T_6\left[1-\left(\frac{p_7}{p_6}\right)^{\frac{\gamma-1}{\gamma}}\right]_{GT}} \tag{10}$$

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

$$\frac{T_{2s}}{T_1} = (\frac{p_2}{p_1})^{\frac{\gamma_{air}-1}{\gamma_{air}}} \tag{11}$$

$$\frac{T_{7s}}{T_6} = \left(\frac{p_7}{p_6}\right)^{\frac{\gamma_{air}-1}{\gamma_{air}}} \tag{12}$$

4.2.4 Solid oxide fuel cell

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. (13) to (17) occur within the anode and cathode of the fuel cell. As a comparing case, methane (CH_4), with a lower heating value of 50 *MJ/kg*, is used for fueling the SOFC stack and combustor. Various reactions corresponding to the methane are listed below:

$$\text{Reforming: } CH_4 + H_2O \rightarrow CO + 3H_2 \tag{13}$$

$$\text{Shift gas reaction: } CO + H_2O \rightarrow CO_2 + H_2 \tag{14}$$

$$\text{Electrochemical: } H_2 + 0.5O_2 \rightarrow H_2O \tag{15}$$

The degree to which an anode supports 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:

$$CH_{4,\text{anode}} + 2O_{2,\text{cathode}} \rightarrow 2H_2O + CO_2 \tag{16}$$

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

$$H_{2,\text{anode}} + 0.5O_{2,\text{cathode}} \rightarrow H_2O \tag{17}$$

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):

$$E_0 = -\frac{\Delta g_f}{z \times F} \tag{18}$$

So, the efficiency of fuel cell can be expressed as

$$\eta_{FC} = U_f \frac{V_{cell}}{E_0} \tag{19}$$

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 'irreversibilities', the efficiency could reach 100%. Fig. 5 shows Carnot efficiency for heat engines, fuel cell efficiency limit, and fuel cell-heat engines combined cycle maximum efficiency (Larminie and Dicks, 2003).The mass balance for SOFC system gives:

$$m_3 + m_{hyd} = m_4 + m_5 \tag{20}$$

Where,

$$m_5 = m_{hyd} \times (1 - U_f) \tag{21}$$

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 thermodynamics to the SOFC and assuming an adiabatic process,

$$m_3 \times h_3 + \left(m_{hyd} \times U_f \times CV\right) + \left(m_{hyd} \times \left(1 - U_f\right) \times h_{fuel}\right) = P_{FC,DC} + (m_4 \times h_4) \tag{22}$$

4.2.4 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:

$$\eta_{inv} = \frac{W_{AC}}{W_{DC}} \tag{23}$$

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

$$\eta_{gen} = \frac{W_{mech}}{W_{elec}} \tag{24}$$

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

4.2.5 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:

$$m_5 + m_{fb} + m_4 = m_6 \tag{25}$$

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

$$(m_5 + m_{fb}) \times (CV \times \eta_{comb}) + (m_4 \times h_4) = m_6 \times h_6 \tag{26}$$

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

4.2.6 Steam Turbine

$$\mathrm{W_{st}} = \dot{\mathrm{m}}_{\mathrm{st}}(\mathrm{h_{13}} - \mathrm{h_{15s}}) \tag{27}$$

We have steam turbine efficiency as,

$$\eta_{\mathrm{st}} = \frac{\mathrm{h_{13}} - \mathrm{h_{15}}}{\mathrm{h_{13}} - \mathrm{h_{15s}}} \tag{28}$$

