A FUEL CELL SYSTEM MODELING FOR AN AUXILIARY SYSTEM ENERGY REQUIREMENT OF A MARITIME SHIP

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GRADUATION PROJECT REPORT

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ABSTRACT

Providing for secondary energy required of a ship with fuel cell modelling

Last decades, global climate change and exhaustible fossil fuels problems become important problems. Related to that, getting energy from the Sun's rays becomes more important. One of the important ways of global transportation is marine is also cause the greenhouse gases. Most of the countries decided to reduce the greenhouse gas emissions and make the emission-free zone until 2050.

The usage of hydrogen fuel cells is suitable for ships because the fuel cell can be integrated into ships and required water for electrolysis can be easily obtained from seas.

The main purpose of the thesis is to model a fuel cell for the ships to provide the energy required.

BU KISMI YAPTIĞIMIZ ÇALIŞMAYI BİRAZ DAHA ANLATACAK ŞEKİLDE GENİŞLETELİM

SYMBOLS

H   **:** Hydrogen

O   **:** Oxygen

H_2O   : Water

OH^-   : Hydroxide

e   : Electron

CO_2   : Carbon Dioxide

KOH   : Potassium Hydroxide

ABBREVIATIONS

AFC   **:**Alkaline   Fuel   Cell

MCFC   **:** Molten Carbonate Fuel Cell

PAFC   **:** Phosphoric Acid Fuel Cell

PEMFC   **:** Proton Exchange Membrane Fuel Cell

SOFC   **:**Solid Oxide Fuel Cell

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1. INTRODUCTION

Energy is the part of our life with different forms increasingly. Energy due to fossil fuel is going to be more challenger related to energy rising needs. Most abundant element hydrogen is come to mind for the more sustainable energy reserve for the future.

Thus, the development of the energy field and reducing the greenhouse effects are important all over the world. Today, the fact that fossil fuel resources are gradually decreasing and their impact on the environment is increasing day by day has led states to seek a different energy source. They wanted to take very confident steps to ensure that this new source both meets their energy needs and is not harmful to the environment. Considering all these, renewable energy sources started to gain value day by day. When considering energy production methods including fossil sources, fuel cells using hydrogen as an energy source have a special place among these new energy production methods due to their environmental friendliness, high amount of energy, and efficiency. Many countries have made a great effort to minimize gas emissions in the next 10-20 years. For both our country surrounded by seas on 3 sides and our world, covered with approximately 70-75% water, the seas and sea transportations are of great importance. Reducing gas emissions in maritime transport, which has a significant role in the emission of greenhouse gases that are harmful to our world, has been an important point for the future of ourselves and our world.

Fuel cells mainly use hydrogen as an energy source. However, although hydrogen can be found in many materials, it cannot be found in nature like fossil fuels. Therefore, the production of hydrogen to be used in fuel cells is also has great importance. In the seas, it is possible to produce hydrogen by electrolysis of water and use it in fuel cells. Produced hydrogen can be used in fuel cells and thus the electrical energy needed by the ship can be met. Thus, a large sector can be made more environmentally friendly.

1.1. The History of the Fuel Cell

The theme of the fuel cell concept starts to use early in the 19th century. It starts with two researchers Christian Friedrich Schönbein and Sir William Grove. Sir William Groove has discovered the first fuel cell and he called this fuel cell as a "gas battery". This type of fuel cell operates two platinum electrodes on one end in a solution of sulphuric acid for the immersing and the other two ends separately sealed in containers of oxygen and hydrogen.

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Grove observed that the water level rose in both tubes as the current flowed. Grove's argument is in the fuel cells, only pure hydrogen could be used as fuel [REF].

In 1889, Ludwig Mond and his assistant developed the Grove's fuel cell. They achieved six amps per square foot at 0.73 volts. They used platinum electrodes. End of the 19th century, Friedrich Wilhelm Ostwald, determined the theoretical understanding of the fuel cells [REF]..

William W. Jacques has developed the first fuel cell with practical applications in 1896. Air was injected into an alkaline electrolyte to react with a carbon electrode. This is called a "carbon battery". In 1900, Walther Nernst has used zirconium firstly as a solid electrolyte in fuel cells [REF]..

Beginning of the 20th century, Emil Baur worked on several types of fuel cells and one of the works included high-temperature devices. The unit uses a solid electrolyte which can be molten silver as an electrolyte, of clay and metal oxides [REF]..

