PERFORMANCE ANALYSIS OF SOLID OXIDE FUEL CELL-GAS TURBINE HYBRID SYSTEM

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Energy Technologies and Management
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Abstract

Fossil fuels which includes coal, natural gas and oil, have been the main sources of energy since the beginning of industrial revolution as they are used in various instruments (gas turbine, internal combustion engines, thermal power plants) for power production. Fossil fuels may offer good efficiencies and high performance, but the fact that they are finite and have severe effects on the environment has always left the researchers of exploring alternative techniques for energy production to overcome the growing energy demands of the world. Although Fuel Cells (FCs) were first introduced more than 170 years ago, but it has been only the last three decades since they have shown great prospects of being commercially suitable. FCs particularly Solid Oxide Fuel Cells (SOFCs) are high efficiency electrical power, heat generating and environment friendly devices which offers a great promise of overtaking the traditionally existing power generating technologies and they have the potentials to meet the uncontrollable increasing energy demands around the globe. Apart from their good performance as a stand-alone power and heat generating units, the performance efficiency can be improved even more when SOFCs are integrated with the waste heat recovery units. Solid Oxide Fuel Cell-Gas Turbine (SOFC-GT) Combined Heat and Power (CHP) hybrid systems are becoming a promising solution to the future energy demands. Integrating the recuperative Gas Turbine (GT) with SOFC, the overall efficiency of up to 70 percent could be achieved. Looking to the rising interest of hybrid system, a detailed thermodynamic and thermal model of SOFC-GT is simulated in MATLAB in this thesis. This thesis aims to analyze the performance of SOFC-GT by investigating the effect of fuel flow rates, current density and pressure ratio change on the temperature and electrical power output of SOFC stack, gas turbine. The model also investigates the effects of the aforementioned parameters on the stack voltage and the efficiency of the whole plant. The results of the tests are compared with the results available in the literature.

Keywords: SOFC, hybrid system, dynamic modeling, gas turbine, CHP

Katı Oksit Yakıt Hücresi-Gaz Türbini Hibrit Sisteminin Performans Analizi

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Özet

Kömür, doğal gaz ve yağ içeren fosil yakıtlar, enerji üretimi için çeşitli enstrümanlarda (gaz türbini, içten yanmalı motorlar, termal enerji santralleri) kullanıldığı için endüstriyel devrimin başlangıcından bu yana enerjinin ana kaynakları olmuştur. Fosil yakıtlar iyi verimlilik ve yüksek performans sunabilir, ama aslında onlar sonlu ve çevre üzerinde ciddi etkileri var her zaman enerji üretimi için alternatif teknikleri keşfetmek araştırmacılar bıraktı büyüyen enerji aşmak için Dünyanın talepleri. Yakıt hücreleri (FCs) ilk 170 yıl önce daha tanıtıldı rağmen, henüz sadece son üç yıl olmuştur çünkü ticari olarak uygun olma büyük umutları göstermiştir. FCs özellikle katı oksit yakıt hücreleri (SOFCs) yüksek verimlilik elektrik gücü, ısı üreten ve geleneksel mevcut güç üreten teknolojiler elden büyük bir söz sunan çevre dostu cihazlar ve onlar var Dünya çapında kontrol edilemeyen artan enerji taleplerini karşılamak için potansiyeller. Tek başına güç ve ısı üreten birimler olarak iyi performans dışında, SOFCs atık ısı kurtarma üniteleri ile entegre olduğunda performans verimliliği daha da geliştirilebilir. Katı oksit yakıt hücresi-gaz türbini (SOFC-GT) Kombine ısı ve güç (CHP) hibrid sistemleri gelecekteki enerji talepleri için umut verici bir çözüm haline gelmektedir. Reperatif gaz türbini (GT) SOFC ile bütünleşme, yüzde 70 oranında genel verimlilik elde edilebilir. Hibrid sistemin yükselen faiz, SOFC-GT ayrıntılı bir termodinamik ve termal model Looking for bu tez MATLAB benzetimli. Bu tez, yakıt debisi, mevcut yoğunluk ve basınç oranı değişimi SOFC yığını, gaz türbini sıcaklık ve elektrik gücü üzerinde etkisini araştırarak SOFC-GT performansını analiz amaçlamaktadır. Modeli de etkilerini araştırıyor AfYukarıda belirtilen parametreler üzerinde yığın gerilimi ve tüm bitki verimliliği. Testlerin sonuçları literatürde bulunan sonuçlarla karşılaştırılır.
Anahtar Kelimeler: SOFC, hybrid sistemleri, dinamik modelleme, gaz türbini, CHP

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Nomenclature

Variable and Constants

ΔG	Gibbs Free Energy at standard Pressure and Temperature J/mol
A_{cell}	Cell Area cm^2
A_{comb}	Area of Combustor
A_{hx}	Area of Heat Exchanger
C_p	Specific Heat Capacity kJ/kg
i_L	Limiting Current Density
i_o	Exchange Current Density
n_e	Number of Electrons Participating in the Reaction
P_{GT}	Gas Turbine Power kW
P_{sofc}	Power of SOFC kW
Q_{comb}	Combustor Heat Generation Rate J/s
Q_{sofc}	SOFC Heat Generation Rate $J\ slashs$
R_eff	Resistivity, 1.7E-05, Ω
V_{loss}	Voltage Loss
E	Reversible cell Potential
F	Faraday Constant, 96485C/mol
H	Enthalpy kJ/kg
I	Stack Current Density A
i	Current Density A/cm^2
LHV	Lower Heating Value kJ/kg
M	Molecular Mass
m	Mass Flow Rate kg/sec
n	Molar Flow Rate $Kmol/sec$
P	Pressure bar
Q	Heat Rate kW
R	Universal Gas Constant 8.314 $J/molk$

T	Temperature K
t	Time sec
V	Cell Voltage V

Subscripts

act	Activation
chem	Chemical
comp	Compressor
cont	Concentration
eff	Effective
gt	Gas Turbine
in	Inlet
out	Outlet

Greek Letters

α	Charge Transfer Coefficient
δ	Thickness
η	Efficiency
η_{act}	Activation Overvoltage
η_{conc}	Concentration Overvoltage
η_{ohm}	Ohmic Overvoltage
γ	Specific heat ratio

1 Introduction

1.1 General Introduction

Energy is the most significant and essential medium or force the whole human civilization depends on.The building pillars of a society depends on 3Es namely Energy, Economy and Environment. The world energy consumption has been continuously increasing since the industrial revolution. If we look into the world energy consumption, fossil fuel power production sources are used to meet most of today's world energy supply. Earlier, since 1960s, oil had been the most important energy or power production source which at present is mostly replaced by the natural gas. Whereas, the world, at large, has become addicted to use fossil fuels for all its energy needs and they are consumed at an unsustainable rate without considering the effect of flue gases on the society and environment. Fossil fuel consumption at this unsustainable rate has resulted in the increase of its prices around the world.

A British scientist, Fredrick. G, said that energy is the invisible currency on which lies all the sciences. Furthermore, history shows that the industrial revolution started with the start of harnessing the energy from the fossil fuels. However, energy conversion could be considered as old as the beginning of human civilization on the earth. The use of fire as source of energy could be traced back to the Middle Pleistocene era 500,000 BC back and the Chinese were using coal for energy purpose in 1000 BC.

Apart from being environment friendly, the power generating techniques should also offer quality, sustainability, high efficiency and cost effectiveness. Companies in all parts of the globe are producing power in order to meet the demand for energy through different non-renewable sources like coal, gas, furnace oil etc. By observing the performance of fossil fuel operated power plants, i.e; thermal power plants, it can be observed that they produces power with good efficiency throughout the clock as long as the fuel is supplied. Fossil fuel which is a non-renewable energy source, are finite and they will be depleted some day, but the demand for energy will keep on increasing with rapid urbanization, increase in world population and the technological development the world is witnessing.

Power production from these sources are responsible for the global warming and other related different environmental issues, which may include the emission of radioactive substances, air pollution, acid precipitation and also the depletion of ozone. According to different studies and research [2], the world population is increasing at a rate of 1.2 to 2% and if the growth or increase in population will continue with this rate the population of earth is expected to be around 12 billion by the year 2050. It could easily be ascertain from these statistics that with the increase in the world's population, the demand in energy will also increase accordingly, and we know that the economic growth directly depends on the continuous and uninterrupted supply of power and about 3% increase in the demand for energy expected by 2050 [7][8].

The power production from the non-renewable sources might offer great deal of high efficiency, yet the concern of them being harmful to the society and environment has always led to the discussion of investigating into new sources and techniques for power production. Many different sustainable techniques with some limitations are already in the market which

Table 1: Countries with highest percentage of CO_2 Emission in 2015 [2]

Country Rank	**Country**	**CO_2 Emission From Fuel Combustion**
1	China	9040.74
2	United States	4997.50
3	India	2066.01
4	Russia	1468.99
5	Japan	1141.58
6	Germany	729.77
7	South Korea	585.99
8	Iran	552.40
9	Canada	549.23
10	Saudi Arabia	531.46

includes power production from solar, wind, geothermal energy etc. Fuel Cells (FC) in this regards, compare to other renewable energy production techniques, offers good efficiency specially when combined with other power production devices. Along with high efficiency, FC are also considered as an effective solution to the environmental problems. The emission of toxic gases such as carbon dioxide, as shown in figure 1, causes environmental issues of global warming resulting in the rise of average earth temperature. Specially during the last century the temperature of the earth has increased at a rate of 0.6 °C which is due to the burning fossil fuels and using other non-renewable energy sources. This dramatic increase in the temperature of both land and the ocean has made the situation very alarming. Various research centres situated in different parts of the world have reported an alarming rise in ocean level in Atlantic, Indian and Pacific oceans over the last few decades, and the Department of Energy (DoE) USA has also reported that a 54% increase in the emission of CO_2 is expected and if this on going trend continues 1.7 to 4.9 °C increase in earth's temperature during the period from 2000 to 2100 will occur.

1.2 Energy Scenario 2040

The International Energy Outlook 2017 (IEO-2017) presents the long-term energy outlook of the world between 2015 to 2040. According to IEO-2017 assessment, the world is divided into 16 regions those regions are further divided into Organization for Economic Cooperation and Development (OECD) members and Non-OECD members. According to the IEO-2017, the consumption of the energy is increasing mostly in the Non-OECD countries with China and India being on top as both countries are experiencing growth and development demanding more energy. The world energy consumption demand between 2015 to 2040 is projected to grow by 28% with Asia on the top. To overcome this increasing demand of energy fossil fuel hydrocarbons are still predicted to be biggest source due to which the prices of hydrocarbons are also increasing. The price of per barrel of crude is predicted to increase up to 229/barrel. In IEO-2017, the total energy consumption is predicted to be 663

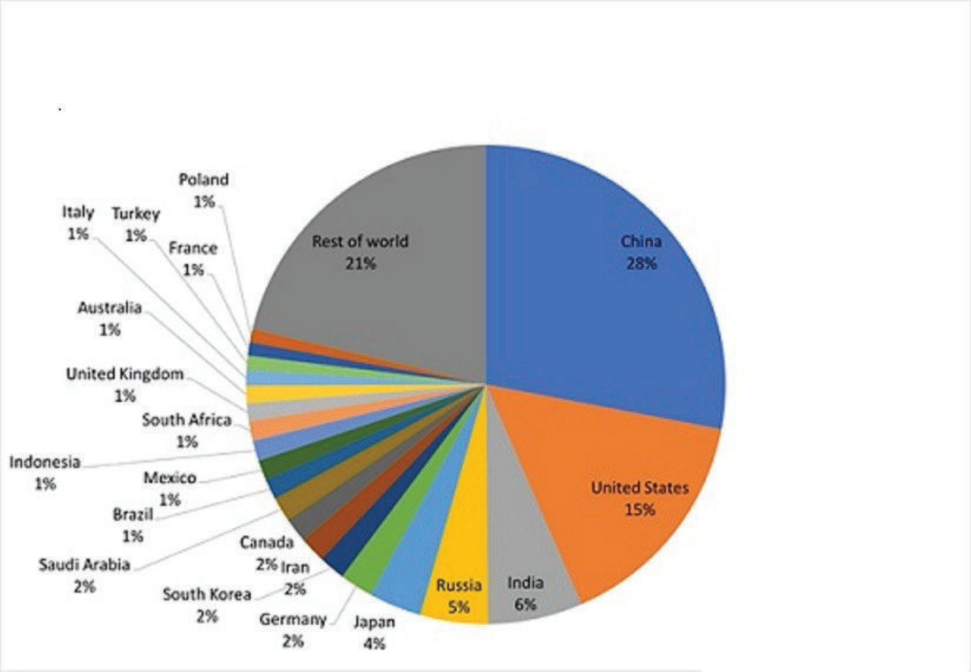

Figure 1: Global CO_2 Emission Share [1]

quadrillion Btu in 2030 from 575 quadrillion Btu in 2015 and to 736 quadrillion Btu in 2040 with major share being produced from fossil fuels. The share of the non-OECD of energy consumption is 41% and only 9 % that of OECD. As mentioned earlier, the demand for energy by most of the non-OECD will be covered by using the sources they are responsible for the emission of Carbon Dioxide resulting in the deterioration of the environment. The energy source on which the world depends the most is depleting quickly and fossil fuel are also the biggest source of the deterioration of the environment as they emit CO_2 and SO_2 as flue gases are being burnt into the environment resulting in the destabilization of the natural equilibrium which consequently is becoming the cause for the global warming as a result of an increase in the earth average temperature. The above discussed reasons have always compelled researchers to explore new alternative resources or options for energy production to overcome the increasing demand for energy consumption in the years to come unlike the existing conventional resources the world is relying on currently. A source of energy production that should be more efficient, durable and cost effective. In pursuit of finding alternative technologies, there have been various highly environment friendly options the developed world has started working on which may include the power production from Solar PVs, Wind Turbine, Hydel power and Nuclear energy [1].

The term "Hydrogen Economy" which aims and focuses on producing energy from hydrogen. Hydrogen is the most abundant element on earth. An energy being produced from hydrogen is considered to have no or minimum impacts on the environment which is what is the main objective of the current energy scenario. The technology that utilizes hydrogen

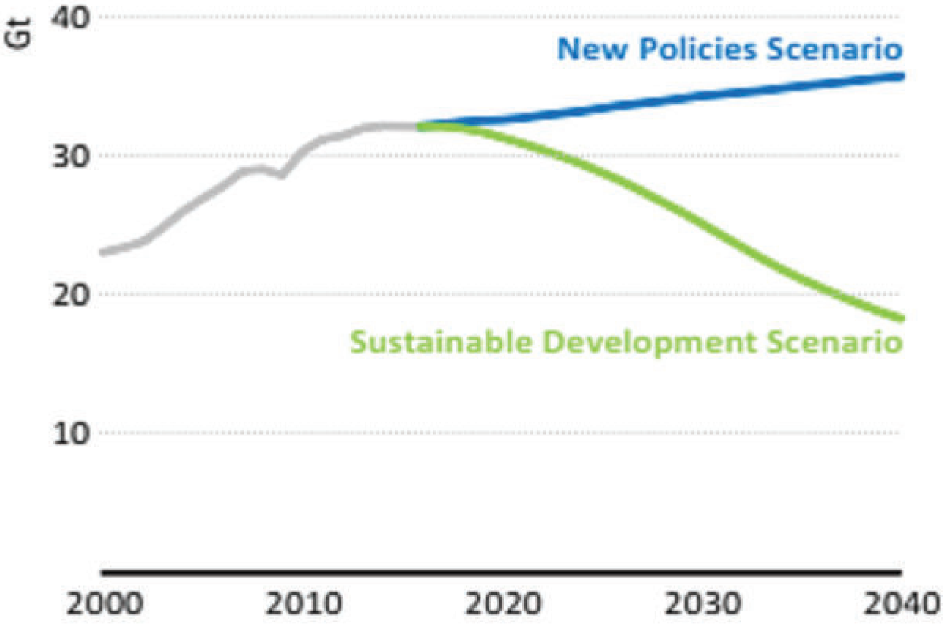

Figure 2: Global CO_2 Emission [2]

for energy production and which could be related to the hydrogen economy is Fuel Cell.