$$W_{net,steam} = m_{steam}(W_{steam,turb} - W_{steam,pump}) \tag{29}$$

4.2.7Pumps

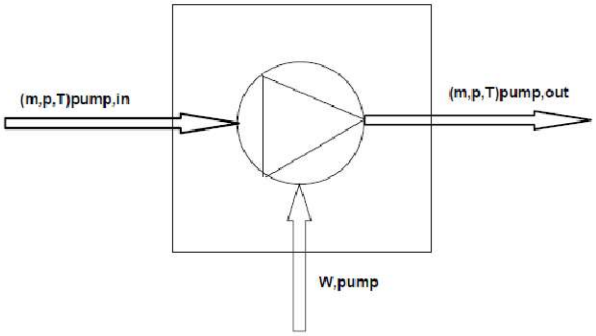

Figure 10 Schematic of pump

$$m_{in} = m_{out} \tag{30}$$

$$w_{pump} = m_{in}(h_{10} - h_9) \tag{31}$$

$$w_{pump} = m_{in}(h_{12} - h_{11}) \tag{32}$$

4.2.8 Open feed water heater

$$y(h_{14} - h_{10}) = (h_{11} - h_{10}) \tag{33}$$

4.2.9 Condenser

$$q_{out} = (1 - y)(h_{15} - h_9) \tag{34}$$

4.2.10 Gas to steam heat exchanger

$$m_{steam}(h_{12} - h_{13}) = m_7(h_8 - h_7) \tag{35}$$

The energy balances on the gas and steam sides are the following:

$$Q_{SU,EV}^{gas} = m_{GTexh}c_p(T_{SUin} - T_{EVout}) \tag{36}$$

$$Q_{SU,EV}^{steam} = m_{STin}(h_{SUout} - T_{EVin}) \tag{37}$$

For the geometric models of the heat exchangers both the LMTD and effectiveness-NTU methods are used depending on the exchanger. A heat exchanger’s effectiveness is the ratio of the actual heat transfer rate to the maximum possible heat transfer rate if an infinite heat transfer surface area were available. The actual heat transfer rate is obtained either by the energy given off by the hot fluid or the energy received by the cold fluid. Therefore

$$\varepsilon = \frac{Q_{act}}{Q_{max}} = \frac{n_{mix}^{h} h_{mix}^{h} \left(T_{h,i} - T_{h,o}\right)}{Q_{max}} = \frac{n_{mix}^{c} h_{mix}^{c} \left(T_{c,o} - T_{c,i}\right)}{Q_{max}} \tag{38}$$

Where the "i" and "o" subscripts refer to inlet and outlet, respectively. The maximum temperature difference occurs on the fluid having the minimum heat capacity. Therefore, the maximum possible heat transfer can be expressed as

$$Q_{max} = n_{mix}^{h} h_{mix}^{h} \left(T_{h,i} - T_{c,i}\right) \qquad if \quad (nc_p)_{mix}^{h} < (nc_p)_{mix}^{c} \tag{39}$$

$$Q_{max} = n_{mix}^{c} h_{mix}^{c} \left(T_{h,i} - T_{c,i}\right) \qquad if \quad (nc_p)_{mix}^{c} < (nc_p)_{mix}^{h} \tag{40}$$

4.2.11 Overall balance equations for integrated cycle

The integrated gas turbine power plant with SOFC in Fig. 9 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:

$$m_1 + m_{fuel} = m_7 \tag{41}$$

$$m_1 = m_2 = m_3 \tag{42}$$

$$m_6 = m_7 = m_8 \tag{43}$$

$$m_{fuel} = m_{hyd} + m_{fb} \tag{44}$$

Overall energy balance can be expressed as

$$(m_1 \times h_1) + \left(m_{hyd} \times U_f \times CV\right) + \left(m_5 + m_{fb}\right) \times (CV \times \eta_{comb}) = (m_7 \times h_7) + P_{FC,DC} + P_{GT} \tag{45}$$

Where $$P_{GT} = m_7 \times (h_7 - h_8) \tag{46}$$

Combined cycle efficiency can be expressed as:

$$\eta_{combined} = \frac{P_{FC,AC}+P_{GT}}{m_{fuel}\times CV} \tag{47}$$

$$\eta_{integrated} = \frac{P_{FC,AC}+P_{GT}+P_{ST}}{m_{fuel}\times CV} \tag{48}$$