In 1933, Thomas Francis Bacon investigated the first alkaline fuel cells. The air and hydrogen were directly converted into electricity through electrochemical processes consisting of hydrogen and oxygen. Related to his work, he built the cell which is consisting of the nickel electrodes a few years later.

In 1955, Thomas Grubb used a membrane made of ion-exchange polystyrene sulfated as an electrolyte. A few years later, in 1959, Harry Ihrig, built a fuel cell of 15kW for a tractor from Allis-Chalmers.

G.V Elmore and H.A. Tanner made a fuel cell in which electrochemical reactions did not occur during the operation itself. The fuel cell could work directly with air instead of pure oxygen.

In the 21st century, fuel cell working is accelerating due to climate change and carbon emissions. Transportation, portable applications, or micro-power applications are kind of the areas.

In vehicles applications, they can use hydrogen gas in internal combustion engines, hybrid or fuel cell electric vehicles. In 2013, Hyundai present their SUV-type vehicle which is operating with a fuel cell. The car produces electricity by combining hydrogen fuel and oxygen which is oxygen taken from the air. Also, in 2017, Hyzon Company supplied hydrogen fuel cell-powered commercial vehicles including heavy trucks.

The first fuel cell powering hydrogen ship developed by Toyota. The ship name was "Mirai". The ship uses the sun's rays, sea water and wind to providing the energy.

In May 2008, a two-seat Dimona airplane was flew powered by hydrogen fuel cells only. Above the sea level flight, the plane uses a combination of battery power and power generated by hydrogen fuel cells. When the plane reaches the 60 miles per hour speed, the fuel cell generated power alone for 20 minutes [REF]..

1.2. Literature Review

1.2.1.   Fuel Cell

A fuel cell is an electrochemical device that does not consist of a combustion phase . Due to not consisting of combustion phase compare to the internal combustions, fuel cells are environmentally friendly energy source.

Classification of the different types of the fuel cell depending on the type of fuel (gases, solids, liquids), depending on the electrolyte used (liquid or solid), depending on how the fuel is consumed (directly or indirectly). Different design type of the fuel cell difference is chemical characteristics of the electrolyte.

Basically the electro chemical reaction equation is:

$$2H_2 + O_2 \rightarrow 2H_2O + energy \qquad (1)$$
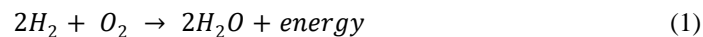
Main working principle of the fuel cells are hydrogen entrance the anode to separate protons and electrons. Electrons are not pass through diffusion layer catalysis and membrane to reach the cathode. Electrons are through an electrical circuit and determines the electric current. While the electrons reach the cathode, they combined with oxygens to resulting in hydrated water or ions.

In fuel cell systems, wanted to get a higher reaction rate needs higher working temperature. One of the effect on the efficiency is distance between electrodes.

fuel cell capacity range is more than photovoltaic power generation system. But compare to the other power generation systems fuel cell efficiency is most efficient one than the conventional distributed energy systems.[2]

Table-1. Types of the fuel cell.

Fuel Cell Type	Mobile Ion	Electrolyte	Working Temperature (~ °C)	Catalyzer	Working Areas
Alkaline Fuel Cell	OH^-	Potassium hydroxide	100-200	Nickel, silver	Military, space, electromobility,
Proton Exchange Membrane	H^+	Ion exchange polymer membrane	50-100	Platinum	Grid support, portable power, P2P
Phosphoric Acid Fuel Cell	H^+	Phosphoric Acid	200-220	Platinum	Distributed generation
Solid Oxide Fuel Cell	O_2^{-2}	Zinc over fastened yttrium	500-1000	Zirconium	Electric utility, auxiliary power
Molten Carbonate Fuel Cell	CO_3^{-2}	Carbonate	600-700	Nickel	Electric utility, distributed generation

If we need to compared to the six fuel cell types, proton exchange membrane fuel cell is dominant one. But solid oxide fuel cell usage is increasing for the last years. [1]

1.2.1.1. Alkaline Fuel Cell (AFC)

NASA is the first used alkaline fuel cell for space applications. They supply drinking water and electric power to shuttle mission.[2].

AFC uses water based alkaline solution which is potassium hydroxide (KOH) as an electrolyte. Using KOH takes risks for absorbs CO2 through the conversion of KOH to potassium carbonate (K2CO3) and defeated the fuel cell.