1.3 Objectives of Thesis

The main objectives of this thesis are:

- To develop an Electrochemical and Thermal SOFC-GT CHP hybrid model using MATLAB
- To investigate the effect of fuel flow rate change on the exhaust temperature of SOFC, GT and Power output of SOFC stack, GT and stack voltage, current density and system efficiency
- To investigate the effect of current density change on SOFC stack, GT exhaust temperature, electrical power output and stack voltage
- To investigate the effect of GT pressure ratio change on SOFC stack, GT temperatures, electrical power Output, stack voltage and current density and the overall plant efficiency
- To develop a dynamic model that could be used for varying electrical power output.

1.4 Thesis Outline

This thesis aims is to evaluate the performance and efficiency of solid oxide fuel cells integrated with gas turbine hybrid system. It is about developing a dynamic electrochemical and thermal model for performance analysis of Solid Oxide Fuel Cell-Gas Turbine hybrid system. The thesis comprises of six (6) chapters, first chapter discusses the introduction, energy and different stages of energy development, energy scenarios around the world, objectives and scope of the thesis. The second chapter discusses the historical perspective of fuel cells and literature review. The third (3) chapter is about the Solid Oxide Fuel Cell technology and its applications. The electrochemical, thermodynamic principles of Solid Oxide Fuel Cell and the bottoming cycle along with their components are discussed in fourth chapter. The second last chapter, i.e; the fifth chapter is about the result and discussions and performance analysis and the last chapter is about the concluding remarks and recommendation.

2 Fuel Cell Technology and Applications

2.1 Fuel Cells

According to the statistics, around 46% of the electricity in the world today is generated by the combustion of fossil fuels. Fossil fuels have high environmental impacts due to the emission of toxic gases in the result of their combustion and it also pertinent to mention that fossil fuels are non-renewable and have got limited quantity and they will deplete one day. Apart from fossil fuels, many other sources are used for power generation, which include Coal, Nuclear Energy, Wind Energy, Solar Energy and Hydel Energy etc. As discussed in the previous sections, with the increase in world population the demand for energy will also increase and the studies show that this demand in increase for energy can not be covered only by utilizing fossil fuels and its related sources. This lead many scientists and researchers around the world to find new alternative sources of energy which could offer great efficiencies, durability, environment friendliness and sustainability.

Fuel cells are devices that are used for direct conversion of chemical energy into electrical energy which is stored in the gaseous molecules of fuel and oxidant. The reaction in the fuel cell takes place at two electrodes which are separated by an ionic conducting electrolyte. The electrodes of fuel cells are porous and conduct electrons. Water and heat are the only by products if the fuel used is hydrogen and the overall process in the fuel cell is the inverse of water electrolysis. Electrolysis is a process in which water is split into hydrogen and oxygen whereas by reversing this process, which is, hydrogen and oxygen are combined and there product is water, energy (electricity) and heat [9]. Electricity being produced from the fuel cells is as usable as the normal conventional grid power.

2.1.1 History of Fuel Cell

Though fuel cell technology is a very hot discussion these days and it is considered as a new technique for energy production, but it has been more than 170 years since the fuel cell is under discussion and intense research. The first scientist who introduced this technology was Sir Humphrey Davy who in 1802 created a simple fuel cell which worked by utilizing carbon/water, ammonia/oxygen/carbon compounds for electricity generation. However, the main invention of the how the basic principle of fuel cell works is discovered by Christan Friedrich Schonbein (1829 to 1868). Another scientist Sir William Grove, who was basically an English Lawyer which later became a scientist, from 1811 to 1896, discovered an improved wet cell battery in the year 1838 and named it the Grove Cell and it followed the principle of reversing the electrolysis [10]. The Nernst's Solid Oxide Electrolytes discovery in 1899 was what led the foundation of the Ceramic Fuel Cells.

In 1800, British scientist William Nicholson and Anthony Carlisle gave this concept of decomposing water by electricity into hydrogen and oxygen and they called this process the process of electrolysis. It could be elaborated with the help of following chemical equation:

$$2H_2O \rightarrow 2H_2{+}O_2 \tag{1}$$

The two basic or fundamental laws of Electrolysis were derived from the theory proposed by Michael Faraday in 1832 stating that elements separated by passing electrical current, the dissolved salt is proportionate to the amount of electric charge passed through the circuit. Later, another scientist William R. Grove took Faraday's idea and did an experiment in a such a way that he used to platinum electrodes and dipped one end of both into a container containing sulfuric acid with the other ends sealed in oxygen and hydrogen containers and noticed that a constant current is flowing between the electrodes, it was also noted that the level of water rises in both the tubes with the flow of current. Grove combined many sets of electrodes and connected them in series of circuits "gas battery" which is the first fuel cell thus he could also be considered as the first inventor of Fuel Cell. The above discussion could further be explained with the help of the following equation;

$$2H_2+O_2 \rightarrow 2H_2O+\text{Energy} \tag{2}$$

Further in 1889 another scientist Ludwig Mond with his assistant Carl Langer did several experiments on gas powered battery in which they used coal to extract the Mond gas from which 6 $amps/ft^2$ at 0.73 volts was produced using the perforated electrodes of thin platinum, and they named this whole set up of their the fuel cell. The founder of Physical Chemistry, Friedrich Wilhelm Ostwald, gave the theoretical aspects of how a fuel cell works. With the help of the experiments he performed, he in 1893 explained the different components of a fuel cell, i.e; electrodes, electrolyte, the reducing and oxidizing agents, both the anions and cations etc. Ostwald solved the un-answered reason of how or why a reaction in Grove's gas battery occur at the contact point of electrode, gas and electrolyte which gave an inspiration and idea to new fuel cell researchers through his drawing by relating the physical properties and chemical reaction that takes place at the fuel cell[11].

The first practical fuel cell which works on the principle of converting air and fuel directly into electricity as result of the electro-chemical process was done by Francis T. Bacon (1904-1992). In the beginning in 1930s he started his experiments by using alkali electrolyte fuel cells and in 1939 he was able to built a cell that uses nickel electrodes and did the experiment at a pressure of about 3000 psi. He developed a fuel cell for the Royal Navy Submarines during the World War-II and later in 1958 he demonstrated a 10 inch diameter alkali cell stack electrodes and he did this research work for the Britain's National Research Development Corporation (BNRDC). The same company then used Bacon's work for Apollo Spacecraft fuel cell. Apollo, for the successful use of hydrogen based fuel cell, spent millions of dollars to power the on board electrical system of Apollo's journey to moon. Many countries including USA, Japan, Canada have significantly been investing in the research and development for the advancement and further improvement in technology for the fuel cell.

2.2 Types of Fuel Cells

There are various types of fuel cells depending on their application following the same working principle. Globally, in the most common fuel cell system, the fuel used is hydrogen with oxygen as oxidant with there product being water, as shown in global equation. It is also important to note that the device has no moving part and it does not produces noise while working.

Fuel cells are of six different types which are divided into these categories based on the type of fuel they use and the electrolyte being used in every respective type. Of those six types, few offer a large variety of usability while few have very limited applications. The types of fuel cells are briefly explained as follows:

2.2.1 Proton Exchange Membrane Fuel Cell (PEMFC)

İt is also called as Polymer Electrolyte Membrane Fuel Cells, because it uses Proton Conducting Polymer as the electrolyte. Water-Based Acidic Polymer Membrane is used as the electrolyte and Platinum-Catalyzed as the Electrodes in this this type of fuel cell. The operating temperature for PEMFC is less than 100 °C and pure hydrogen or reformed natural gas with carbon monoxide removed as the fuel. Whereas, in high temperature-PEMFC, the electrolyte is changed to Mineral Acid based system fro Water based due to which it can operate upto a temperature of 200 °C. Due to it's low temperature operation, it starts quickly and it also has the advantage of offering high power density. Such a specific type fuel cell has it's application in automotive vehicles, laptop computers, mobile phones and bicycle etc. The disadvantage of the PEMFC is sometimes in it's low operating temperature, due to which the reactant and the products are in liquid form and there extraction from the porous electrodes is not an easy task also it uses Platinum Catalyst which is very costly and is intolerant to carbon monoxide. Another disadvantage is the lower efficiency, which lies between 40 to 45%.

2.2.2 Direct Alcohol Fuel Cells (DAFC)

This type of fuel is derived from the PEMFC in which liquid methanol and ethanol are used as the fuel instead of hydrogen in gaseous form. The electrolyte used in this type of fuel cell is nafion whereas the catalyst used is the same as that in PEMFC. The advantage is that the external reformer is not required in this type of fuel cell. Hydrogen ion and electrons are produced by oxidizing methanol or ethanol in water. The efficiency is decreased by the crossover of the fuel to the cathode side through the electrolyte which is the main disadvantage of this type of fuel cell. To overcome this issue, an organic molecule Formic Acid (HCOOH) is used as a liquid fuel with PEM electrolyte and by using Direct Formic Acid Fuel Cell the does not pass through or crossover the nafion electrolyte resulting in higher efficiency

2.2.3 Alkaline Fuel Cell (AFC)

They are considered as the earliest fuel cells with practical application being first used by NASA for their space missions. They were used for space exploration on the basis of their high efficiency which could be around 70%. Along with high efficiency, they are operated at low temperature ranging between 70 to 100 °C. The electrolyte in Alkaline Fuel Cells is the aqueous solution of Amonium Hydroxide (KOH). The OH- ions are transported from Cathode with an oxygen from from CO_2 is given to the system. Hydrogen, as fuel, is supplied from anode resulting water as the product at anode. The quick start-up and stop time is the advantage of such a system which is because of their low operating temperature. Whereas, on the other hand the disadvantage with this type of fuel cells is the sensitivity of electrolyte to CO_2 and the alkaline electrolyte gets corroded due to which the life of these fuel cells is very limited.

2.2.4 Direct Borohydride Fuel Cell (DBFC)

This is an alkaline fuel cell type and are fed directly by sodium or potassium borohydride as fuel and air or oxygen or hydrogen peroxide as oxidant. This type of fuel cell is relatively a new type of fuel cell and are currently in the development phase. The operating temperature for DBFC is approximately 70 °C. The advantage of there reason of attraction it's high open circuit potential approximately 1.64 eV [8]. The disadvantage is the usage of sodium borohydride as it is very expensive and the recycling of sodium borohydride is still an intensive research issue.

2.2.5 Phosphoric Acid Fuel Cell (PAFC)

This type of fuel cell operates when hydrogen ion transport from anode to cathode through hot phosphoric acid at approximately 200 °C temperature. Oxygen or air is fed to the system as oxidant. Phosphoric acid fuel cell is operated at high temperature as they do not necessarily need water and this factor of high operating temperature results in many advantages for this particular type of fuel cell, which may include; due to high operating temperature, PAFC is more tolerant to impurities and carbon monoxide impurity of upto 1.5% could easily be tolerated by it, thus reformed hydrocarbons could be used as fuel [12]. At cathode, the hot water exhaust could be used for co-generation of power. It ionic conductivity on the other hand on low temperature is lower the catalyst got poisoned by CO. The electrical efficiency is 40 to 50% and with co-generation it rises up to 85% [13].

2.2.6 Molten Carbonate Fuel Cell (MCFC)

This type of fuel cell is one of the high temperature fuel cells, also the efficiency of this type of fuel cell is high, i.e; 50 to 60%. Different types of fuels could be used in MCFC, with the limitation that those fuel must not have Sulphur as they are highly sensitive to even a tiny amount of sulphur. The molten carbonate is in contact with porous ceramic electrodes in the cell and carbonate ion is the charge carrier. As in every fuel cell, hydrogen as fuel or hydrocarbons are fed at anode whereas the air or oxygen is fed at cathode. In order to supply the electrolyte with carbonate ions, the carbon dioxide is circulated between anode and cathode through the outside duct. This type of fuel cell has also high ionic conductivity like those of Phosphoric Acid Fuel Cells and Alkaline Fuel Cells at the operating temperatures.

Table 2: Fuel Cells Types and Properties

Fuel Cell Type	**Temperature Range**	**Efficiency Range**
Direct Methanol Fuel Cell (DMFC)	50 - 120	25 -40%
Proton Exchange Membrane Fuel Cell (PEMFC)	60 - 100	40 - 50%
Alkaline Fuel Cell (AFC)	90 - 100	50 - 70 %
Phosphoric Acid Fuel Cell (PAFC)	100 - 250	40 - 45%
Molten Carbonate Fuel Cell (MCFC)	600 - 700	50 - 60%
Solid Oxide Fuel Cell (SOFC)	600 - 100	50 - 60%

2.3 Working Principle of Fuel Cells

Fuel cells are an electro-chemical devices that produce electrical energy as a result of the electro-chemical combustion taking place in the fuel. The fuel cell is basically composed of three component, they are;

1. An Electrolyte
2. Anode Electrode
3. Cathode Electrode

The two electronic conducting porous electrodes in the fuel cells, Cathode and Anode, are responsible for the reaction resulting in the generation of electricity and heat. The electrolyte is to resist the flow of electrons between the electrodes and only allowing the flow of ions to pass through and the electrons are forced to flow through the external load. The hydrogen on the anode electrode is ionized to H+ ions and the electrons from the anode electrode are conducted through the load/circuit to the cathode electrode to form oygen ions combining with O_2, that is the reason why an electrolyte to should be very thin so that it could minimize the path for the ions to flow through. It is also very important to know that the electrodes should have large surface area for the maximum reaction rate. The electrodes, along with having large surface area, are suppose to be highly conductive to electrons which will then reduce the ohmic losses. The basic design of fuel cell could be seen in Figure 3.

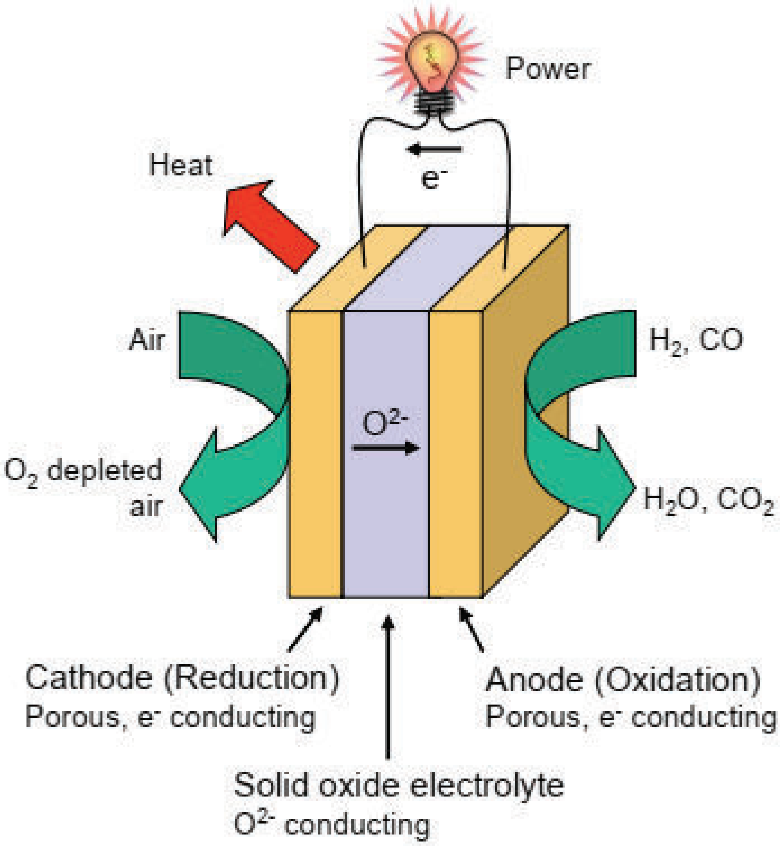

Figure 3: Planer Fuel Cell Design [3]

2.4 Applications of Fuel Cells

The operating temperature in fuel cell, which the electrolyte governs, determines the efficiency, start-up time and dynamic behavior. The efficiency of the fuel cell increases with the increase in temperature as the internal resistance and polarization is decreased with the increase in temperature. The time to reach the optimal operating temperature is the start-up time and it is also dependent on temperature. The dynamic behavior on the other could this way be defined that the change in load leads to the change in temperature this could result in the contraction or expansion thus changing the material in the stack, which result in the mechanical stress effecting the lifetime. This parameter of high efficiency is taken into primary consideration of high importance for large stationary applications whereas the start-up time and dynamic behavior are the parameters of secondary importance. On the other hand the primary parameter for portable applications are short start-up time and high load following dynamics. MCFC or SOFC are the examples of stationary application and PEFC is an example of portable applications. The next important parameter for fuel cell technology is the availability fuel. Hydrogen, by far, is considered to be the best fuel from electro-chemical point of view because hydrogen after reaction gives high power density. But hydrogen usage results in logistic challenges in fuel supply. That is the reason why liquid fuel is preferred. Methanol, among the liquid fuels, does direct electro-chemical reaction at nominal rates but with lower power density than that of hydrogen approximately less 20% of H_2.