The gas turbine cycle efficiency can be expressed as

$$\eta_{GT} = \frac{P_{GT}}{m_{fuel}\times CV} \tag{49}$$

$$\eta_{ST} = \frac{P_{ST}}{m_{fuel}\times CV} \tag{50}$$

The required mass flow rates of hydrogen and air in *kg/s* are expressed in Eqs. (50) and (51) respectively, and the value of utilization coefficient U_f in Eq. (34) refers to the ratio of hydrogen reacted in the fuel cell (Holland and Zhu, 2007; Kumm, 1990).The required hydrogen mass flow rate can be expressed as:

$$m_{hyd} = \frac{1.05\times P_{FC,AC}}{10^5\times V_{cell}} \tag{50}$$

The required air mass flow rate can be written as:

$$m_{air} = \frac{3.57\times\lambda_{air}\times P_{FC,AC}}{10^4\times V_{cell}} \tag{51}$$

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

$$m_{hyd,cons} = m_{hyd} \times U_f \tag{52}$$

The hydrogen formula in Eq. (50) 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. (53) 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),

$$Fuel\ flow\ rate = \frac{P_{FC,AC}}{\eta_{FC}\times CV} \tag{53}$$

$$P_{hea} = P_{FC,AC} \times (\frac{1.25}{V_{cell}} - 1) \tag{54}$$

CHAPTER 6

RESULT AND DISCUSSION

4.1 SOFC-GT-ST power plant results

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.11 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. 11, 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. 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 different 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. 12 show the effect of fuel cell voltage on the consumption of hydrogen gas 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.