Nickel is the most useful catalyst to speed up reactions in cathode and anode. Main working reaction equations:

$$2H_2 + 4OH^- \rightarrow 4H_2O + 4e^- \tag{2}$$

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \tag{3}$$

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

Equation 2 is the oxidation equation for the AFC. Released electrons from the oxidation equation, reach the cathode to generate the OH- ions. Equation 3 is the reduction equation for the AFC and the sum of these equations is Eq. 4.

1.2.1.2. Proton Exchange Membrane Fuel Cell

As a name of it, it uses the polymer membrane to the protons pass through the membrane. Membrane is not transport the protons anode to cathode, it is block the electrons. Efficiency is inversely proportional to the membrane thickness due to that thin membrane has high efficiency. Over the boiling point of the water, water causing dehydration and negatively effect on the proton conductivity of the membrane. Due to low temperature fuel cell, it has rapid start-up process. Due to low temperature fuel cell, it has rapid start-up process.

Compared to the other type of fuel cells, portable usage is the difference of the proton exchange membrane fuel cell. Common usage area is portable systems which is the example of fuel cell vehicles.

PEMFC's working reaction equations:

$$H_2 \rightarrow H^+ + 2e^- \tag{5}$$

$$1/2O_2 + 2H^+ + 2e^- \rightarrow H_2O \tag{6}$$

$$H_2 + 1/2O_2 \rightarrow H_2O \tag{7}$$

Equation 5 shows the anode reaction. Equation 6 shows the cathode reaction and equation 7 shows the sum of the reactions.

1.2.1.3. Phosphoric Acid Fuel Cell

Due to ionic conductivity of the phosphoric acid is low, the PAFC working temperature rate is between 150-220°C. This means that, it capable to working on the higher boiling temperature of the water. PAFC's working reaction equations:

$$2H_2 \rightarrow 4H^+ + 4e^- \tag{8}$$

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \tag{9}$$

$$2H_2 + O_2 + 2CO_2 \rightarrow 2H_2O + 2CO_2 \tag{10}$$
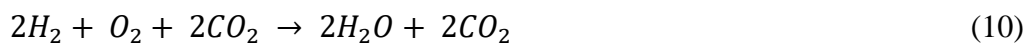
Equation 8 shows the oxidation reaction for the PAFC. Equation 9 shows the reduction reaction for the PAFC and the sum equation shown in equation 10.

Result of the reaction is electrical current and heat. The heat causes water heating and steam. The steam reforming the reactions produce some CO. So the result of the heat is affected the performance of fuel cell

1.2.1.4. Solid Oxide Fuel Cell

The specific property of the solid oxide fuel cell is the working temperature range. SOFC are high-temperature fuel cells with a solid electrolyte. Some of the limitations are long start-up and cool-down times.

(YSZ) ytrria stabilized zirconia has high chemical and thermal stability so it is useful for the SOFC. SOFC's working reaction equations:

$$O_2 + 4e^- \rightarrow 2O^{-2} \tag{11}$$

$$2O^{-2} + 2H_2 \rightarrow 2H_2O + 4e^- \tag{12}$$

$$2H_2 + O_2 \rightarrow 2H_2O \tag{13}$$

Eq. 11 shows the oxidation reaction for the SOFC. Oxygen is oxidized at the cathode and fuel oxidation happens at the anode. Eq.12 shows the reduction for the SOFC and the sum equation shown in Eq.13.

1.2.1.5. Molten Carbonate Fuel Cell

As a name on it, molten carbonate salt mixture used as electrolyte Due to the high temperature, reaching operating temperature is need long time.

MCFC's working reaction equations:

$$2H_2 + 2CO_3^{-2} \rightarrow 2H_2O + 2CO_2 + 4e^- \tag{14}$$

$$O_2 + 2CO_2 + 4e^- \rightarrow 2CO_3^{-2} \tag{15}$$

$$2H_2 + O_2 + 2CO_2 \rightarrow 2H_2O + 2CO_2 \tag{16}$$

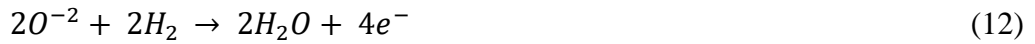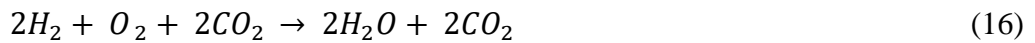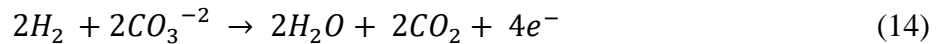Where equation 14 is the anode reaction, equation 15 is the cathode reaction and the sum of the equations is shown in equation 16.