2.4.1 Portable Applications of Fuel Cell

Generally, a portable fuel cell is one that could be moved including Auxiliary Power Units (APU). The power range for the portable application of fuel cells is between 25 W to 5 kW [10]. Fuel cells provide power where grid stations are not available and as they make no noise, so they are also used instead of those loud generators which could also be a source of pollution, as the conventional generators could not only make noise but will also emit toxic pollutants which could deteriorate the environment. Along with the aforementioned usage, the portable FCs are also used in emergency for power backup particularly in military operations/applications. Fuel cell are very much light in weight than those of batteries and have long life too.

2.4.2 Consumer Electronic Micro Power

Fuel cells are expected to bring about a revolutionary change in the telecommuting world. Using of fuel cells in powering the laptops, cellular phones etc are expected to run for longer time than batteries. Many companies have experimented claiming that fuel cell supported mobile phones will run for 30 days and laptop for about 20 hours without recharging. Meter readers, hearing aids, smoke detectors and hotel locks etc are the other low power remote devices they could be run and operated through fuel cells. And most importantly, these micro fuel cells are generally run using methanol.

2.4.3 Stationary Applications

By far, over 2500 fuel cells system are estimated to have been installed all around the world. Those include the installation of fuel cells at hospitals, nursing homes, office buildings and utility power plants etc. They could either be connected to the grids to provide supplemental or backup power during critical situations in remote areas or they could be installed as an independent generator for the power services required on site particularly in areas which do not have access to the power lines or power grids.

Utilizing hydrogen, as a fuel, fuel cells have been able to achieve power efficiency over 45 %. They not only are efficient sources of power generation because of them being very silent and also they do not emit pollutants into the environment but the excess heat that fuel cell plants releases could be captured and utilized for any useful work/purpose, e.g; co-generation. By utilizing the excess, the co-generation system for fuel cells could reduce the energy service cost from 20 % to 40 % and an increase in efficiency of up to 80 % [14]. Other application included in the stationary application are; usage of fuel cells in telecommunication sector. These days, the use of computer, internet etc are increasing and they need more reliable power source and fuel cells in this regards are the best option as they are considered to have 99 percent reliability. Fuel cell is a good replacement for batteries as they can provide power from 1 kW to 5 kW at telecom sites that are not easily accessible. Fuel cells power could also be used for both primary and backup power for switch nodes and cell towers.

Fuel cells also have application in transportation sector. Almost all the major automobile manufacturing companies are working on vehicles that could be run on fuel cells. Those vehicles of different companies are either in development phase or in testing phase. Several buses have also be demonstrated on using fuel cells in different parts of the world. It is considered that if the fuel cells operated buses use fossil fuel as a source of fuel, there would be less emission of carbon dioxide, whereas, that emission could be zero if the hydrogen is used as a fuel. Along with these uses fuel cells are utilized in several other things for power generation forklifts and material handling, auxiliary power units, trains and planes etc.

2.5 Solid Oxide Fuel Cell Technology

Solid oxide fuel cells are becoming a promising high temperature fuel cell technology over the last few decades. They are becoming an alternative to the conventional power generation techniques. They are expected to be a very useful technology for large and high power applications which may include full scale industrial stations and large scale power generation stations and motor vehicles etc. SOFC utilizes ceramic material as the solid electrolyte and could operate for temperature conditions between 600 to 1000 °C. High operating temperature in SOFC allows internal reforming and also promotes rapid electro-catalysis with matels and as a result produces heat as a by-product which could be utilized for co-generation.

A ceramic material, zirconia, is what the solid electrolyte of solid oxide fuel cell is made which is a good conductor of oxygen ions or it could be said that it is the solid electrolyte zirconia the due to which it stands different from the other types of fuel cells. Zirconia is, as mentioned above, a good conductor of oxygen ions and in late 1980s Nernst discovered this property of zirconia. With the passage of time, the technology has, though, evolved very much, but still the best electrolyte for solid oxide fuel cells is zirconia. At the temperature over 700 °C the conducting of oxygen ions get started in zirconia, due to the reason, solid oxide fuel cells are considered to be best suited for the purpose of co-generation utilizing the waste heat from the system. The waste heat after being utilized through the bottoming cycle could help in improving the energy conservation efficiences of the complete system more than 60 % [4]. That condition of clean environment is also satisfied for solid oxide fuel cells when it operates in it's temperature ranges as at this temperature, the emission of NO_x will be equal to non or very small.

2.5.1 History of Solid Oxide Fuel Cell

Two Swiss scientists, E.Baur and his colleague H.Preis in late 1930s experimented with Solid Oxide electrolysis and they used zirconium, yttrium, cerium, lanthanum and tungsten oxide.

They, however, achieved the first practical operation of ceramic fuel cell successful at 1000 oC in 1937. In order to increase the mechanical strength and conductivity, a Russian scientist O.K.Davtyan in 1940s added monazite sand to the mixture of sodium carbonate, soda glass and tungsten trioxide for conductivity and mechanical strength increase, his design had the disadvantage of unwanted chemical reactions and short life. The real research on solid oxide technology accelerated in late 1950s in the Netherlands Central Technical Institute in Hague, in Pennsylvania at Consolidation Coal Company and at General Electric in New York. The problems noted in 1959 that solid electrolytes had, which included high internal electrical resistance, melting and short circuiting as a result of semi-conductivity did not disheartened all researchers, rather many continued their effort of establishing high temperature that could be tolerant to CO and would use stable solid electrolyte[7].

The continuous rise in the prices of energy and the materials have even made the researches and companies more enthusiastic for the development of solid oxide fuel cell technology. That could be evident with the fact that more than 40 companies around the world are working on the development of fuel cell technology. Global Thermoelectric Fuel Cell Division is one of the most promising name working on the development of fuel cells designs at Julich Research Institute Germany. Another company, Cermet Advanced Ionic Technologies is working on the development of up to 10 kW capacity cell which is run on diesel fuel. The US Department of Energy (DoE) is also very keen towards the development of Solid Oxide Fuel Cells Technology particularly there area of focus related to the SOFC is the SOFC-micro-turbine co-generation. The fuel cell that was built by Siemens Westinghouse with an operating condition of 220 kW SOFC run and operated on natural gas was observed to have achieved efficiency of 60%. Siemens Westinghouse also operated a 140 kW peak power SOFC co-generation system, working in Netherland operated for over 16,600 hrs, was the longest test run being accomplished by any cell. The Department of Energy US and Siemens Westinghouse operated a SOFC co-generation system of 1 MW successfully.

2.6 Working Principle and Design of SOFCs

There are many aspects they make Solid oxide fuel cells different from other fuel cells. Unlike many other fuel cells, solid oxide fuel cells are composed completely of solid state material, the second aspect that makes Solid Oxide Fuel Cells different from other fuel cells is it's operating temperature. The operating temperature for SOFC is 1000 °C, which is a very high temperature that no other fuel cells can work on. Due to it's composition of solid state material, there is no constraint on the design and configuration of solid oxide fuel cells. There are two main configuration of SOFCs, they are, tubular cells and flat-plates. Tubular cells are also called rolled tubes and there example could be one being made and designed by Westinghouse Electric Corporation in the late 1950s.

SOFC follow the same working principle like every other FC follows. SOFC is an electro chemical reactors that converts the chemical energy of the fuel directly into electricity with the fuel being hydrogen and oxygen as an oxidant. SOFC has got the same physical structure like other fuel cells consisting of two porous electrodes which are separated by an electrolyte. The electrodes in SOFC are anode electrode and cathode electrode. There are also flow channels for fuel and air delivery and collection in the cell.

The operating principle of Fuel Cells or Solid Oxide Fuel Cells follow the same operating technique. The fuel, in preferable conditions, is hydrogen or generally hydrocarbon (i.e; methane and other hydrocarbon chain elements) is supplied to the fuel cell from the anode whereas the air or O_2 on the other hand is supplied to cell through cathode. In a case if the hydrogen used is not pure, H_2 and CO diffuse through porous anode and onto the Three Phase Boundary (TPB) which is made between the anode,the electrolyte and the gaseous H_2. Oxygen, on the other hand, diffuses in the same fashion through the cathode to the TPB where it accepts the electrons and give away oxygen ions, this could further be elaborated through equation given below:

$$\mathrm{O_2 + 4e \rightarrow 2O} \tag{3}$$

These oxygen ions react with the hydrogen after traveling through the porous electrolyte.

$$\mathrm{2H_2 + 2O \rightarrow 4H_2O + 4e} \tag{4}$$

The two electrodes are connected through an external circuit and the electrical current is generated their. If carbon monoxide is present in the stream of H_2, hydrogen and carbon dioxide is generated as a result of the water gas shift reaction between the CO and H_2O. The chemical reaction could shown as;

$$\mathrm{CO{+}H_2O \rightarrow CO_2{+}H_2} \tag{5}$$

2.7 Solid Oxide Fuel Cell Components

Solid oxide fuel cells are composed of two electrodes, cathode and anode electrodes, separated from each other by an electrolyte. Electrodes in the cell are responsible for the reaction between the reactant, fuel and oxygen, and electrolyte and during the course they should not get corroded and this is one of the main advantage of solid oxide fuel cells, also bringing in contact the three phase, i.e; the solid electrolyte, the electrodes and the gaseous fuel. Those electrons released from hydrogen are a source of power through the external circuit.

The cathode electrode, which is the positive post in the fuel cell is supplied with the oxygen or air which it distributes it over its surface equally an d the electrons from the external circuits are conducted and recombine with the oxygen ions. Those ions then passes through the electrolyte and react with the hydrogen to form water.

The most important component of a fuel cell is the electrolyte which is responsible for many functions in the fuel cells including determining the temperature of the fuel cell, preventing the electronic contact of the two electrodes by blocking the electrons. The charged ions are allowed to flow from one electrode to the other through the electrolyte for the overall electrical charge balance. Solid Oxide Fuel Cell is given in the Figure4.

Every component of SOFC serves many functions and need to meet some requirements, which may include the stability of all the chemicals, phase and dimensional stability, all the components should have proper conductivity and they all must have chemical compatibility with each other. To avoid cracking during the operation, all the components must have similar thermal expansion. The electrolyte should be dense so that it could avoid or prevent the gas from mixing and the electrodes, cathode and anode, must be porous so that the gas could flow to the site of reaction. The components in the cell must have high strength and should be tough enough to withstand the working conditions and last but not the least, the cost of the components should be low.

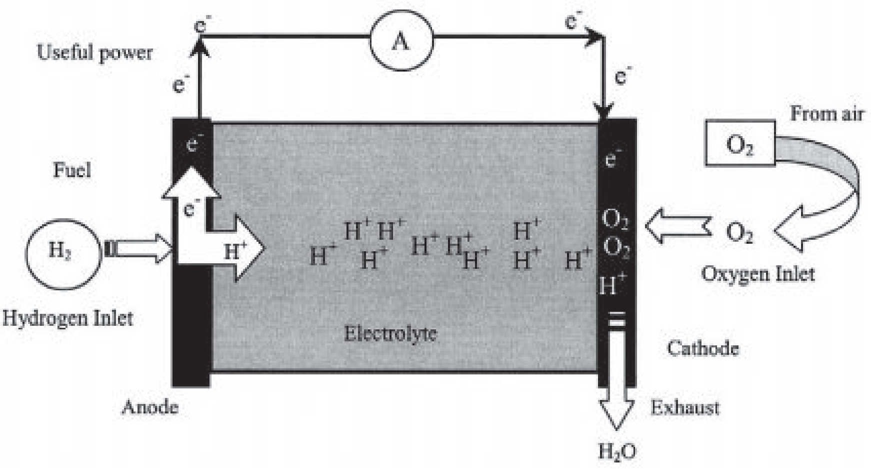

Figure 4: Solid Oxide Fuel Cell [4]

2.8 Solid Oxide Fuel Cells Material

Many companies manufacturing solid oxide fuel cells including Westinghouse Electric Corporation, Fuji Electric, Siemens Westinghouse (previously known as Siemens), and Global Thermo-electric Company are manufacturing SOFC with the assurance to offer long term stability. As it has been mentioned above that the solid oxide fuel cell is composed of three main elements; electrolyte, anode electrode and cathode electrode, we will discuss what are the material of these components one by one.

2.8.1 Electrolyte

Today, several ceramic materials are employed for the current technology for SOFC, and there have been different oxide combination experimented for nonporous solid electrolytes. Of many, the most common and accept one to date is the stabilized zirconia that has the conductivity based on oxygen ion that is, Yttria-Stabilized Zirconia abbreviated as YSZ ($Y_2O_3 - stabilized - ZrO_2$), the chemical formula is; $(ZrO^2)0.92(Y_2O^3)0.08$.

This type of electrolyte contains a very little amount of "yttrium" with a silvery grey metal added with zirconia. One of the reasons of selecting this type or opting this choice is because of it's cost and availability. For every zirconium ion, the zirconia crystalline array has two oxide ions whereas the yttria has only half oxide ions to every yttrium ion, which result in vacant spaces in crystal structure with oxide ions missing and the oxide ions leap hole to hole from cathode till they reach anode. CaO, MgO, Y_2O_3 are the commonly used stabilizing dopants and Nd_2O_3, Sm_2O_3, Yb_2O_3 are some rare earth oxides.

2.8.2 Anode

Due to the reducing conditions of fuel gas, for anode material in SOFC, metal can be used and the metals used should have to be non-oxidized because during the operation of the cell the composition of the fuel changes. Composite powder mixture of different electrolyte material and nickel oxide are used to fabricate the anode for SOFC, those electrolyte composite powder mixture may include YSZ, GDC or SDC[26]. With YSZ electrolyte, NiO/YSZ anode material are best suited for use in SOFC and with Ceria-Based electrolyte material NiO/SDC and NiO/GDC anode material are considered best. For the mass transport of reactant and product gases, the anode structure is fabricated with 20 to 40% porosity.

2.8.3 Cathode

Noble metals or electronic conducting oxide are only used as the cathode material because of the high operating temperature of solid oxide fuel cell. For practical applications, the noble metals are not suitable because they do not offer long term stability and high cost. Experiments are in progress in recommending some new oxides, particularly hetero-metallic oxides, for cathodes and the choice for selecting the electrodes material depends on the chemical design of electrodes, temperature range, ceramic fabrication methods etc. With zirconia electrolytes, lanthanum Calcium Manganite (LCM) with chemical formula $LaCaMnO_3$ and Perovskite type Lanthanum Strontium Manganite (LSM) with chemical formula LaSr MnO_3, offers great thermal expansion and excellent performance above 800°C operating temperature. Like anode, cathode too has porous structure that allows for reactants and products the mass transport.

2.9 SOFC Classification

The Solid Oxide Fuel Cells are broadly classified based on different temperature operating levels, support types, the design of cells and stack, flow patterns and fuel reforming. These classifications are explained below in detail.

2.9.1 Classification of SOFC based on Temperature

The Solid Oxide Fuel Cells have Low Temperature-Solid Oxide Fuel Cell (LT-SOFC), Intermediate Temperature-Solid Oxide Fuel Cell (IT-SOFC) and High Temperature-Solid Oxide Fuel Cell (HT-SOFC) classifications. The low-temperature SOFC has the advantage of low cell component resistivity due to which the ohmic overvoltage or polarization is decreased too. In the IT-SOFC, the kinetics of electrodes increases resulting in the decrease of reaction sluggishness hence the activation overvoltage is decreased and the HT-SOFC has high temperature out at the anode and hence in such case the thermal integration of a bottoming cycle with SOFC is better which results in better efficiency complete plant. There exist some disadvantages too with the HT-SOFC, as they have longer start up and shut down time and also have weak structural integrity, high corrosion rates and very importantly the cost of the material.