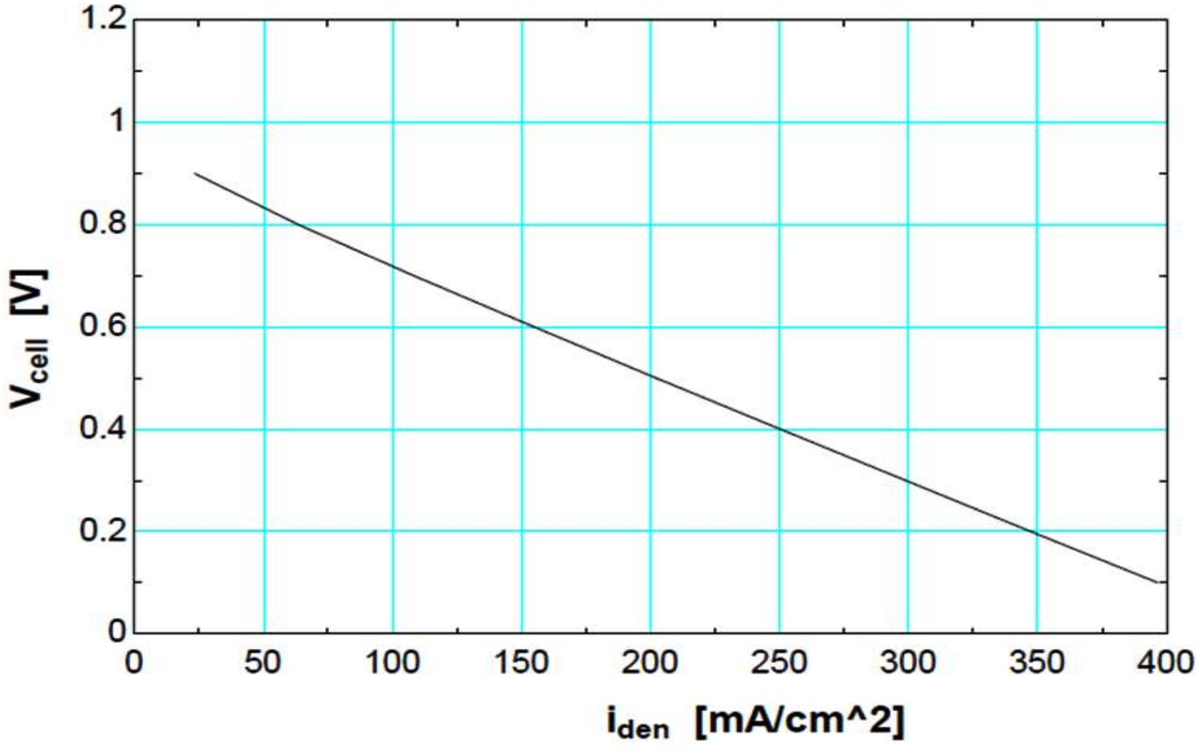

Fig.11 Current density at different SOFC voltage.

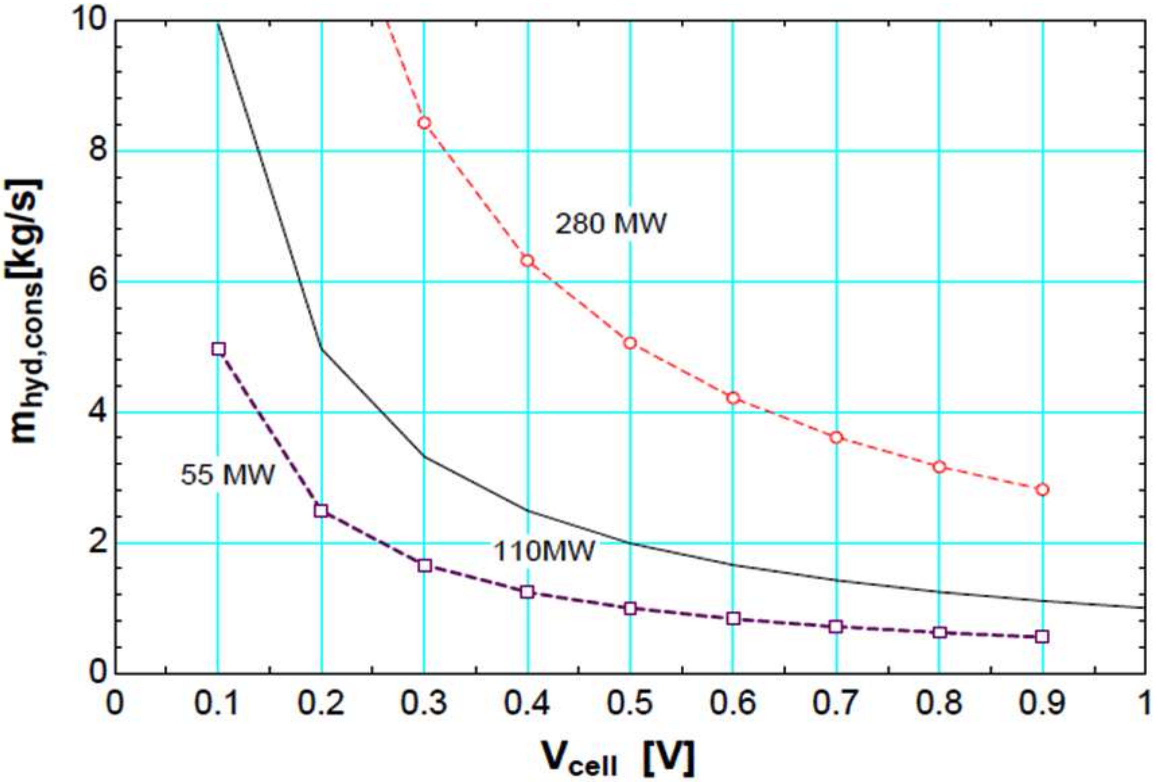

Fig. 12 Hydrogen fuel consumption for SOFC a different electric powers.