AFC, PAFC, SOFC, MCFC and PEMFC are exhaust O_2 in air result of the oxidation reaction. AFC, PAFC and PEMFC are required pure H_2 for the fuel. Max output power and max operating temperature is seen in SOFC. Max efficiency is seen in AFC. PEMFC is more ideal for transportation applications.

Mazda, Renault and ZeTech companies used hybrid fuel cell battery directly with using hydrogen for the fuel. [2]

1.2.2. Hydrogen Technology

Hydrogen technology is ongoing technology so it has incomplete infrastructure. Hydrogen energy is going to be a future energy because of it can be generated various energy sources, reducing carbon emission just because of it is sustainable energy. [1]

Hydrogen is the combination of the two Greek words are hudro and genēs. Hudro means water and genēs mean producing. The combination of the two words means "to make water". Hydrogen is the most abundant element in the universe and it can be found abundant free in the stars, planet.

Result of some calculations hydrogen energy storage capacity is 1 kg hydrogen is about 120MJ nearly 33.33 kWh. If compared the liquid and gaseous hydrogen to other fuels, both hydrogen has the maximum lower heating value and maximum higher heating value [4]

Hydrogen can produce easily and generated from various energy sources because hydrogen is a very active element. Hydrogen is active elements so it cause some safety problems Hydrogen can be stored as a medium or long term and transported in different stored type.

Related to these properties hydrogen carries some risks to use at home or in public places. Hydrogen has a high diffusion coefficient so it causes some storage problems.

Compared to various fuels, gas and liquid hydrogen energy/mass (J/kg) and energy reserved factor is very high. High energy/mass ratio prove the hydrogen is ecologically friendly. [1]

If we compared the applications, stationary applications are common compared to the portable and transport. Also it is increasing day by day. Also Asia has the largest implementation units compared to North America, Europe. [1]

Hydrogen properties are listed on the Table-2:

Table-2. Properties of Hydrogen

Characteristics	Value
Atomic Weight	1.00782519 (on ^{12}C scale)
Molecular Weight	2.0159
Density	$0.0838 \; kg/m^3$
Density (liquid)	$70.8 \; kg/m^3$
Boiling Point	$20.41 \; K$
Freezing Point	$13.97 \; K$

Burning Speed	$2.75\ cm/s$
Ignition Temperature	560˚C
Diffusion Coefficient	$0.61\ cm^2/s$
Specific Heat (c_p)	1.89 J/(kg-K)

1.2.3. Hydrogen Producing Methods

We can classify the method of hydrogen production methods with use single and two forms of energy. Some of the hydrogen production methods require high temperature heat which are thermolysis, thermochemical, thermo-catalytic, solar energy and biomass energy.

Catalysis is the process that dissociation of hydrogen molecules or recombination rapidly and effectively. Expensive metal of palladium is good catalyst for other metal hydrides due to require less or no activation energy and has a dissociative ability. [4]

1.2.3.1. Water Electrolysis

This process occurs with the electrons movement at constant pressure and temperature with the work energy transmitted. Efficiency and current density are important parameters. Increasing current density is require catalysis, due to catalysis also reaction rate is improved. Water must be desalinated and demineralized before electrolysis to do not damage the sensitivity of PEM electrolysers. Alkaline, polymer membrane, and solid oxide electrolyzers are common subtitles of electrochemical hydrogen production technology.

Water thermolysis method is single-step thermal dissociation of water and requires high temperature heat to dissociation of water. [3]

1.2.3.2. Thermolysis & Thermochemical Water Splitting

The thermolysis process means water is directly split using thermal energy as the energy input or some other chemical materials. This reaction requires high-temperature heat sources. The below equation (equation 17) shows the reaction for thermolysis.

$$H_2O \xrightarrow{Heat} H_2 + \frac{1}{2}O_2 \tag{17}$$

In thermolysis operation, working in high temperatures occur the material selection importance. Cause the material has to be suited in the high temperatures.

Water splitting thermochemical cycles do not require and membrane for separation oxygen

hydrogen, less and sometimes no require any electrical energy to drive the processes, the process are thermally driven. So the temperature range is in not very high or very low.

1.2.3.3. Photonic

Photonic energy main source is solar radiation or sun. Due to that, photo-catalytic water splitting hydrogen production reactions are perform with photo-oxydation or photo-reduction. Photo-electrochemical cell's remarkable advantage is solar energy absorption and water electrolysis happen in a single unit.

1.2.3.4. Biomass Gasification

This process serves as a reduced carbon emission related to replacing fossil fuels with sustainable biomass fuel, getting rid of municipal solid wastes and crop residues increases the value of agricultural output.