2.9.2 Classification of SOFC based on the Type of Support

There are three types of supports according to which SOFCs are manufacture, they are:

1. Anode Supported SOFC
2. Cathode Supported SOFC
3. Electrolyte Supported SOFC

Such types of FCs are also called self-supporting configuration. The Electrolyte supported configuration is selected in high-temperature SOFC as the ionic resistivity of the electrolyte decreases with the increase of temperature. Electrode supported configurations are used in low or intermediate-temperature SOFC as the electrolytes in this case are made very thin.

2.9.3 Classification of SOFC based on the Design of Cell and Stack

Based on cell and stack design, Solid Oxide Fuel Cells could be classified as:

1. Tubular
2. Planar
3. Segmented-in-series, and
4. Monolithic

Among the above mentioned SOFC stack design, the Tubular designs are the most developed and this is because Siemens-Westinghouse has been working on the development of this design for the last several decades. Although the geometric configuration of planar design is very simple, yet they have not been developed very much due to the sealing issues, but it's been recent since many manufacturers have started considering the planar design as the sealing issue of planar SOFC has been resolved due to the SOFC material development and the use of Low-Temperature-SOFC. The new design, segmented-in-series SOFC, is the combination of both the tubular and planar SOFC design and this classification of SOFC has the advantage of having the freedom of thermal expansion like that of tubular SOFC and the cost of the component fabrication is low like the planar SOFC. The monolithic SOFC has the power density higher than any other design yet they are not made anymore because the fabrication of this design is a difficult task.

2.9.4 Classification of SOFC based on Flow Configuration

The flow of fuel in FC for electrochemical reaction may be either co-flow, cross-flow or counter-flow. The flow pattern or configuration have very important effect on the distribution of temperature in the stack. Co-flow configuration is considered good for uniform temperature distribution in the cell or stack.

2.9.5 Classification of SOFC based on Fuel Reforming

For electrochemical reaction in SOFC, a fuel used other then H_2 or CO should be reformed to H_2 or CO and this process of reforming can take place both inside and outside the stack. The reforming that takes out the stack is called the external reforming and internal reforming is when the reforming takes place inside the stack. The internal reforming is divided into two types,

1. Indirect Internal Reforming (IIR-SOFC)
2. Direct Internal Reforming (DIR-SOFC)

The reformer in the IIR-SOFC is separate from the other components yet in close thermal contact with anode section whereas the reforming in the DIR-SOFC takes place on the anode catalyst.

2.10 SOFC Stack Configuration and Geometry

Solid oxide fuel cells exist in many forms and can be connected in array to form a stack. Since a single fuel cell is small in size and can only generate DC electricity of voltage between 0.5 to 0.9 V that is why for more power generation the cells are combined in series. Following are the main types of SOFC:

1. Tubular SOFC Configuration
2. Radial Planar SOFC Configuration
3. Planar Flat-Plate SOFC Configuration

The tubular configuration consists of meter long tubes which operates in such a manner that the fuel is on the outer side of the tubes with the oxidant inside and the the electrolyte and electrodes in the tube makes a sandwich in such a manner that the air or oxidant electrodes is inside with electrolyte in the middle and fuel electrode on the outer-side as shown in the figure5. The other type of SOFC is the radial planar, as shown in figure 6 which is like the shape of a disc in which the reactant gases diffuse from the center to the disk periphery and through the micro-structure porous of electrodes as shown in figure.

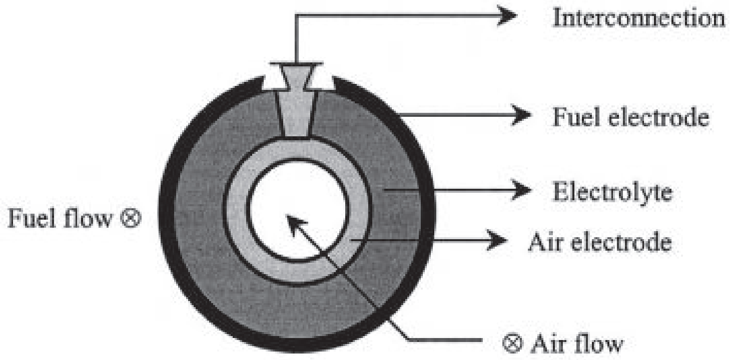

Figure 5: Tubular Solid Oxide Fuel Cell [4]

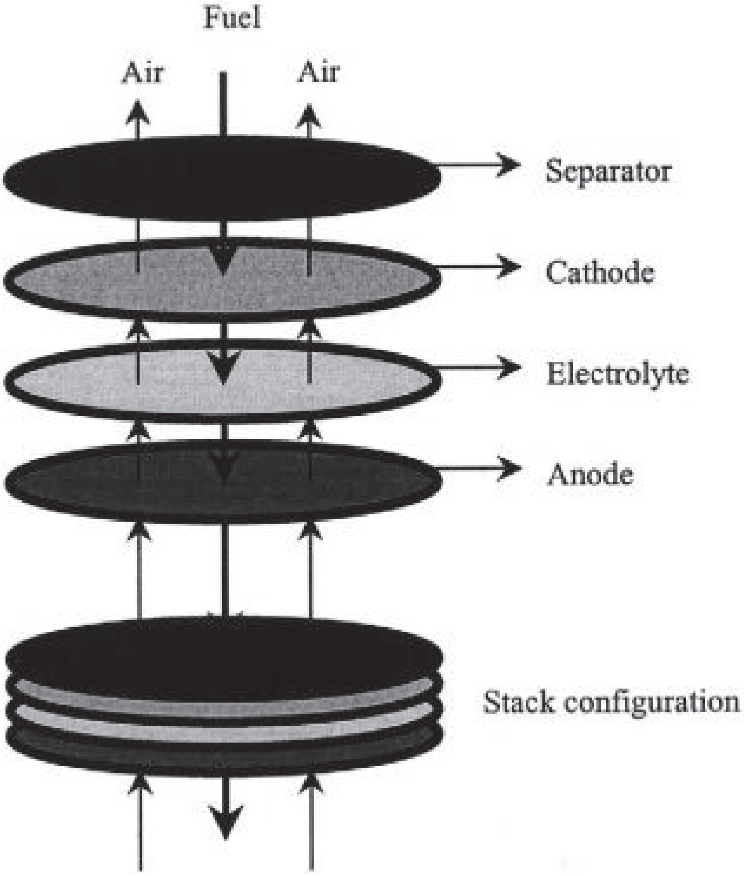

Figure 6: Radial Planar SOFC [4]

The third type of fuel cell mentioned here, planar flat-plate SOFC, was first established by

Siemens and Fuji Electric. This type of SOFC is, as the name indicates, flat-plates as shown in figure 7 are made in such a manner that plates are placed one over the other to make or form a stack. During the working, each of the electrodes face is open for the reactant gases, with oxygen entering through the cathode compartment, adsorbed through the cathode and is diffused to the cathode electrode-electrolyte interface reduces by gaining electrons by the incoming charge electrons whereas the fuel, commonly hydrogen, enter through the anode compartment and is adsorbed through the anode and diffused at the anode electrode-electrolyte interface. Tubular SOFC and Planar Flate-plate SOFC configurations are the two common types of solid oxide fuel cell configuration commonly used these days. For any particular or specific amount of power generation, all the elements are assembled in multi-layered sandwich in a stack which includes an interconnecting plates (that connect anode of one cell to cathode of another cell), anode, cathode and electrolyte. The interconnecting plates are commonly made of doped Lanthanum Chromite ($LaCrO_3$), which is suitable for high conductivity, compatibility and stability in fuel cell environment with the other parts or components of the stack. The design and shape of the interconnecting plates are so that they allow the flow of fuel and oxygen or air in the hierarchy. Low cost stainless steel interconnect material are not recommend because they have the problem of long term instability and mismatch with the other components of SOFC particularly the thermal expansion.

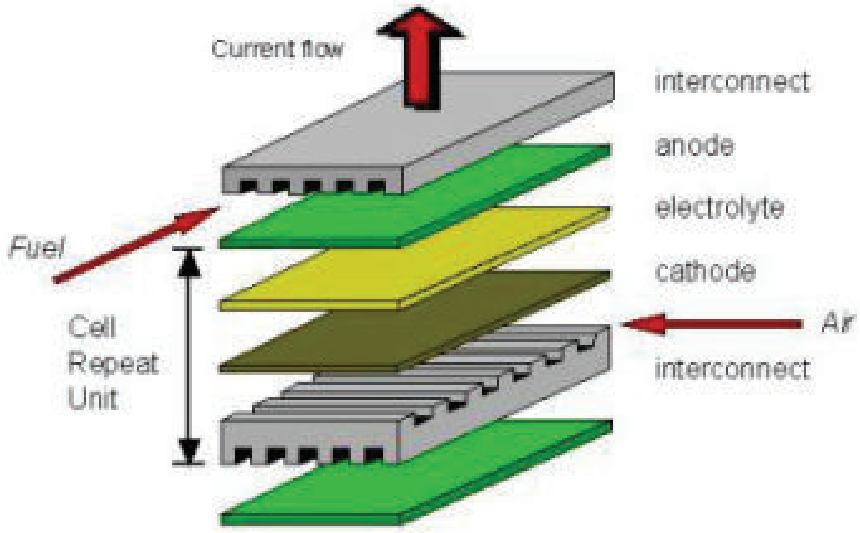

Figure 7: Planar SOFC Cell Design [4]

Rolls Royce has designed and used an integrated planar SOFC in which both planar and tubular solid oxide fuel cells were used. This particular types of SOFC consisted of an assembly of planar solid oxide fuel cell which is fabricated in a ceramic housing that provides manifold for the fuel gas and also there are no separate bipolar plates instead the interconnects are fabricated itself on the cell housing.

In an SOFC stack for the required output voltage the cells are connected in series or commonly known as electrical series with configuration of being in either single unit, series, parallel or series-parallel primarily depending on the type of any respective application. The total voltage could be determine by the number of fuel cells in stack and each cell's surface then gives the total current. During the electrochemical reaction, the unconsumed fuel in SOFC react with the oxygen in the environment as soon as they come in contact with each other, resulting in the generation of heat which could be used to keep the temperature of the stack at desired level. Of all the types of SOFC stack designs mentioned and discussed above, planar flat-plate SOFC stack is most commonly used around the world, because they are relatively easy to manufacture and also they have lower ohmic resistance of electrolyte which is helpful in avoiding energy losses.

2.11 SOFC Hybrid Systems

The performance efficiencies of conventional Solid Oxide Fuel Cell supported power plants could be enhanced significantly if a gas turbine is connected to the system for waste heat recovery. The United States department of energy (DOE) at National Energy Technology Laboratory (NETL) in Morgantown, developed and investigated SOFC-GT hybrid systems facility which simulates SOFC coupled with GT in an hybrid system. The hybrid SOFC-GT system offers a significant increase in efficiency with considerable amount of decrease in emissions and also the natural resource management with respect to generating power improves too.

Both Solid Oxide Fuel Cells and Molter Carbonate Fuel Cells (MCFC) are high temperature operating fuel cells and due to their high operating temperatures, they share some advantages while being operated, which may include: To generate extra power from the elevated temperature exhaust, SOFC can incorporate bottoming cycle for waste heat recovery. Due to high operating temperature, SOFC also has the ability of hydrocarbon reforming. This capability of operating at high temperature make SOFC capable of operating at various fuel types. The high operating temperature of SOFC is most suitable for hybrid system particularly for distributed generation. The fuel cell hybrid system have classified as type-1 and type-2 system wherein, the first type is considered to be suitable for combined power generation and backup power generating system. SOFC-GT is a good example of type-1 hybrid system in which the flue gas from the SOFC is expanded in GT to further increase the electrical power output and performance efficiency of the complete system. Further more, the example of hybrid system type-2 are the combination of FC with solar power generation or wind power generation system, Rajashekara [15].

According to Winker et al [16] combination of FC and heat engine is FC hybrid system. The FC off-gas heat energy, in these configurations, could be used to generate extra power in the heat engines. Thus, the combination of a FC or more specifically SOFC with GT or ST or combination of GT and ST combined cycle, integrated gasification plant operated by either coal or any other fuel, transcritical carbon dioxide cycle (TRCC) etc are all hybrid combined heat and power (CHP) systems.

Dicks et al. [5] explained the basic working principle of how a solid oxide fuel cell converts chemical energy of a fuel directly to electrical energy and explained that an electrical efficiency of 55% can be achieved from SOFC. Apart from the sufficient energy efficiency as the operating temperature for SOFC is high, the efficiency of the overall system could further be increased up to 70% from a power range over 100 kW to a few MW by adding gas turbine (GT) to the system. Meng et al. [17] analyzed the thermodynamic behviour of combined power SOFC/GT with transcritical carbon dioxide cycle TRCC. The basic purpose of their research work was to propose They developed a mathematical model to analyze the performance of the system in accordance with the laws of thermodynamics. Like other combined power generation systems, TRCC is also considered a system of great significance in converting waste heat into useful power. From their research work, they concluded that the overall system efficiencies of upto 69.36% could be achieved which could be enhanced even more if the compressor pressure ratio is increased, further more, it was also concluded that the overall electrical efficiencies of the system decrease with the increase in the air or fuel flow rate as more power is consumed by the compressor for increase air or fuel flow rates.

Cheddie et al.[18] studied and proposed fossil fueled SOFC integrated with Gas Turbine power plant. The gas turbine has the power generating efficiency of 30% but after integrating the SOFC, the hybrid system had the efficiency increased to 66.2%.

Facchinetti et al. [19] studied and analyzed the design of Solid Oxide Fuel cell/gas turbine (SOFC-GT) hybrid system which according to their study could be considered for its application in residential buildings. Saisirirat [20] developed and implemented SOFC-GT hybrid system model in MATLAB and found that the fuel cell performance is an important function of operating temperature of the system which depends on the preheating of input stream. According to the auther, the factors that limit the performance of the cycle include the SOFC temperature, turbine inlet temperature and the exhaust temperature.

Arsalis [21] in his work used tubular fuel cell model Siemens-Westinghouse SOFC, in which he integrated steam turbine (ST) with gas turbine (GT) as a heat recovery steam generator (HRSG) for additional power output. The thermodynamic analysis results showed that higher electrical efficiencies of 73.8% could be achieved by using such an SOFC/GT/ST cycle.

Wang et al. [22] studied the performance of an integrated system bases on Solid Oxide Fuel Cell (SOFC), GT and KC. Their study shows that the overall electrical and exergy efficiency could reach to about 70% and 67% respectively under the stated conditions. They further concluded that the electrical efficiency of SOFC and overall system and exergy efficiency could further be improved by increasing the air flow rate.

Akkaya et al. [23] developed and analyzed the exergetic performance thermodynamic model of Combine Heat and Power (CHP) based on SOFC with GT under steady state operating conditions. The authors in their work investigated the variations of all exergetic performances which includes exergetic performance coefficient (EPC) a new criteria which is the ratio of total exergy output to the loss rate of availability, the exergy efficiency, the total exergy output and exergy loss for the main design of SOFC/GT CHP system by analyzing the parameters of the systems, such as, fuel utilization factor, current density, air compressor pressure ratio, recuperator effectiveness and minimum temperature difference. It was concluded from the analysis that SOFC/GT CHP systems on maximum EPC will have least entropy generation rate for given total exergy output, that is, the lowest value of the exergy losses is 151.6 kW and the highest value for the total exergy is 248.9 kW.

Akkaya and Sahin [24] presented a study by analyzing the exergetic performance of a combined power generation system which consists of SOFC and ORC by developing a mathematical model under steady state conditions. In that study the model was used to determine the effects due to the changes in the design parameters on the energetic performance of the SOFC and ORC combined system. The changed design parameters which were studied include turbine inlet pressure, condenser temperature for ORC and fuel utilization, current density, compressor pressure ratio and operating temperature of SOFC. The results of their work show that the efficiency of the system was 14 to 25% increased by recovering the waste heat of SOFC through ORC. They also concluded that with the increase in the ORC turbine inlet pressure, the electrical power and efficiency of the combined system increases too and it was also observed and concluded that the electrical power and efficiency of the system enhances with the increase of cell temperature.