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. Fig. 13 shows the heating power losses from SOFC with cell voltage at different ranges of output power. SOFC heating power in *kW* can be calculated from Eq. (54) (Larminie and Dicks, 2003):

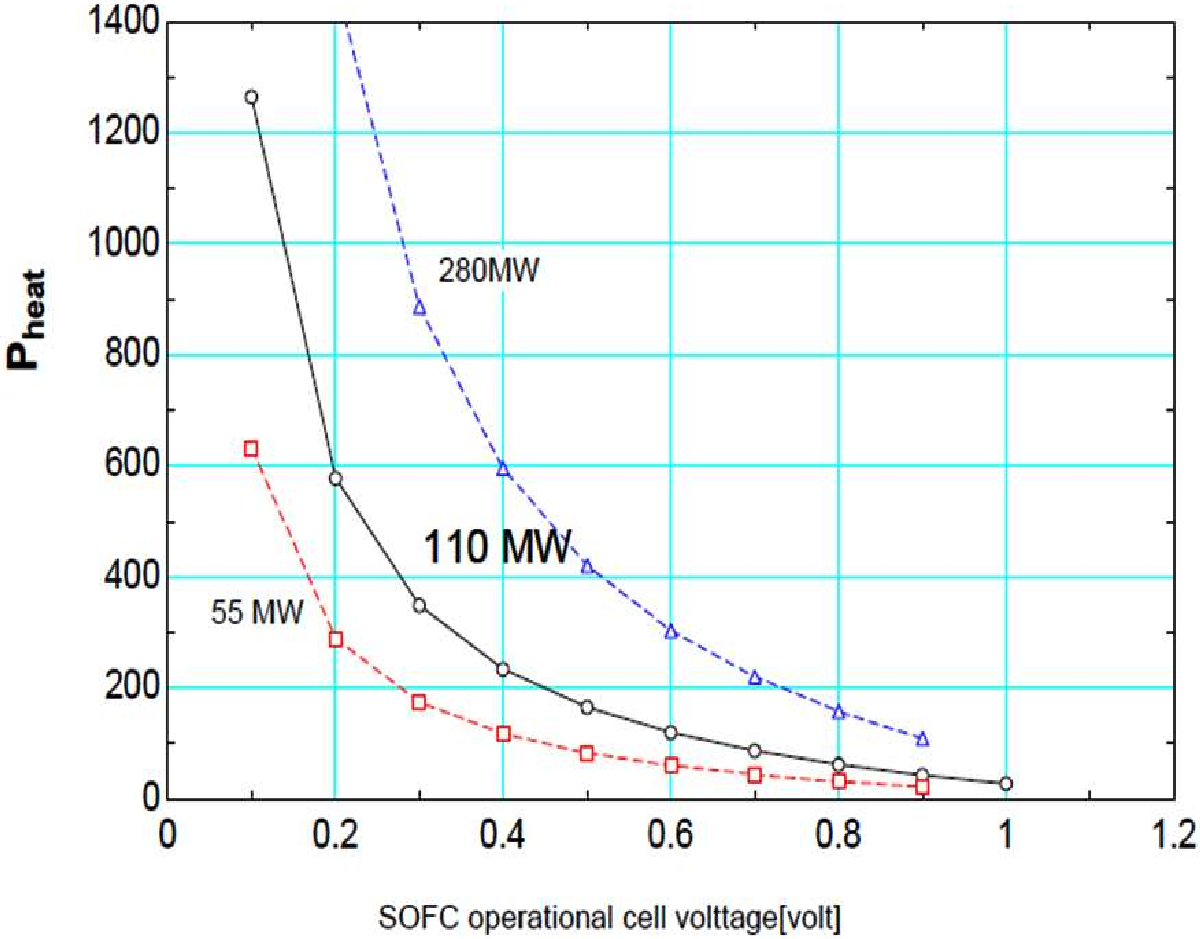