When oxygen is completely absent or is present in very reduced quantities biochemical conversion can occur and important for the generate hydrogen from organic waste. [3]

It has some disadvantages to use biomass gasification, one of them is seasonal availability. It has some processes limitations such as pressure, resistance and hydrogen aging.

1.2.4. Hydrogen Storage

Hydrogen storage technologies can categorized in three subtitles which are physical storage, adsorption and chemical storage. Chemical storage consisting of metal hydrides and chemical hydrides. Hydrogen can store in gas or liquid form and rarely in solid form.

Stationary hydrogen storage systems weight an volume is not cause a problem and can take up more space compared to mobile applications. [4]

Physically storage the hydrogen gas need high pressure because of the element low density. Related to need of high pressure, salt cavern method can usable for seasonal hydrogen storage. One of the important project related to storage hydrogen in underground is "HyUnder" project. [4]

Hydrogen can stored in a metal container, aboveground vessels or underground in gaseous state. Compressor is main component of gas storage system cause each type of the storage has require to achieve desire pressure values. Hydrogen density and storage specific volume is inversely proportional. Pipe storage has the maximum storage pressure and approximately 100 bar. [5]

At the atmospheric pressure high hydrogen storage densities can achieve saturated liquid hydrogen. Hydrogen boiling point is extremely low and not cool down during throttling process for temperatures. Due to these circumstances, liquefaction of hydrogen requires substantial input of energy. Liquid hydrogen requires good insulation, as a result of this insulation surface-to-volume ratio and boil-off rates are low. [5]

Metal hydrides is the more acceptable compare to the chemical hydrides. Cause chemical hydrides easily release hydrogen under operating conditions. Metal hydrides is safer solution to storage hydrogen cause hydrogen molecules bond into metal much lower than compressed gas tanks. Added energy is supply the hydrogen molecules dissociate into hydrogen atoms, then diffuses into the bulk and occupy solid solution with a lesser amount of hydrogen. [4]

Intermetallic molecule consist of one weakly bounded element and one strongly bounded element to hydrogen and can use for the hydrogen storage applications. Some type of the intermetallic hydrides can achieve very high hydrogen storage density.

Ammonia volumetric hydrogen storage densities is the highest one. [5]

2. Hydrogen Fuel Cell System for Ships Application

Nowadays, most of the ships which are used in marine transportation generate electricity as required power, utilizes diesel generators. In recent years, with the increasing need for clean energy sources, switching to clean energy sources as fuel in ships has become an increasingly important issue. Many countries are currently working on this issue. Many countries have goals such as creating zero carbon emission zones in the next 25-30 years and reducing the carbon emission rate to a large extent.

Troya J. et al perform studies about using hydrogen fuel cell system in ships. In their study[5], In their study, they used low-temperature fuel cells and one of the conclusions was low-temperature based fuel cells have an advantage that offers a solid resolution for a ship with a refueling period of around ten of hours. But one of the other conclusions was the system size comparison. Based on long route ships, the system which will be used is expected to be 5 times bigger than compared to high-temperature fuel cells. It is expected to be extra energy-compact fuel for ships with long route mission needs.

To mention some of these studies, in 2012, DNV announced that a true hybrid energy system is currently being developed for installation on board the offshore supply vessel

Viking Lady. Viking Lady propulsion system use fuel cell, this makes Viking Lady very first merchant ship. The fuel cell has a capacity of generates 330kW electric output. This output offers 18,500 hours run for the ship.
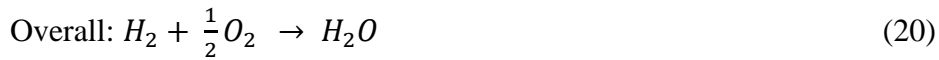
3. AIM OF STUDY

Sustainable and environmentally friendly technologies are gaining more importance day by day and many countries are investing in these technologies through companies. We have one earth, and pollution damage cause our life. Also, energy sources are limited and most of them will going to give out.

In this thesis, a fuel cell system has been designed to meet the energy requirements of the secondary systems to make the ships with high carbon emissions more environmentally friendly.