Yan et al. [25] studied the thermodynamic analysis of SOFC-GT-ORC with LNG as heat sink to recover the cryogenic energy of LNG. They developed a mathematical model to simulate the new integrated power system under steady state conditions. A parametric analysis was also conducted in order to examine the effects of thermodynamic parameters on the performance of system. From there mathematical modelling and sensitive analysis of thermodynamic parameters, they concluded that the overall efficiency of the system can reach to 67.38%. It was also concluded that by increasing the flow rate of fuel, the net power output could also be increased but this could have negative effect on the electrical efficiency of both SOFC and the overall system. But this effected electrical efficiency of SOFC and the complete plant could be improved by increasing the compressor pressure ratio. The power output with ORC as the bottoming to SOFC-GT was observed to be higher than that of Kalina cycle by utilizing the cryogenic energy of LNG. It was also observed that by increasing the air flow rate or steam to carbon ratio the net power output, the electrical efficiency and the overall electrical efficiency will be affected negatively.

Mitsubishi Heavy Industries (MHI) [26] is considered to be one of the first companies that studied the potentials of SOFC for large scale power generation systems and has been working on the system development since 1980s. In a joint project with New Energy and Industrial Technology Development Organization (NEDO), MHI has been working since 2004 on the production and operation of 200 kW on Solid Oxide Fuel Cell-Micro Gas Turbine (SOFC-MGT) and since then the company is promoting the practical application of SOFC technology and has successfully installed a 200 kW hybrid system featuring SOFC-GT technology in Japan in 2006. MHI is currently working to develop a triple combined cycle system (which integrates a utility GT and SOFC having an SOFC working pressure of 1-2 MPa) Integrating Gas Turbine Combined Cycle (IGTCC) with SOFC particularly for practical use with Tohoku Electric Power Co. Inc.

For the development of SOFC-MGT combined cycle system, MHI with NEDO manufactured a 200 kW which conducted a performance test in 2007 and demonstrated the then highest world's highest class gross power output of 229 kW-AC (with SOFC 204 kW/AC and MGT 41 kW/AC) with a power efficiency of 52.1% lower heating value (LHV) at the operating point of net power out of 204 kW-AC. The MHI-SOFC is on the way to commercialization as a power generation system and is developing 50 kW type and a 100 kW unit in the tubular type modules. MHI is currently working on the development of 250 kW SOFC-MGT hybrid system which is in trial phase.

Siemens Westinghouse [27] has been working and established the best known tubular solid oxide fuel cell by far. They have established a 250 kW solid oxide fuel cell with combined heat and power (SOFC-CHP) system operating at Kinetrics Inc. Facility, Toronto, Canada with an electrical efficiency between 40 to 50% and they are also expecting that this could be the commercial product of its type of Siemens-Westinghouse. Siemens-Westinghouse operated successfully SOFC-CHP system of 100 kW fed with the natural gas for 29,000 hours with an efficiency of 46%.

2.12 SOFC Benefits and Limitations

Solid oxide fuel cells gives high efficiency, higher power density, and there design are simple than those of the liquid electrolytes fuel cells. The activation polarization of SOFC is reduced due to the high operating temperature in the cell as the high operating temperature of the cell results in high reactant activity and this consequently facilitate fast electrodes kinetics, i.e; large exchange currents. This high operating temperature is advantageous in way that platinum electro-catalysts are not required due to which the electrodes do not get poisoned by CO, and as a result carbon monoxide could be used as potential fuel for the cell. Performance problems are not related to activation polarization because the operating temperature of the stack or cell is very high however the performance issues are related to the ohmic polarization because of the charge transport across and through the interface of the components. Other advantages of SOFCs may include; energy security, i.e; it reduces the overall oil consumption resulting in cut on the oil imports. The operational and maintenance cost of SOFCs are very low, it produces power continuously and it could be operated at a variety of oil/fuels.

Solid oxide fuel cells offer great fuel efficiency while operating at 1000°C temperature, but this high temperature at the same time lower down the lifetime of the cell which then ultimately increase the cost of the materials because both alloys used for cells housing and ceramics for interconnections are very costly and the operating temperature between 600-1000°C for SOFC needs high start-up time. However, the lower operating temperature decreases the cost of SOFC. Which clearly indicates that using low temperature or reducing the operating temperature least priced or cheaper component for both interconnections and structural composition will be used, stainless steel is a good example. Though the fuel efficiency will somehow be effected while operating at lower temperature however the overall performance and efficiency of the system still remain great. Also lower operating temperature will result in the lower thermal stresses for the active ceramic structures which will result in an increase in the lifetime of the system and this will allow the use of cheaper interconnect material, e.g; Ferritic steels, which will not have protective $LaCrO_3$ coating.

3 Modeling of SOFC-GT System

First fundamental thermodynamic principle of the overall process are reviewed here. Lets assume that only expansion is taking place with no shaft work is extracted, we will have to consider the following thermodynamic identity for a reversible process;

$$dG = VdP - SdT \tag{6}$$

where G is Gibbs free energy, V is the volume in m^3, P is pressure in bar, S is entropy and T is the temperature in K. For isothermal process the above equation will becomes:

$$dG = VdP \tag{7}$$

as we know the ideal gas relation;

$$PV = nRT \tag{8}$$

Where n is number of moles of gas and R is Universal gas constant and the value of R is 8.314 $J/Kmol$. Using equation (7) in equation (8), we will have;

$$dG = nRTln\frac{dP}{P} \tag{9}$$

by integrating equation 6 from state 1 to 2 and state 1 is replaced by a standard state with G_o and P_o as the standard Gibbs free energy and standard pressure. For and state ”i” the Gibbs free energy could be:

$$g_i = g_o + RTln\frac{P_i}{P_o} \tag{10}$$

Now, lets assume a chemical reaction, a reaction that takes place at constant Temperature and Pressure,

$$\mathrm{aA + bB \rightarrow mM + nN} \tag{11}$$

The coefficient a, b, m and n are the Stoichiometric coefficient for the reactants A and B and products M and N respectively. Using these coefficient with their respective reactant and products in equation (8), we get;

$$\Delta G = \Delta G_o + RTln\frac{pM_m pN_n}{pA_a pB_b} \tag{12}$$

ΔG_o is the standard Gibbs Free energy change for reaction:

$$\Delta G_o = mgM^o + ngN^o - agA^o - bgB^o \tag{13}$$

For any respective reaction in SOFC the Gibbs free energy change for that reaction could be determined by the equation (10). The part that one has to be interested is to know how the energy change could be related to the work the system performs. In order to find this relation, we consider a thermodynamic identity (i.e; $dQ = TdS$) for a reversible process;

$$dG = \delta W + PdV + VdP - SdT \tag{14}$$

equation (14) will change at constant temperature and pressure to:

$$dG = \delta W + PdV \tag{15}$$

Since there is no expansion in the cell, therefore, the change in volume will also be neglected leaving equation (15) as;

$$dG = \delta W_e \tag{16}$$

Equation (16) shows the relationship between the Gibbs free energy change and maximum electro-chemical work, which can be extracted from the reaction of the reactants A and B resulting in the product M and N under the given conditions of constant pressure and temperature having the reaction being reversible.
Next the electro-chemical work is derived, i.e; the maximum electro-chemical work related to the Electromotive Force (EMF) of the cell. This EMF which is produced due to half cell reaction tends to move the electrons towards the cathode from anode in a cell. Now, assuming that if n_e is the mole or number of electrons moving from anode to cathode per unit time and E is the EMF of the cell, the extracted power is EMF times the current, given as;

$$W_e = n_e F E \tag{17}$$

F is Faraday Constant which is the total charge of 1 mole of electrons participating in the reaction and its value is 96485 C/g mole electrons. By combining the equations (16) and (17), we will get;

$$\Delta G = -n_e F E \tag{18}$$

ΔG is Gibbs free energy change whose value for the global equation is calculated as -237kJ/ mol, n_e is the number of moles of electrons participating in the reaction, which are 2 for fuel and 4 for air or O_2, E is reversible potential which is 1.229 V for the chemical reaction given in equation.
For a fuel cell reaction, the enthalpy change Δ H indicates that at constant the entire heat is released by the reaction. For Δ H, the fuel cell potential is defined as thermo-neutral potential, E_t given by the following equation

$$\Delta H = -nFE_t \tag{19}$$

Using equation (18) in equation (19) we get Nernst Equation,

$$E = E_o - \frac{RT}{n_e F} ln \frac{P_M^m * P_N^n}{P_A^a * P_B^b} \tag{20}$$

Lets take an example of the global equation. The reaction occurring in SOFC is,

$$\mathrm{H_2} + \tfrac{1}{2}\mathrm{O_2} \rightarrow \mathrm{H_2O} \tag{21}$$

The reversible cell potential for the above reaction can be written as;

$$E = E_o - \frac{RT}{2F} ln \frac{P_{H2O}}{P_{H2} P_{O2}^{\frac{1}{2}}} \tag{22}$$

3.1 Electrochemical Principle

Open Circuit Voltage (OCV) which is the maximum theoretical voltage E can be measured when there is no current in the circuit. It is also important to note that the maximum OCV can be achieved by the high concentration of the reactants [28]. Though the maximum OCV could be achieved from the equation (18) however this could not be fuel cell's operating voltage. Due to the losses associated with the production of the current, the OCV is always greater than the operating voltage. The electrochemical reactions taking place in fuel cell determine the performance of a respective fuel cell. The electrochemical reaction occurs in different mannar for different types of fuels and both the fuel and reactions varies for all types of fuel cells. An SOFC that is operated with pure hydrogen as a fuel and air, the electrochemical reactions considered are:

$$\mathrm{O_2 + 4e\cdot \rightarrow 2O_2} \tag{23}$$

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

This gives us the following global reaction

$$\mathrm{H_2 + \tfrac{1}{2}O_2 \rightarrow H_2O} \tag{25}$$

The voltage of the cell is calculated by:

$$V_{sofc} = E - V_{loss} \tag{26}$$

V_{loss} is the sum of the three overvoltages which includes activation, concentration and ohmic overvoltage.

$$V_{loss} = \eta_{act} + \eta_{conc} + \eta_{ohm} \tag{27}$$

The reversible cell voltage or open circuit voltage can be calculated from the Nernst's Equation:

$$E = E_o - \frac{RT}{2F} ln \frac{P_{H2O}}{P_{H2}P_{O2\frac{1}{2}}} \tag{28}$$

R is the universal gas constant and it's value is 8.314 J/mol.K, and p is the partial pressure of the species participating in the reactions taking place in the fuel cell.

$$E_o = -\frac{\Delta G_o}{2F} \tag{29}$$

The energy balance for SOFC gas streams between the electrodes (Anode and Cathode) and material of fuel cell can be determined by using the general equation for energy conservation;

$$\frac{dT}{dt} = \frac{1}{mC_{psofc}}(E_{in} - E_{out}) + Q_{sofc} \tag{30}$$

Whereas:

$$E_{in} = (E_{in,fuel} + E_{in,air})T \tag{31}$$

$$E_{out} = (E_{out,fuel} + E_{out,air})T \tag{32}$$

The energy that is not converted to electrical power due to the Lower Heating Value (LHV) of hydrogen generates heat in the fuel cell stack which is given as:

$$Q_{sofc} = \frac{(1 - \eta_{sofc})P_{sofc}}{\eta_{sofc}} \tag{33}$$

η_{sofc} is Efficiency of SOFC,P_{sofc} is the Electrical Power of SOFC. The Electrical Power of SOFC can be determined by using the equation:

$$P_{sofc} = I * V \tag{34}$$

I is the Stack Current and V is the Stack Voltage.

3.2 Voltage Losses

Three main types of voltage losses or which could also be called as polarization are there;

1. Activation over-voltage
2. Concentration over-voltage
3. Ohmic over-voltage

3.2.1 Activation Polarization

At the electrodes, the energy intensive activities that make or break the chemical bonds is what an activation polarization is associated with. The oxygen coming from the cathode side enters into the reaction site and form oxygen ions after extracting electrons from the catalyst. These ions formed make a bond with catalyst surface while the electrons wait for another oxygen molecule comes and start reacting with catalyst and break the bond with the ion. The same scenario is at anode, the hydrogen fuel is broken into components by the catalyst where it form water reacting with oxygen ions with the electrons released at anode. The overall energy of the cell reduces because the energy or amount of energy required for the breaking and forming chemical bonds comes from the fuel. For high reaction rates or high current density, the flow rate of fuel must also be increased which will also increase the kinetics and thus less energy will be needed to break the bonds. The activation over-voltage is the resistance to charge transfer and it is losses at lower current densities. The factors which can lower the activation polarization includes; Increase in temperature, electrodes active area, electrodes activity using suitable catalyst [29].

$$\eta_{act} = \frac{RT}{\alpha nF} ln \frac{i}{i_o} \tag{35}$$

α is electron transfer coefficient, (0-1), n is the number of electrons participating in the reaction, i is Current Density $[A/cm^2]$ and i_o is Exchange Current Density $[A/cm^2]$

3.2.2 Ohmic Polarization

In solid electrolytes ohmic polarization occurs due to the flow of ions and in electrodes and metallic interconnects it occurs due to the flow of electrons. In electrodes it is caused by the electrical resistance of electrodes and in electrolytes it is caused by the transport of ions. This polarization could be reduced using three techniques or methods, use of high conductivity electrodes, designing and using appropriate interconnect material and using thin electrolyte could be useful in reducing ohmic polarization[29]. This polarization could be calculated using the following expression;

$$\eta_{ohm} = i * R_{eff} \tag{36}$$

where R_{eff} is the effective ohmic resistance and i is the stack current. The ohmic resistance is the function of stack temperature and can be determined by the following formula. The value of R_{eff} is 1.7E-05
The Ohmic polarization or overvoltage can by also be determined using the equation,

$$\eta_{ohm} = I * R_{ohm} \tag{37}$$

R_{ohm} in the above equation is the ohmic resistance and I is the stack current. The ohmic resistance is the function of stack temperature and can be determined using the following equation.

$$R_{ohm} = \Sigma\delta_n * A_n * exp(B_n * T^-1) \tag{38}$$

Where T is the temperature of Fuel Cell stack and $A_n.exp(B_n.T^-1)$ is the resistivity of the corresponding material and A and B are Ohmic loss constant parameters whose values are given in the 3

Table 3: Ohmic Loss Constant

Components	**A(ω - m)**	**B(m)**
Electrolyte	2.9E-5	1.05E+4
Interconnects	1.20E-3	4.69E+3

3.2.3 Concentration Polarization

Also known as diffusion polarization. The restriction in the transport of gases to the reaction sites causes this polarization. High current densities are what results in causing this polarization because at the reaction site the rate of hydrogen consumption is higher than diffusion. When the hydrogen is less at the reaction sites, this will effectively reduces the activity of the electrodes which leads to the loss in output voltage. Concentration polarization reduces the electrochemical potential because to drive the electrochemical reaction in required and desired forward direction energy is needed, the reduction of oxygen at cathode and fuel gas oxidation at anode is how this polarization occurs.

$$\eta_{conc} \equiv \frac{RT}{nT} ln[1 - \frac{i}{i_L}] \tag{39}$$

i_L is limiting current.

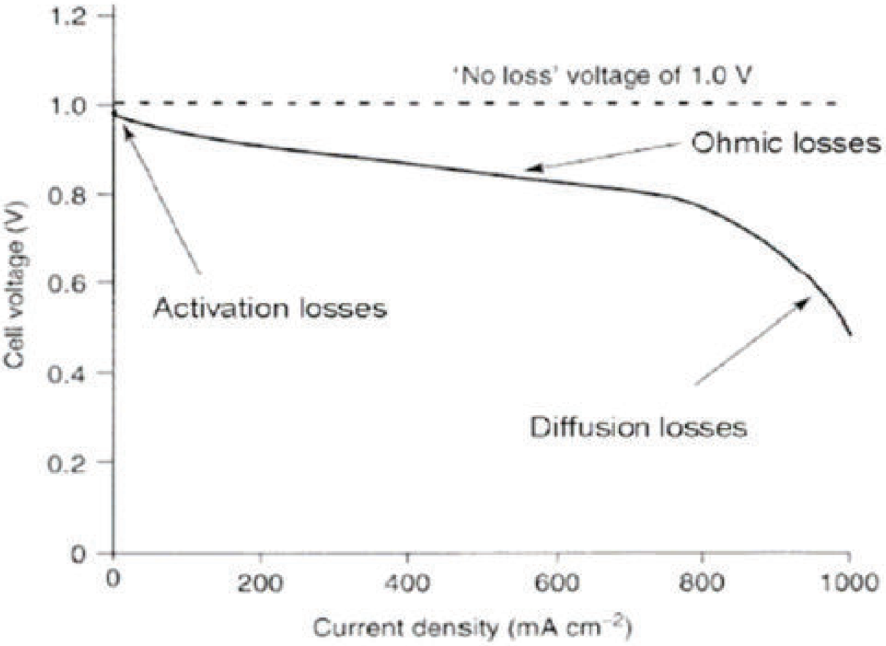

Figure 8: SOFC Polarization Curve [5]

3.3 The Bottoming Cycle

From a fuel cell, the maximum work extracted is equal to the change in Gibbs Free Energy for a reaction that occurs in a cell. Figure 9 shows that the efficiency of SOFC combined with heat engines or GT increases with the increase in temperature and it also shows that efficiency of combined cycle is greater than their efficiencies when they are operated independently. Thus it can be incurred that the efficiencies of hybrid system offer great potentials.