Fig 13 Heat losses from SOFC at different electric powers

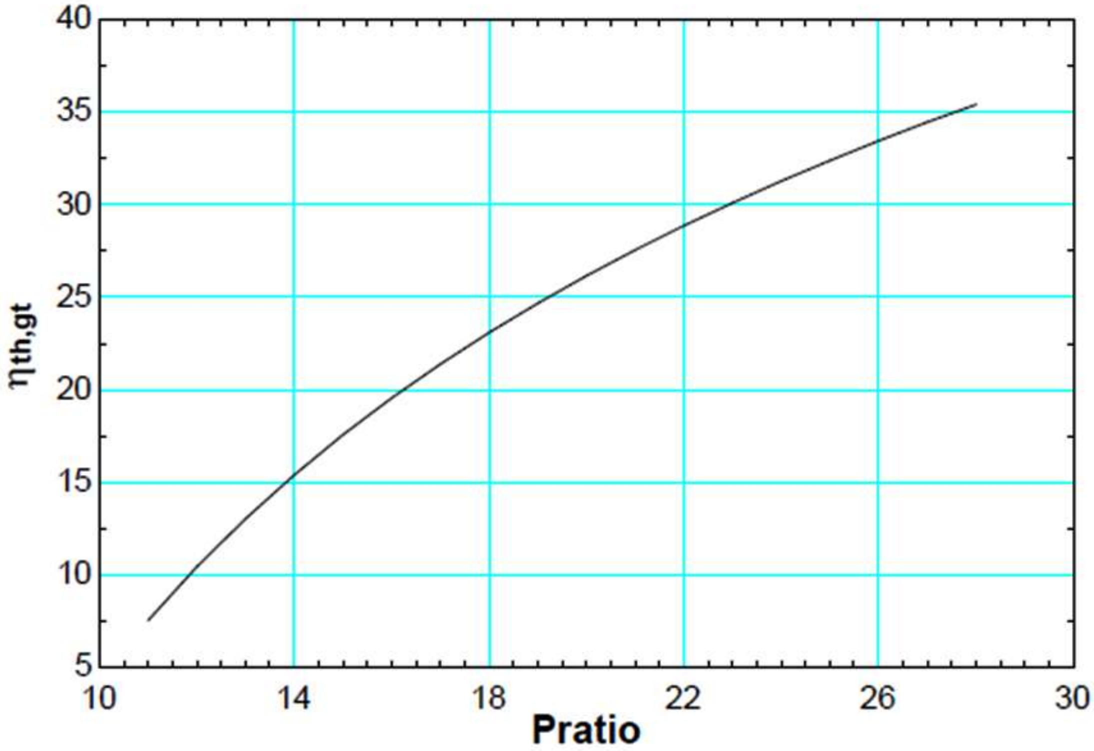

Figure 14 Gas Turbine efficiency at different compression ratio

Figure 14 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.

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.