4. METHODOLOGY

4.1.Equations

In this chapter, we start with an analysis the one of the fuel cell's electric power consisted with its losses. This analysis consisting of electrochemical reactions and law of thermodynamics. We assume hydrogen and oxygen are in stored in tanks. Reactions are happen simultaneously at anode and cathode in fuel cells. Most common and basic explanation of the reactions equations are:

$$\text{At the anode: } H_2 \rightarrow 2H^+ + 2e^- \tag{18}$$

$$\text{At the cathode: } \frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \tag{19}$$

$$\text{Overall: } H_2 + \frac{1}{2}O_2 \rightarrow H_2O \tag{20}$$
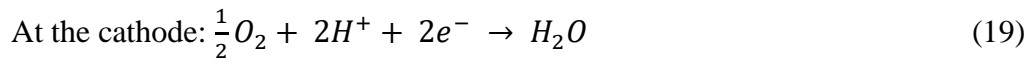
This reactions may change type of the fuel cell, adding some intermediate steps which are unwanted reactions.

Heating reaction is an exothermic reaction because of end of the reaction we observed heat is come out.

4.1.1.   Heat of Reaction

Overall the heat of reactions are same as the reaction of hydrogen combustion (equation 20). Combustion is an exothermic process. Exothermic processes means energy is released in the form of light or heat. Conversely of the endothermic process, energy is transferred into the surrounding instead of taking from the surrounding.

The enthalpy of the chemical reaction is calculated with the difference between the products and reactants.

$$\Delta H = (h_f)_{H_2O} - (h_f)_{H_2} - \frac{1}{2}(h_f)_{O_2} \tag{21}$$

In the Appendix Figure 1 shows us, molar enthalpy of formation of various substances. With the help of that chart, heat of formation of liquid water is -285,820 kJ/kmol at 25ºC. Heat of formation of elements is by definition equal to zero. Therefore, the above equation (21) equals to :

$$= \text{-285,820} - 0 - 0 = \text{-285.820 kJ/kmol} \tag{22}$$

The result contains negative sign. This means that, heat is released to surrounding, so the reaction is exothermic reaction. If we rewrite the equation (22):

$$H_2 + \frac{1}{2}O_2 \ \rightarrow \ H_2O + 285,820 \ kj/kmol \tag{23}$$
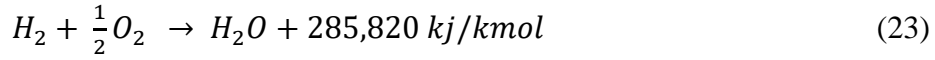
Now, in equation 23, the enthalpy has a positive sign because of the enthalpy is a product of the reaction now.

This equations are only valid for both the product water and reactant gases are at 25°C in atmospheric pressure. Also in 25°C and atmospheric pressure conditions, water occur in liquid form.

4.1.2.   Nerst Equation

To describing the ideal performance of a fuel cell there are different ways. Nernst equation provides a relationship between the standard potential for the cell reaction and the open circuit voltage. The Nernst equation assign us to determine the cell potential under nonstandard conditions. In the fuel cell, voltage is reversible. So the potential energy of the cell obtained in open circuit thermodynamic balance. In the fuel cell systems, electrons are moving around the external circuit. Energy for the external work, neglecting any work done by changes in pressure or volume. This can be also defined as the, deriving the Gibbs free energy. Chemical reactions are tent to minimize the Gibbs free energy. The equation of the Gibbs free energy is:

$$G = H - T\Delta S \tag{24}$$

Where the G is the Gibbs free energy, H is the enthalpy, T is the temperature and ΔS is the entropy change. This equation show, the Gibbs free energy is dependent on the temperature. Gibbs free energy equals to maximum energy of the fuel cell produce. The change in the Gibbs free energy for a per mole can write down with the following equation:

$$\Delta(g_f) = (g_f)_{products} - (g_f)_{reactants} \tag{25}$$

The difference between Gibbs free energy products and reactants can apply our equation 20 and given by:

$$\Delta(g_f) = (g_f)_{H20} - (g_f)_{H2} - \frac{1}{2}(g_f)_{O2} \tag{26}$$

As we know, in hydrogen fuel cell, two electrons pass around the external circuit for using each hydrogen molecule and producing each water molecule which is shown in equation form in equation 18 and 19. Therefore, one mole hydrogen using 2 times of the Avogadro's

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number electrons pass around the external circuit

If e is the charge on one electron, than charge is,

$$-2Ne = -2F \qquad (27)$$

Where N is the Avogadro's number (number of molecules per mole), e is the charge of electron and F is the Faraday's constant which is the value is 96485 Coulombs/electron-mol.