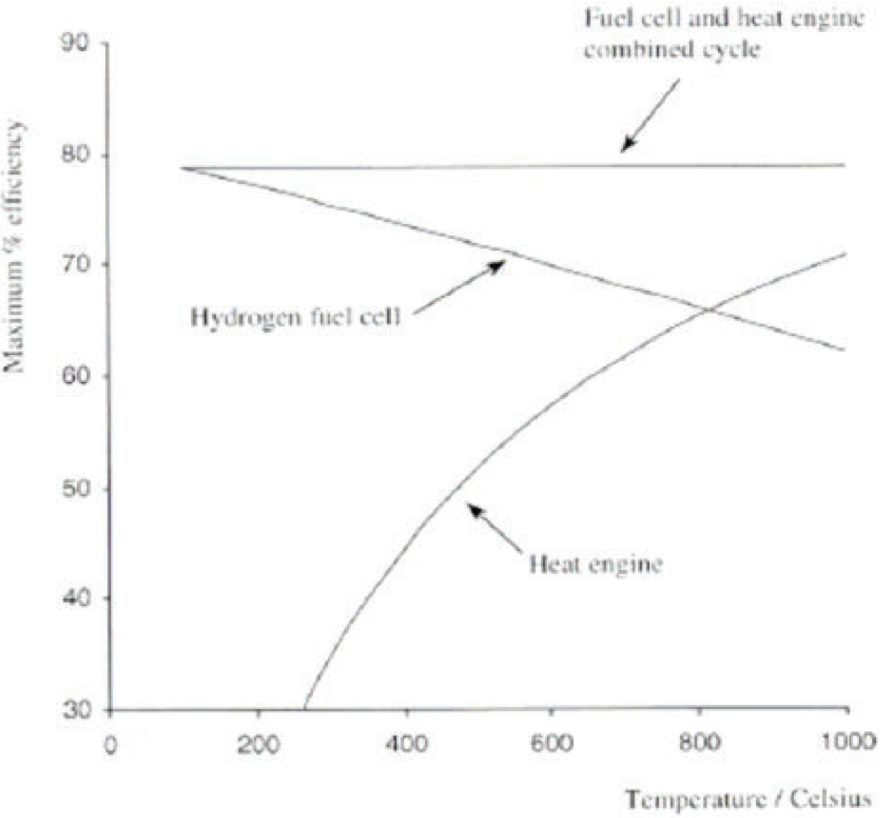

Figure 9: Efficiency of Heat Engine, Fuel Cell and Combined Cycle [5]

3.3.1 Compressor

Ambient air is compressed and supplied to SOFC through the heat exchanger in an hybrid system. The compressor used here is based on the ideal gas equation and polytropic transformation. Air flow rate and pressure ratio are the required inputs. Exit stream temperature, the required power to drive the compressor and efficiency are the outputs. The compressor process is assumed to polytropic, the polytropic transformation can be determined the following equation:

$$Tv^{\gamma-1} = P^{\frac{1}{\gamma}}.v \tag{40}$$

T, P and v are the absolute temperature, pressure and volume respectively and γ is polytropic coefficient. The compressor exit temperature can be calculated using:

$$T_e = T_i\frac{P_e}{P_i}^{\frac{\gamma_a-1}{\gamma_a\eta_C}} \tag{41}$$

P_i and P_e are the inlet and outlet pressure of compressor, T_i and T_e are the inlet and outlet temperature of compressor, γ_a is the specific heat capacity ratio and η_C is the efficiency of compressor. we can determine the mechanical power consumed by operating the compressor by knowing the mass flow rate, m_{air}

$$W_c = m_{air} * \Delta H_c \tag{42}$$

when the exit temperature of the air stream is known, the change in enthalpy can be calculated by the following equation:

$$\Delta H_c = C_P * T_i \frac{P_e^{\frac{\gamma_a - 1}{\gamma_a \eta_C}}}{P_i} - 1 \tag{43}$$

with the known temperature, the efficiency of the compressor can be calculated using the equation given below:

$$\eta_c = \frac{\frac{P_e}{P_i}^{\frac{\gamma_a - 1}{\gamma_a}} - 1}{\frac{P_e}{P_i}^{\frac{\gamma_a - 1}{\gamma_a \eta_C}} - 1} \tag{44}$$

3.3.2 Gas Turbine

Brayton cycle is followed by the gas turbine cycle and is series of compression, combustion and expansion. The cycle consist of a Compressor, a combustor and a Gas Turbine as the principle components of the cycle. It is also important to note that the system or cycle is does not necessarily consist of only those three component and might consist of more than one compressor and turbine. The basic working principle followed here is, the ambient air is compressed and sent to the combustor. Constant pressure combustion takes place in the combustor and the exhaust combusted gas or steam is sent to the turbine where this high pressure exhaust drive the compressor and generator generating power. It is also pertinent to mention that heat exchanger is also used as part of the whole system which is used to preheat the stream that enters the combustor. Power production ranging from few kilowatts to several megawatts are generally produced from the gas turbine with an electrical efficiency of upto 40 % can be achieved.

Gas turbine could directly or indirectly be connected to Solid Oxide Fuel Cell. The combustor, in an indirect integration of gas turbine with SOFC, is replaced with heat exchanger which heated the air coming from the compressor by either the fuel cell exhaust or the exhaust of turbine itself and the SOFC can thus operate under atmospheric condition.

The turbine is modeled in the same manner as that of compressor. The turbine power output and efficiency could be determined by giving the expansion ratio, the inlet temperature of the turbine, and polytropic efficiency. The exhaust temperature could be determined using the following equation;

$$T_e = T_i \frac{P_e^{\frac{\gamma_g \eta_T}{\gamma_g}}}{P_i} \tag{45}$$

Where T_e and T_i are the exhaust and inlet temperature of turbine calculated in K, P_e and P_i are exhaust and inlet pressures respectively of turbine in bar.

The mechanical power output of the gas turbine can be determined using the following expression:

$$W_T = m_g \Delta H_T \tag{46}$$

Where, m_g is the mass flow rate of the gas through turbine. Δh_T is the enthalpy change for the turbine which could be calculated using the following equation

$$\Delta H_T = C_p * T_i \frac{P_e}{P_i}^{\frac{\gamma_g \eta_T}{\gamma_g}} - 1 \tag{47}$$

The efficiency of the turbine can be calculated using,

$$\eta_T = \frac{1 - \frac{P_e}{P_i}^{\frac{\gamma_g - 1}{\eta_T}} \gamma_g}{1 - \frac{P_e}{P_i}^{\frac{\gamma_g - 1}{\gamma_g}}} \tag{48}$$

The net mechanical power produced can be calculated by the equation given below,

$$W_{net} = W_T - W_C \tag{49}$$

3.4 Heat Exchanger

They are used to preheat the air stream and fuel in an hybrid systems using the hot exhausts. They play a role of an important component to fuel cell systems. Heat recovery and rejection is provided by heat exchanger when needed. The placement of heat exchangers in high temperature fuel cell is important for thermal stability and that also helps in improving the over all efficiency of the system. There are two configurations of heat exchangers, parallel flow and counter flow heat exchangers.

3.4.1 Parallel Flow Heat Exchanger

The profiles of temperature of both the hot and cold streams could be seen in the given figure for parallel heat exchanger.10 and 11 show the parallel flow heat exchanger configuration and temperature for both hot and cold streams.

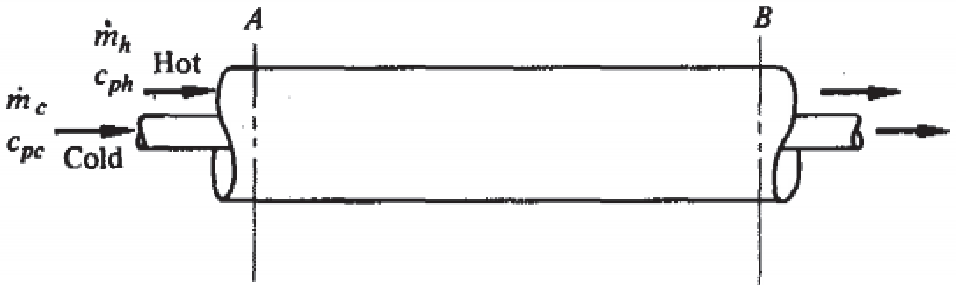

Figure 10: Parallel Flow Configuration Heat Exchanger [6]

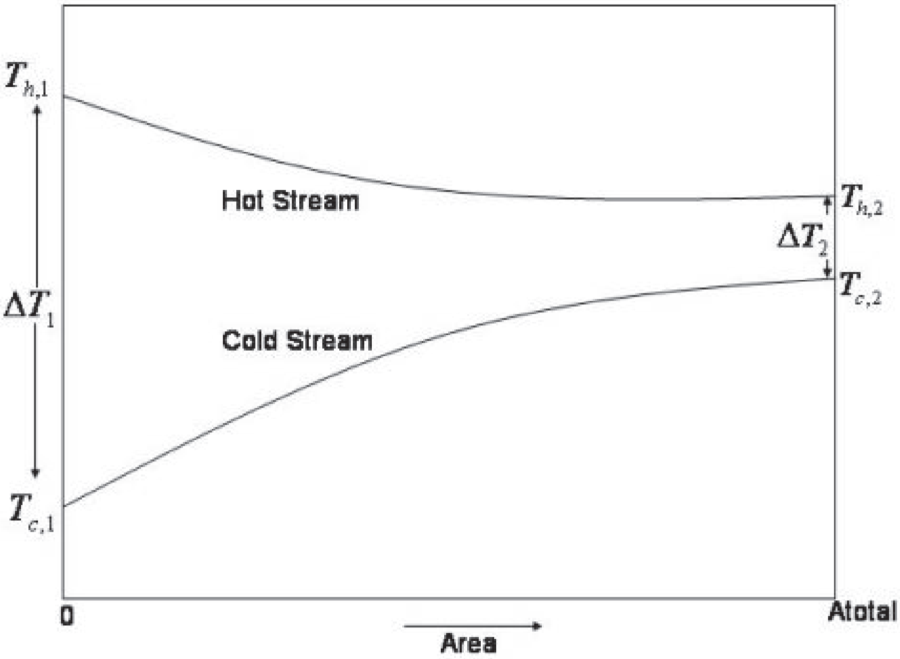

Figure 11: Parallel Flow Heat Exchanger Temperature Profile [6]

This model that is discussed and presented here is used to calculate the temperatures of the exit streams using the log mean temperature difference (LMTD), with the inlet conditions and heat capacities given.

$$ln\frac{\Delta T_1}{\Delta T_2} = \frac{1}{C_h} + \frac{1}{C_c} \tag{50}$$

C_h is the heat capacity of the hot stream, C_c is the heat capacity of cold stream, ΔT_1 and ΔT_2 are the front and back sections stream to stream temperature differences for the heat ex-chnager. These temperature differences can be calculated as follows;

$$\Delta T_1 = T_{h1} - T_{c1} \tag{51}$$

$$\Delta T_2 = T_{h2} - T_{c2} \tag{52}$$

The relationship between the heat transfer rate q and heat exchanger surface overall thermal conductance is given as:

$$q = UA\Delta T_{lm} \tag{53}$$

The expression ΔT_{lm}, which is the log mean temperature difference, can be calculated using the equation,

$$\Delta T_{lm} = \frac{\Delta T_2 - \Delta T_1}{ln\frac{\Delta T_2}{\Delta T_1}} \tag{54}$$

3.4.2 Counter Flow Heat Exchanger

In this type of heat exchanger, the area becomes bigger, and the hot and cold fluid temperature distribution difference becomes smaller. This means that the hot fluid is cooled equal to the temperature of the cold fluid inlet temperature and the cold fluid is heated equal to the temperature of hot fluid inlet temperature. Only counter flow heat exchanger could be used for this purpose. A more reversible heat exchange of the heat exchangers is efficient in such cases and thus for a given area transfer more heat.

Figure 12: Counter Flow Configuration Heat Exchanger [6]

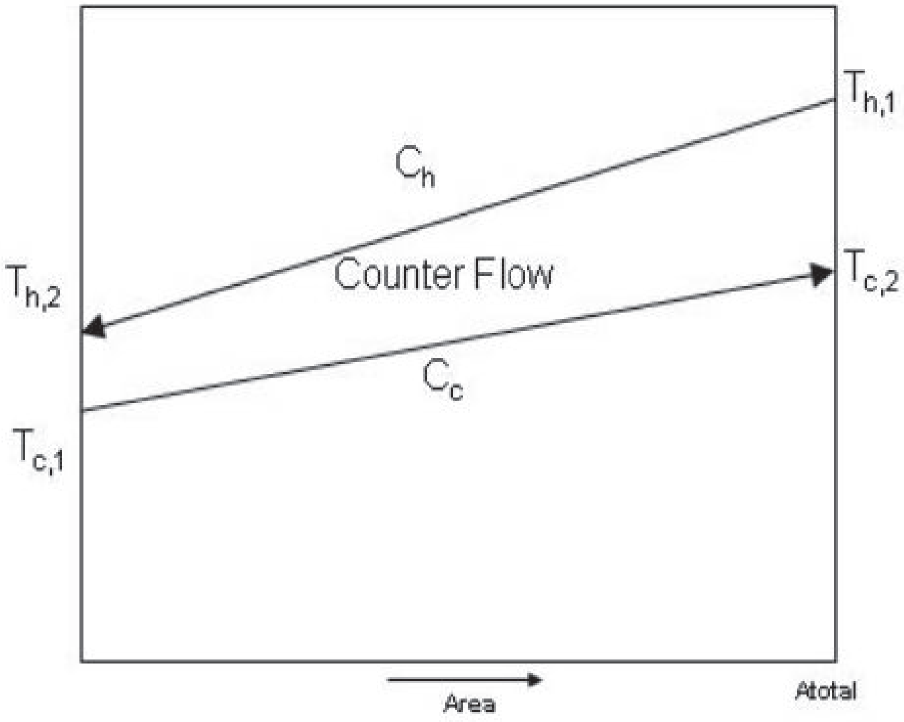

Figure 13: Counter Flow Heat Exchanger Temperature Profile for Hot and Cold Streams [6]

$$Q = -m_h C_h \Delta T_h \equiv m_c C_c \Delta T_C \tag{55}$$

where m_h is the mass flow rate of hot fluid, m_c is the mass flow rate of cold fluid, C_h is the heat capacity of hot fluid, C_c is the heat capacity of cold fluid, ΔT_h is the change in temperature for the hot stream, ΔT_c is the change in temperature for the cold stream.
ΔT_h and ΔT_c can be determined by:

$$\Delta T_h = T_{h,in} - T_{h,out} \tag{56}$$

$$\Delta T_c = T_{c,out} - T_{c,in} \tag{57}$$

3.5 Combustor

The stream of air and fuel coming out of SOFC, in this particular model, an additional air and fuel is mixed with it in combustion chamber. This mixture, for high exhaust temperature, is combusted in the combustor. Combustion is assumed to have been done at constant pressure. All the released energy is also assumed to have been converted into energy, and this energy released leaves the combustor at adiabatic temperature. The 1st law of thermodynamics needs:

$$H(mix) = H(SOFC)_{exhaust} + H(Fuel)_{additional} + H(Air) \tag{58}$$

The main purpose of developing combustor model here is to capture the enthalpy change and changes of chemical species concentration as a result of the combustion of un-utilized fuel or other exit products from SOFC. This unconsumed fuel or air from the SOFC is burnt or combusted in combustor which produces hot gases. The outlet temperature of the combustor can be calculated using the following equation;

$$\frac{dT_{comb}}{dt} = \frac{1}{mC_{p,comb}} \sigma_{coeff} A_{comb} (T_{exh}^4 - T_{comb}^4) \tag{59}$$

where C_p is the constant pressure specific heat capacity, σ_{coeff} is 5.67e-8.
Q_{comb} can be calculated by using the following formula:

$$Q_{comb} = \frac{n_{fuel} - n_{H_2}}{2} \Delta H_{fuel} K_{coeff} - P_{sofc} - Q_{sofc} \tag{60}$$