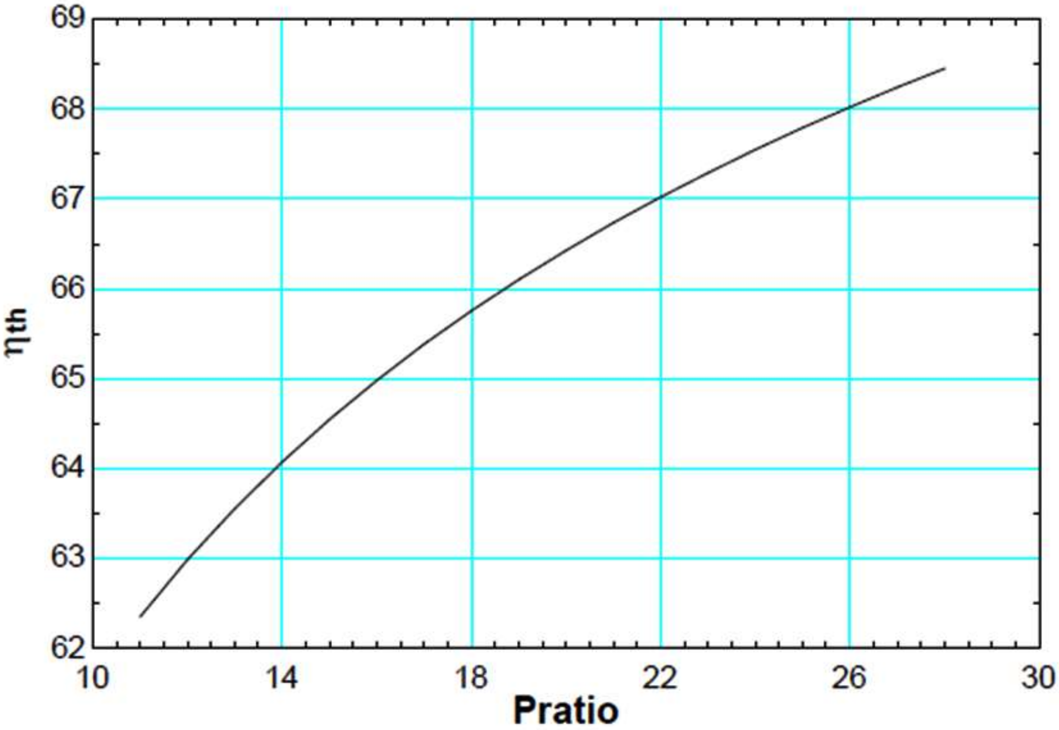

Figure 15 integrated cycle efficiency at different compression ratio

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. 15 & 16 shows the variation integrated cycle efficiency at different compression ratio and air mass flow rate. 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.