While moving the electrons around the circuit, electrical work done occurs. If E is the voltage of the fuel cell, electrical work done is:

$$\text{Electrical Work Done} = -2FE \qquad (28)$$

As we know our system is reversible, so the electrical work done will be equal to Gibbs free energy released. Therefore:

Electrical Work Done = $-2FE = -\Delta G$, Thus:

$$E = \frac{-\Delta G}{2F} \qquad (29)$$

As we shown the table in the appendix figure 2, we can determine the Gibbs free energy value. Also Faraday number is constant, we can calculate the theoretical fuel cell potential of hydrogen/oxygen is:

$$E = \frac{-\Delta G}{2F} = \frac{237178,408}{2(96485)} = 1,229 \, V \qquad (30)$$

As a discussion of the result of the equation 30, at 25ºC, our theoretical fuel cell potential is 1,229 Volts.

In the fuel cell, volume is fixed and isothermal, also the process is reversible. Therefore, the differential of the Gibbs free energy is given by:

$$dG = v_m dP \qquad (31)$$

Where v_m is the molar volume ($\frac{m^3}{mol}$) and P is the pressure (Pa). For the ideal gas:

$$Pv_m = RT \qquad (32)$$

Where R is te universal gas constant and value is $8,314 \, \frac{kJ}{kmol \, K}$. Therefore we can rearrange the equation 31 and:

$$dG = RT \frac{dP}{P} \tag{33}$$

If we integrated the equation 33, we get:

$$G = G_0 + RT \ln\left(\frac{P}{P_0}\right) \tag{34}$$

Where G_0 is Gibbs free energy at 25°C and 1 atm, and P_0 is the standard temperature. We rearrange the equation related with the partial pressure of the reactant and product, for the fuel cell reaction we get the Nernst equation becomes:

$$\Delta G = \Delta G_0 + RT \ln\left(\frac{P_{H_2O}}{P_{H_2} P_{O_2}^{0.5}}\right) \tag{35}$$

Also we can write the above equation 35:

$$E = \left(\frac{\Delta H}{2F} - \frac{T\Delta S}{2F}\right) + \frac{RT}{2F} \ln\left(\frac{P_{H_2} P_{O_2}^{0.5}}{P_{H_2O}}\right) \tag{36}$$

For the liquid water $P_{H_2O} = 1$, $P_{O_2} = 1/3$ and $P_{H_2} = 2/3$.

4.1.3.   Activation Losses

In the fuel cell, electrical circuit is the open circuit the practical potential energy is lower than the theoretical potential energy. We expect that, our practical potential energy is lower than 1V. This is corroborate we have some loses in the circuit. Some of the factors which are effects on the voltage losses, some of them are listed by the following:

- Internal current

- Internal electrical and ionic resistance

- Kinetics of the electrochemical reactions

- Crossover of reactants

Butler-Volmer equation, contains the relation between the current and applied potential. The equation related electrical current to changes in metal potential caused by an external power source. We can find the current density with the help of Butler-Volmer equation which is shown in equation 37. In equilibrium, the standard reduction and oxidation processes occur at equal rates and the exchange currents produced by the two reactions balance each other. [6]

$$i = i_0 \left[exp\left(-\frac{2\alpha F V_{act}}{RT}\right) - exp\left(\frac{2(1-\alpha)F V_{act}}{RT}\right)\right] \tag{37}$$

Where; i_0 = exchange current density (A/cm^2)

α = charge transfer coefficient

V_{act} = activation losses (Volt)

If we examine the equation 37; R, α, and F are the universal constants. α is coefficient and depends on the material of the electrode. So the exchange current density (i_0) depend on temperature and the concentrations of the oxidizing and reducing factors. As we show the activation losses simply with the help of the Tafel equation is:

$$V_{act} = a + b \, \log(i) \qquad (38)$$

Where:

$$a = -2.3 \, \frac{RT}{\alpha F} \log(i_0) \qquad (39)$$

And,

$$b = 2.3 \, \frac{RT}{\alpha F} \qquad (40)$$

If the reaction occurs slow, the Tafel slope of the b is higher. Also, if the reaction is faster, i_0 is higher and higher i_0 means lower voltage loss in activation loss. Effect of the temperature on the overvoltage is, increasing the temperature increase the overvoltage. At higher temperature and pressures enable the less importance of the activation loss.

4.1.4. Ohmic Losses

While electrons are flow through the external circuit, they face resistance to the flow of ions in the electrolyte and also face resistance to the flow of electrons through the electrically conductive fuel cell components. The resistance is proportional to thickness of electrolyte. If thickness of the electrolyte is decrease, resistance is decrease. Due to that, ohmic losses occur. Ohmic losses can be expressed by Ohm's Law:

$$V_{ohm} = iR_i \qquad (41)$$

Where i is the current density (Acm^2) and R_i is the total internal resistance (Ωcm^2).