K_{coeff} can be calculated by using the following equation:

$$K_{coeff} = \frac{T_{comb} - 273}{200} \tag{61}$$

3.6 Performance Evaluation

The electrical efficiency of solid oxide fuel cell system could be calculated using the equation given below,

$$\eta_{sofc} = \frac{W_{sofc}}{m_{fuel}} LHV \tag{62}$$

W_{sofc} is the total power out of solid oxide fuel cell, m_{fuel} is the molar flow rate of the fuel, LHV is the Lower Heating Value of the fuel.
The net electrical efficiency of the whole integrated system can be calculated by the equation given below;

$$\eta_{elect} = \frac{W_{sofc} + W_{gt} - W_{comp}}{m_{fuel} * LHV} \tag{63}$$

W_{gt} = Power output of the gas turbine (kW)
W_{comp} = power required to run the compressor (kW)

4 Result and Discussion

4.1 SOFC-GT Dynamic Model

A MATLAB dynamic model is developed for SOFC-GT hybrid system with the capability of simulating the dynamic and transient behavior. The experimental system designed in thesis work includes a Compressor, heat exchanger, SOFC Stack, Combustor and Gas Turbine as shown in the schematic figure 14. The dynamic model designed here is operated initially with steady state condition and the changes are imposed to check the resulting behavior of the model. For the initial operating conditions, one option is to select or specify the current density, air ratio and fuel utilization factor. The fraction of the total fuel, that has entered into the system, which is used to produce electricity in the cell is called the fuel utilization factor and the air ratio is the excess air that is used to cool the cell. The fuel efficiency, which is the output or resulting factor, is the total chemical energy in the fuel entering the system that is converted to electrical energy or power. The chemical energy that is consumed for the production of electrical energy and heat generation in a cell is the result of entropy change of electro-chemical reactions, over-potential losses and the resistance to the flow of current.

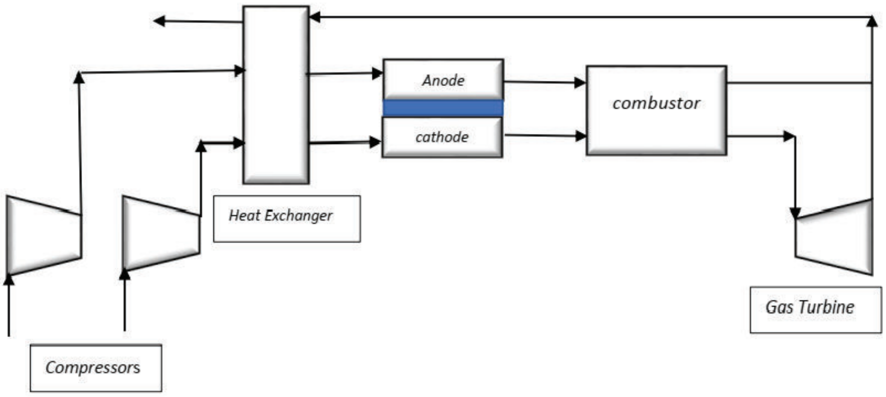

Figure 14: Schematic of Solid Oxide Fuel Cell/Gas Turbine Hybrid System Components

The results of the model presented in this chapter are based on different configurations for the integrated SOFC-GT hybrid system dynamic modeling. There are three(3) subsections and those respective subsections observe the effect of current density, fuel flow rate and pressure ratio change parameters on the temperature, electrical power output and voltage of SOFC and GT. The results of these tests are then compared with the results taken from the literature for comparison. kourdosh et.al [28] did dynamic and transient analysis of power distribution in SOFC-GT integrated system by checking the effect of a step change in stack current and fuel flow change on the stack temperature, voltage and electrical power output.

Subsection (5.1.1) is to check the effect of current density disturbance or change on the

Table 4: Operating Parameters for SOFC-GT Plant

Parameter	**Symbol**	**Value)**
Faraday's Constant	F	96485
Universal Gas Constant	R	8.314
Area of Cell	A_{cell}	100
Number of Cells	N_{cell}	4000
Number of Modules	N_{module}	10
Area of Heat Exchanger	A_{hx}	2000
Area of Combustor	A_{comb}	5
SOFC inlet Temperature	K	700
Compressor Efficiency	η_{comp}	0.9
Turbine Efficiency	η_{turb}	0.9

SOFC stack, Combustor and GT temperature. The same subsection also observe the effect current density change on the power output of SOFC stack and GT and SOFC stack voltage. The second subsection (5.1.2) investigates the effect of pressure change on SOFC, Combustor and Gas Turbine temperature and also observe the behavior of this change over the power output of the SOFC stack and GT. The last subsection (5.1.3) is related to investigating and finding the effect of molar fluid flow change in the system. The parameters defined for the plant components are given in table 4.

4.1.1 Effect of Current Density

In this subsection the effect of step change in the stack current from 0.7 to 1.0 A/cm^2 is applied. The flow of the fuel and air in this section is kept constant. Figure 16 shows the effect of step change on SOFC stack electrical power output and the stack current is shown in Figure 15.

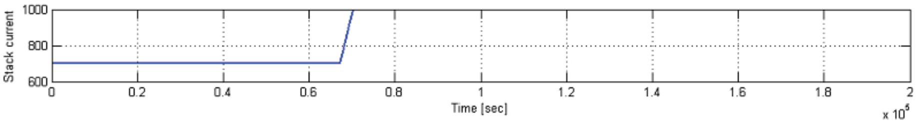

Figure 15: SOFC Stack Current Profile

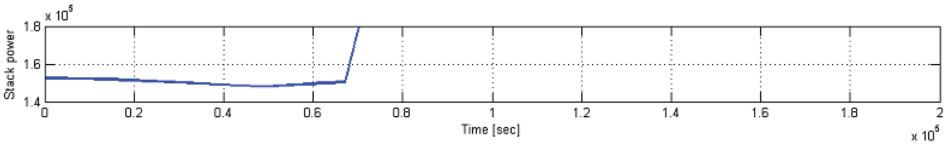

Figure 16: SOFC Stack Electrical Power Output for Current Change

The power output increases with the increase in the stack current from 150 kW to 180 kW. However, the SOFC stack temperature decreases with the increase in the stack current from 1015K to 970K and stabilizes at 70000sec as shown in figure 17.Table 5 shows the operating parameters for the current density change.

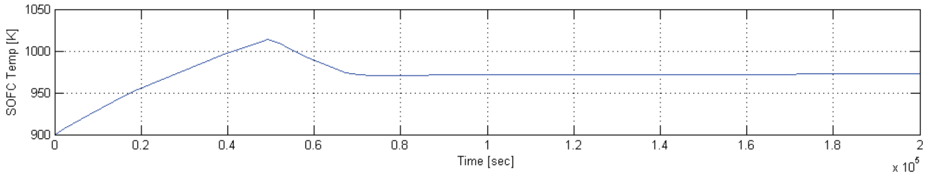

Figure 17: SOFC Stack Temperature for Current Change

The Power output for GT is slightly effected by this step change in the stack current and it gives a power output from 114 kW to 108 kW as shown in figure 18 and the stack voltage decreases for the step increase of SOFC stack current from 215 V to 180 V given in figure 19.

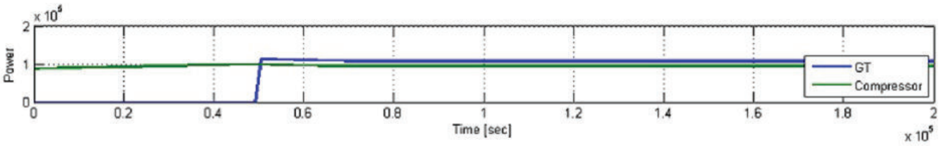

Figure 18: Compressor and GT Power Output for Current Change

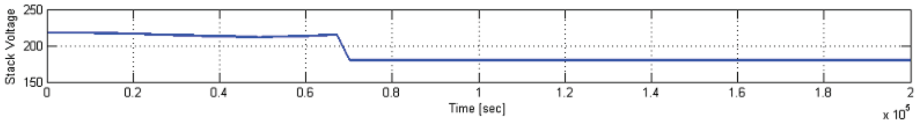

Figure 19: SOFC Stack Voltage Output for Current Change

Like the temperature of SOFC stack, the temperature for combustor and GT also initially increases but then decrease with the step change in the stack current. The combustor temperature initially increase to 1015 K and then decreases and takes the same time as that of SOFC stack stabilizes at 970 K as shown in figure 20 and figure 21 shows the temperature variation for GT and the turbine exit temperature is 540 K and figure 22 shows the efficiency of the plant for current step change configuration.

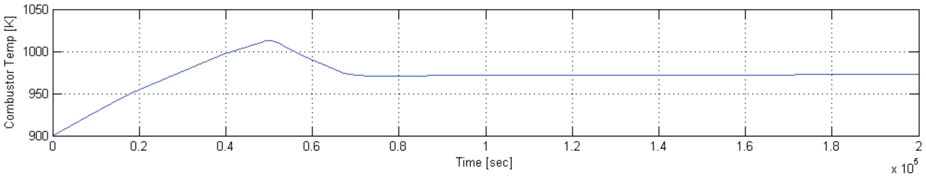

Figure 20: Combustor Temperature for Current Change

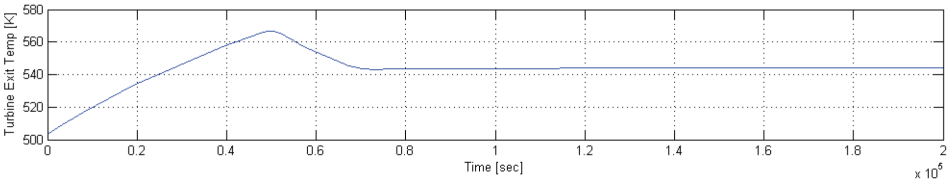

Figure 21: Temperature Output of GT for Current Change

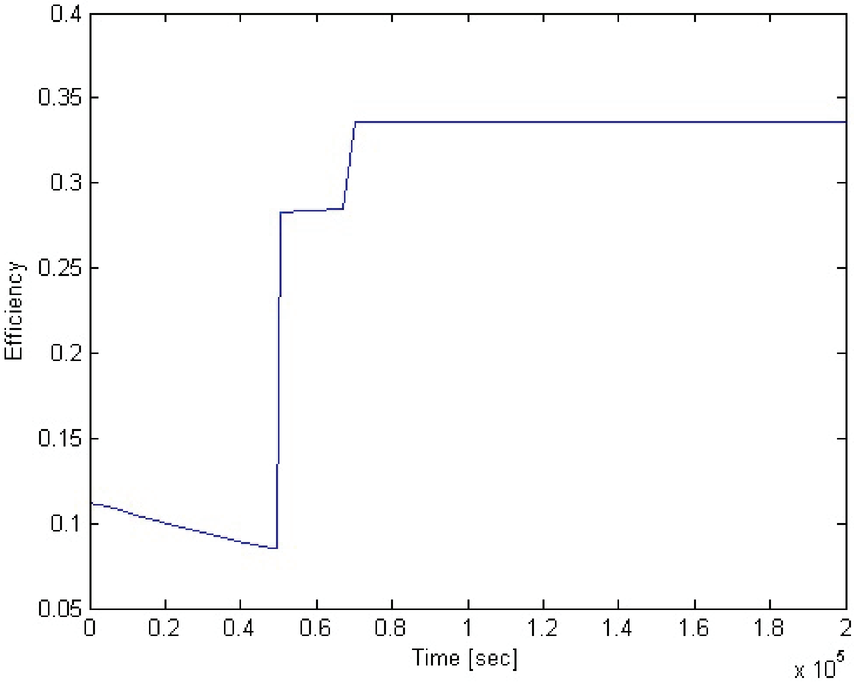

Figure 22: Efficiency for Current Change

Table 5: Operating Parameters for Current Change

Parameter	Symbol	Value
SOFC Stack Operating Temperature	K	970
SOFC Stack Current Density	A	1000
SOFC Stack Voltage	V	180
SOFC Electrical Power	kW	180
Gas Turbine Electrical Power	kW	108

4.1.2 Effect of Fuel Flow

In this second subsection the step change in fuel flow rate from 1.05 kmol /sec to 1.25 kmol /sec was applied. A step change of the fuel flow at a time interval of 70000 sec is applied and figure 23 shows the electrical power in GT increases from 112 kW to 134 kW at the applied step change.

whereas, the effect of fuel flow over the electrical power output of SOFC stack has no significant effect at the same time interval the step change of fuel flow is applied as shown in figure 24. The electrical power output for SOFC stack reaches to 216 kW at a time interval of 50000 sec and then stabilizes.

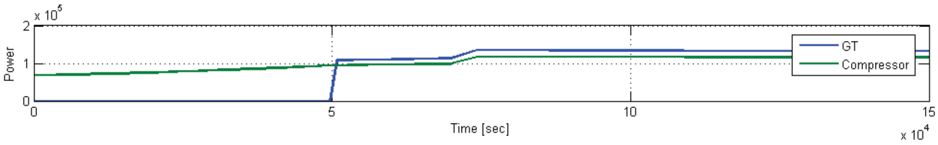

Figure 23: Gas Turbine Electrical Power Output for Fuel Flow Change

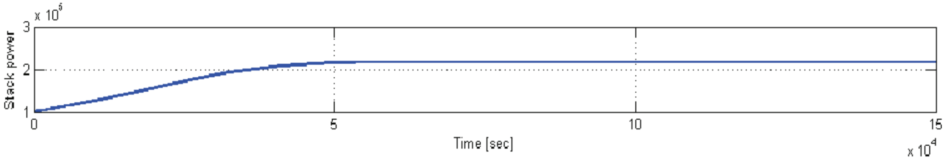

Figure 24: SOFC Stack Electrical Power Output for Fuel Flow Change

Both the SOFC stack current density and voltage increase with the increase of fuel flow. Figure 25 show the SOFC stack current of 1247 A and figure 26 show the SOFC stack voltage response for the fuel flow increase which has a value of 175 V and stabilizes at a time interval of 7000 sec.

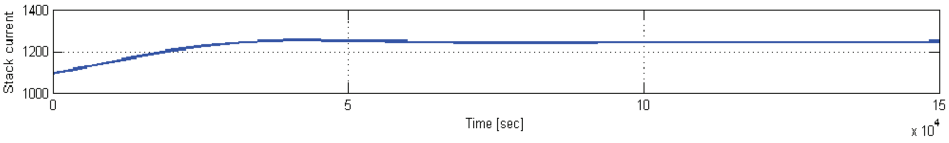

Figure 25: SOFC stack Current for Fuel Flow Change

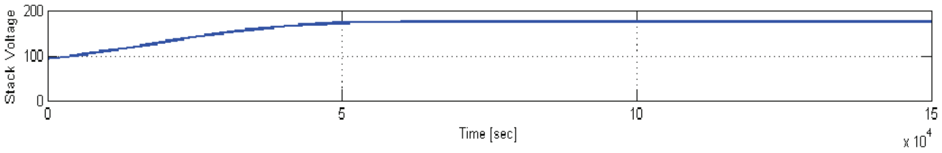

Figure 26: SOFC Stack Voltage for Fuel Flow Change

The SOFC stack temperature increase to 1006 K when the step change is applied and then stabilizes at 985 K as shown in figure 27. The exit combustor temperature also shows a slight increase at the time when the step change is applied and reaches to 1006 K shown in figure 28, the GT exit temperature is 554 K and fig 29 shows the temperature behaviour of GT.