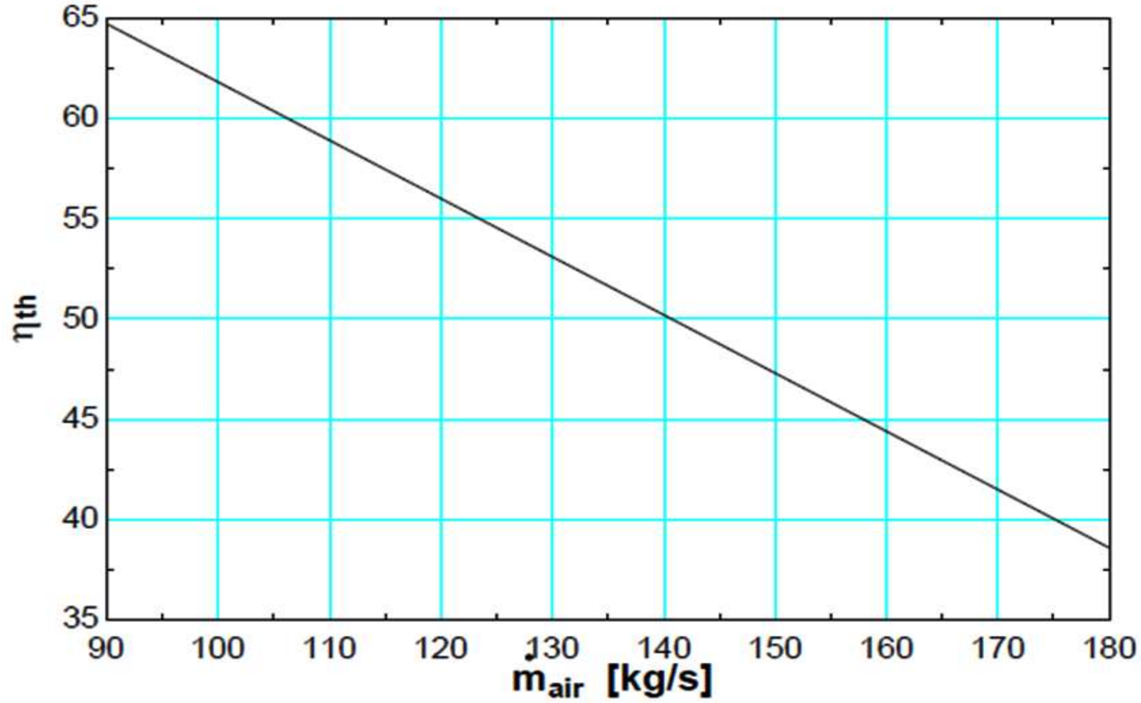

Figure 16 Integrated cycle efficiency at different mass flow rate of air

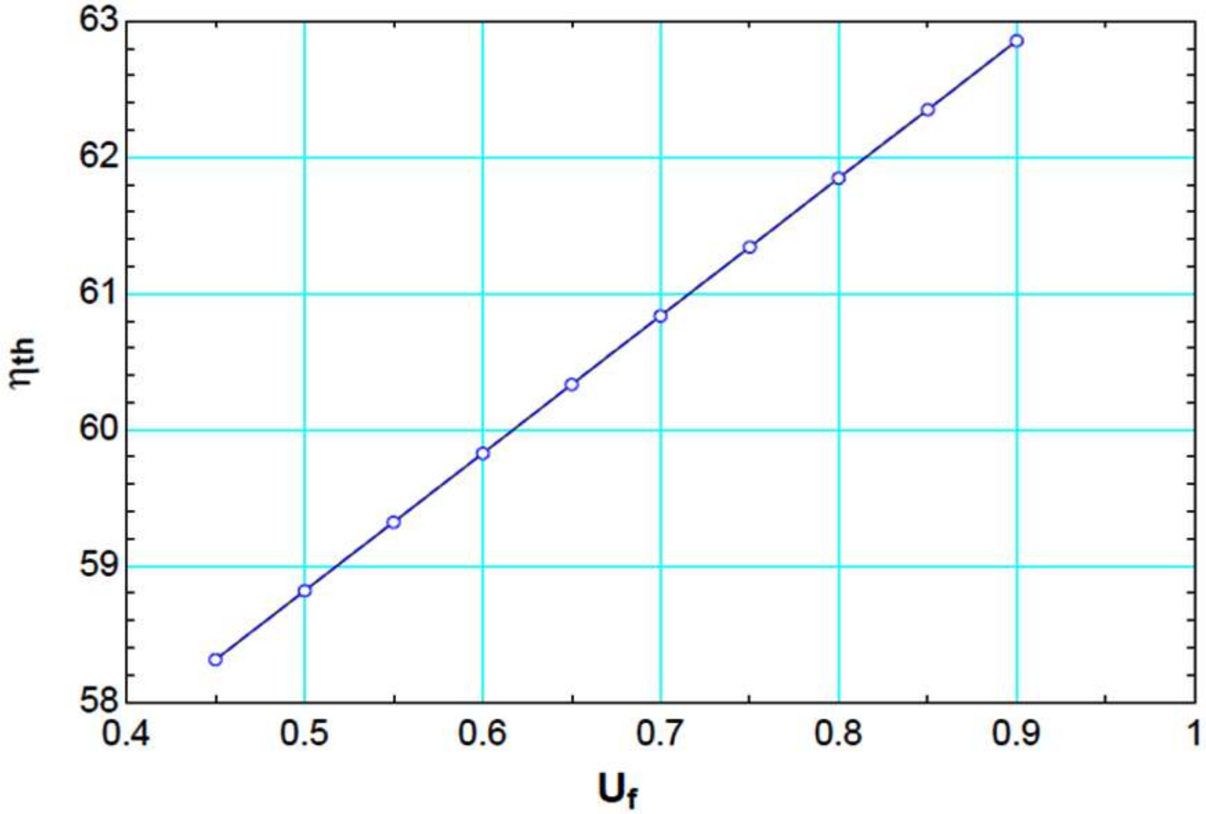

Figure 17 integrated cycle efficiency at different SOFC fuel utilization coefficient

CHAPTER 6

CONCLUSION

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. Layouts were studied, combining to 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 10.089 *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 65*%*. So, the integrated SOFC-GT-ST exceeds the GT plant by 20.2*%* 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.

CHAPTER 7

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