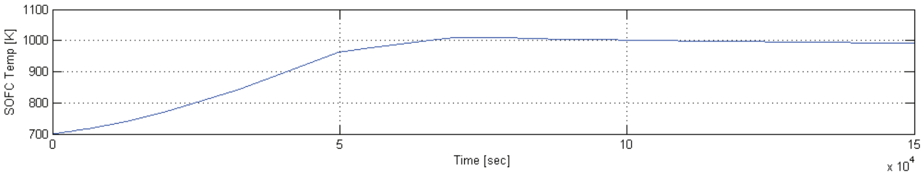

Figure 27: SOFC Stack Temperature for Fuel Flow Change

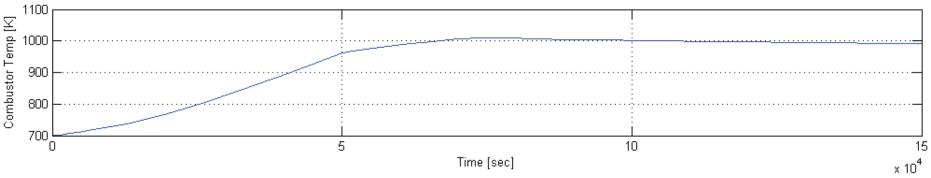

Figure 28: Combustor Temperature for Fuel Flow Change

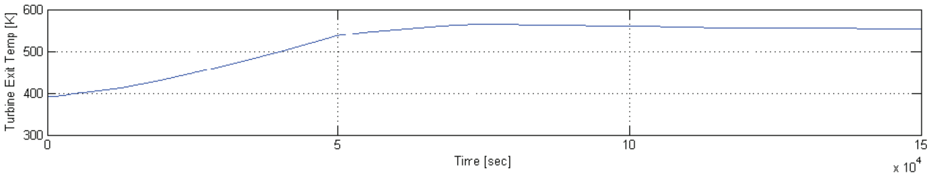

Figure 29: Gas Turbine Temperature for Fuel Flow Change

If we compare the effect of fuel flow to the current change, the electrical power output for both the SOFC stack and Gas Turbine increases resulting in the increase of electrical power output of complete plant. The operating temperature for SOFC stack, combustor and GT also increase with the increase of fuel flow. The fuel flow increase also increases the SOFC stack current density and voltage. Figure 30 shows the efficiency of the plant which shows that the efficiency of the system decreases after the fuel flow increase and that is because the heat absorbed by the fuel flow increases with the increase of fuel flow rate, table 6 shows the operating parameters for fuel flow change.

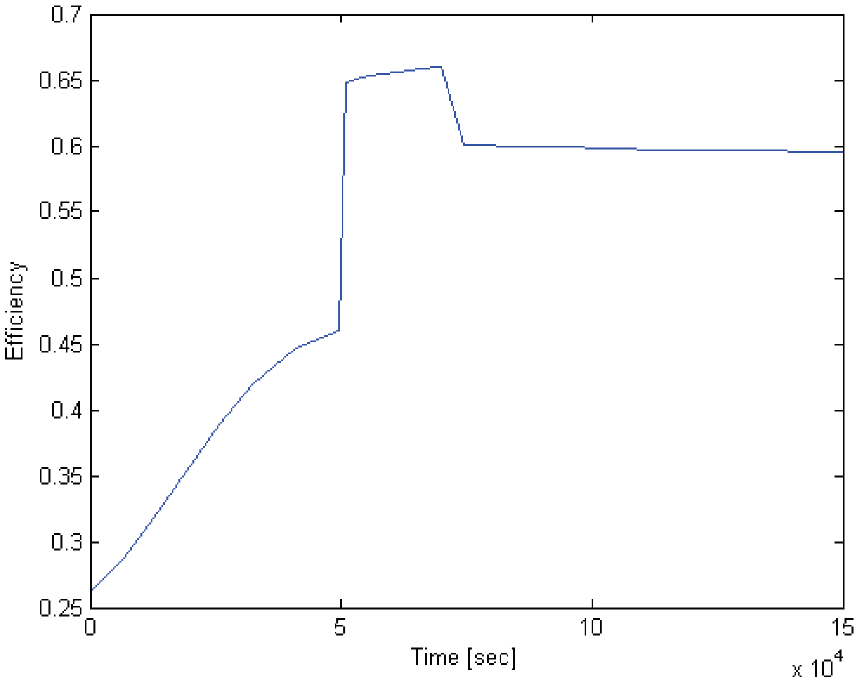

Figure 30: Efficiency of Plant for Fuel Flow Change

Table 6: Operating Parameters for Fuel Flow Change

Parameter	**Symbol**	**Value**
SOFC Stack Operating Temperature	K	985
SOFC Stack Current Density	A	1245
SOFC Stack Voltage	V	174
SOFC Electrical Power	kW	217
Gas Turbine Electrical Power	kW	131
Net Electrical Power Output	kW	233

4.1.3 Effect of Pressure Ratio Change

In this subsection, the effect of pressure ratio change in the gas turbine observed. A step change at 50000 sec time interval is applied and the effect of this pressure ratio change results in the increase of exiting temperature for gas turbine. The SOFC stack temperature, combustor temperature and gas turbine exit temperatures are 1012 K, 1012 K and 625 K respectively and are shown in figure 31, figure 32 and figure 33. The gas turbine shows a sudden temperature increase from 548 K to 598 K when this pressure ratio step changed is applied.

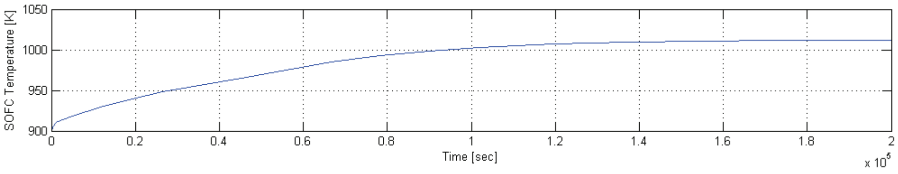

Figure 31: SOFC Stack Temperature for Pressure Ratio Change

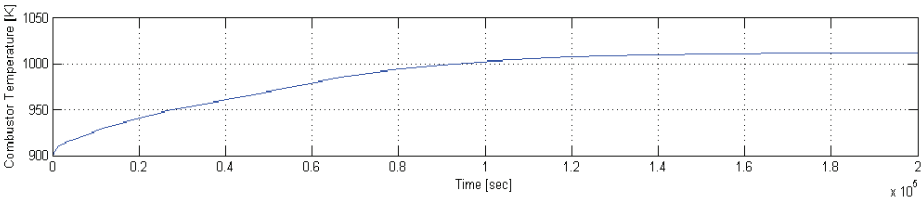

Figure 32: Combustor Temperature for Pressure Ratio Change

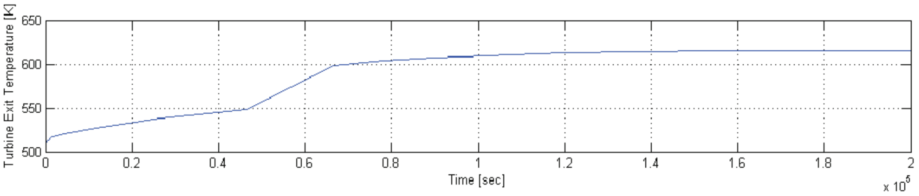

Figure 33: Gas Turbine Temperature for Pressure Ratio Change

The electrical power for SOFC stack is 217 kW and the gas turbine electrical is 215 kW and this high electrical power output in the gas turbine is increase in the gas turbine exit temperature due to the pressure ratio change. The SOFC stack voltage and current density are 175 V and 1242 A respectively. The SOFC stack electrical power is shown in figure 34, the electrical power generated by the gas turbine and the power required to run the compressor are given in figure 35. Figure 36 and fig 37 show the SOFC stack voltage and current density profiles respectively and figure 38 shows the overall efficiency of the plant. Table 7 shows the parameters for SOFC-GT for pressure ratio change.

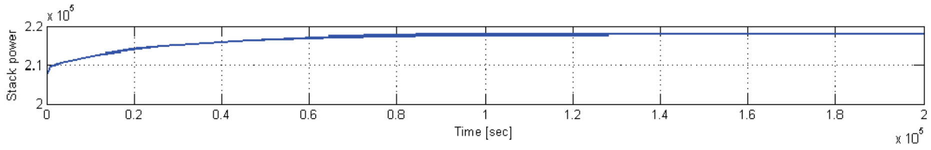

Figure 34: SOFC Stack Electrical Power Output for Pressure Ratio Change

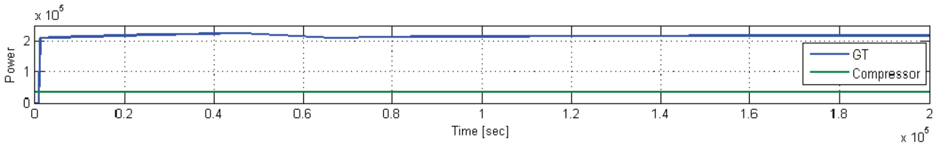

Figure 35: Gas Turbine and Compressor Electrical Power for Pressure Ratio Change

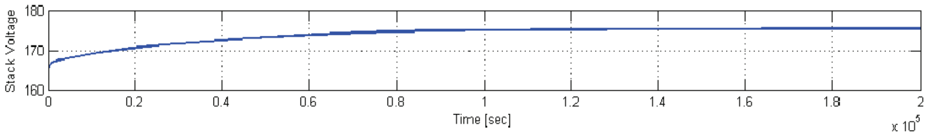

Figure 36: SOFC Stack Voltage for Pressure Ratio Change

Table 7: Parameters for Pressure Ratio Change

Parameter	**Symbol**	**Value**
SOFC Stack Operating Temperature	K	1012
Combustor Temperature	K	1012
SOFC Stack Current Density	A	1242
SOFC Stack Voltage	V	175
SOFC Electrical Power	kW	217
Gas Turbine Electrical Power	kW	215
Power Consumed by Compressor	kW	33
Net Electrical Power Output	kW	399

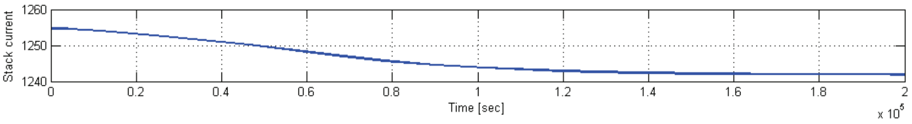

Figure 37: SOFC Stack Current Density for Pressure Ratio Change

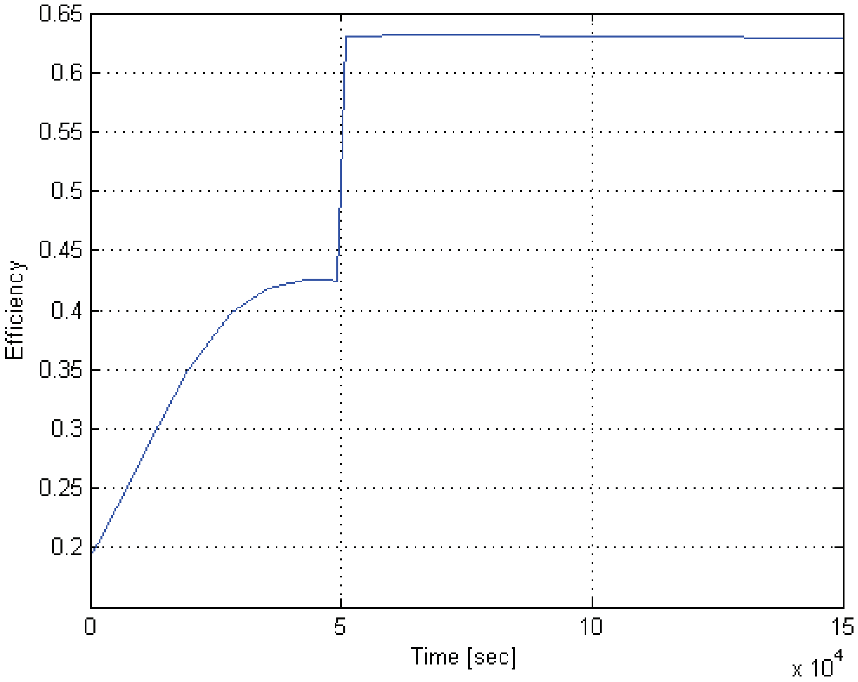

Figure 38: Efficiency of the Plant for Pressure Ratio Change

Table 8: Comparative Analysis for all Configuration

Parameter	Current	Fuel Flow	Pressure Ratio
Area of Cell	100	100	100
Number of Cells	4000	4000	4000
Number of Stacks	1	1	1
SOFC Stack Operating Temperature	970	985	1012
Stack Current	1000	1245	1242
Stack Voltage	180	174	175
Net Electrical Power Output	189	233	399
Efficiency	34	59	62

4.2 Configurations Comparison

The comparisons for the three tests and reference model are given in table 8. From the data given in table 8 the performance of pressure ratio is better than the other two configurations. The configuration with a current density change has the lowest performance with system efficiency of 45 percent and that can be attributed to the low operating temperature of the stack. The operating temperature of the stack increases as we move from current density change to fuel flow change to pressure ratio change the operating temperature of the stack increases resulting in the increase of the overall efficiency and electrical power output of the system.

The results from the pressure ratio test in the preceding subsections are compared with the work of Kourosh et.al[28]. They developed a Fuel Cell dynamic model and performed the dynamic and transient analysis of power distribution systems with fuel cells. Table 9 shows the comparison of the results between the pressure ratio test and reference from the literature.

Table 9: Design Performance Analysis with Reference

Parameter	Pressure Ratio Change	Kourosh Results
Area of Cell	100	1000
Number of Cells	4000	384
Number of Stacks	1	1
SOFC Stack Operating Temperature	1012	1273
Stack Current	1242	300
Stack Voltage	175	286
Net Electrical Power Output	399	100
Efficiency	62	80

Both the result shows that as the temperature increases the performance efficiency of the system increases as well. But an excessive increase in the SOFC stack temperature effect the stack voltage due to different over-potential losses.

5 Conclusion

Solid Oxide Fuel Cells are considered to be the most viable energy conversion devices. They convert the chemical energy of the fuel directly into electrical energy and operates at high temperature between the range of 600 to 1000 °C. Due to their high temperature operating mechanism, SOFCs offer very magnificent efficiencies and low emission of pollutants, toxic gasses or greenhouse gasses emission. They are considered to be the best option for stationary electrical power generation due to their capacity of fuel flexibility, high operating temperature, the solid state structure and their high efficiencies. Simulation modeling is required to evaluate the performance of devices like this and MATLAB dynamic modeling is carried out in this thesis work to analyze the performance of SOFC-GT hybrid system. Figure 14 shows the schematic of SOFC-GT CHP hybrid system components used in the model analysis in this thesis work.

In this thesis work, it has been observed and concluded that a step change in the stack current will result in the increase of the SOFC stack electrical power, however, the electrical power and stack temperature do not increase significantly due to the decrease of the stack voltage as the load increases and hence the overall efficiency of the plant also does not increases significantly.

For the fuel flow change configuration, the electrical power output of both the SOFC stack and GT has increased, however, the performance efficiency decreases after when the fuel flow step change is applied. The decrease in this efficiency for this configuration after step change is because the heat absorption quantity for the fuel flow increases with the increase of flow rate which is effecting the efficiency of the plant.

The exhaust gas from the gas turbine in this model goes through the heat exchanger wherein the air and fuel coming from the compressor have temperature transmitted from the hot exhaust gas of GT to the desired level required to operate SOFC stack with. When the pressure ratio increases in the GT, the temperature of exhaust gas from GT increases resulting excessive temperature imparted to the air and fuel in the heat exchanger thus resulting in high electrical power output in both the SOFC stack and GT along with the increase in SOFC stack operating temperature. Both the increase in electrical power output and operating temperatures of the components result in the increase of the overall efficiency of the plant in the last of the three configurations.

The main motivation behind this thesis was to develop and analyze the performance of a dynamic SOFC-GT hybrid model that could be operated and controlled in accordance with the energy demand and also to discover manipulating which particular parameters will help in getting the desired result while operating the SOFC supported power plant. It is, thus, concluded that development of a model is extremely useful to study operating conditions to obtain the desired electrical output and temperatures by engineering the values of stack current, fuel flow rates and pressure ratios if at any time an increase or decrease in electrical power is required.

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