Using highest possible conductivity for the electrodes, good design and making the electrolyte as thin as possible are the factors of reduce the internal resistance of the fuel cell.

4.1.5. Concentration Losses

In fuel cell systems, mass transfer of uncharged species must be continuously for maximum fuel cell efficiency and continuously be supplied fuel and oxidant to produce electricity. So, the reactant and product concentrations within the catalyst layers become important. This is used to determine the fuel cell efficiency. The loss can be optimized by control or optimize the mass transport in the fuel cell electrodes and flow structures.

The reactant concentration at the catalyst surface thus depends on current density. The effect is the higher current density means lower surface concentration. While this circumstance happens, current density called the limiting current density, i_L. A fuel cell cannot produce more than the limiting current because there are no reactants at the catalyst surface. [7]

Concentration loss can describe as the following equation:

$$V_{con} = \frac{RT}{2F} \ln\left(\frac{i_L}{i_L - i}\right) \qquad (42)$$

4.1.6.　　Fuel Cell Output Voltage

As we shown in the below figure 1 , output voltage obtained by removing the losses which are activation loss, ohmic loss and concentration loss to the Nernst equation.
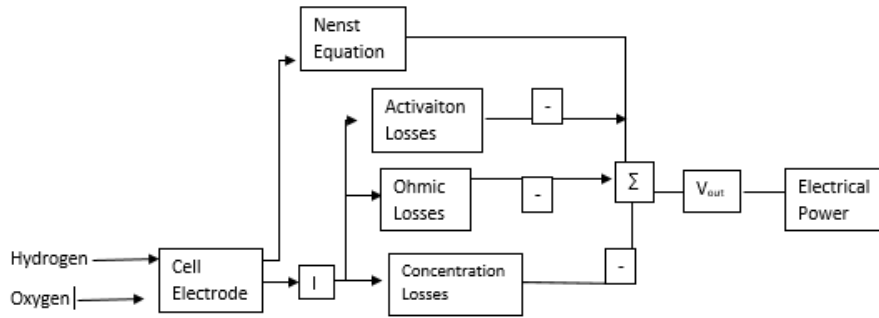
Figure 1. BAŞLIK [REFERENCE]

On the other hand, on the figure 2, shows the correlation of the three types of the losses between the current density and potential loss in the fuel cell. One of the result of the graph is activation losses has the largest losses at any current density.
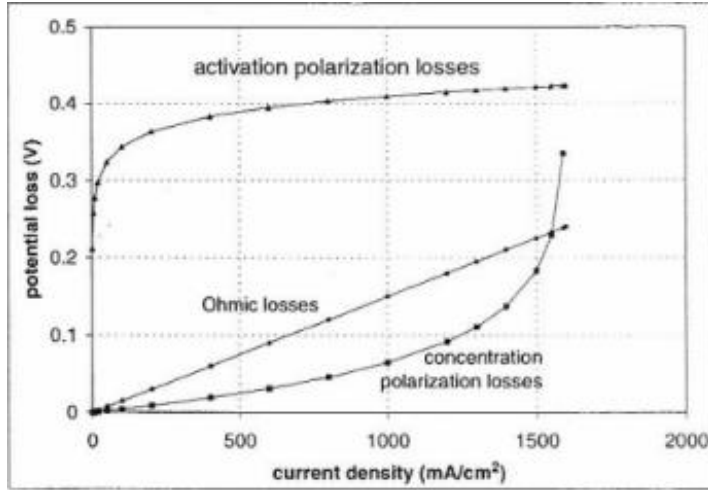
5. <mark>Figure 2. BAŞLIK</mark> [REFERENCE]

5.1.1. Fuel Cell Efficiency

The fuel cell efficiency can be calculated with the ratio of the electricity produced and hydrogen consumed, the unit is Watts or kilowatts.

$$\eta = \frac{W}{W_{H_2}} \tag{43}$$

Thus,

$$W = IV \tag{44}$$

Where I is the current (Amperes) and V is the cell potential (Volt). Energy value of hydrogen consumed can be calculated with the help of the Faraday's Law:

$$W_{H_2} = \Delta H \frac{1}{2F} \tag{45}$$

The unit of the hydrogen consume is Joule per second (Watts).

5.2. Flow Chart

1- Determine the inside of the fuel cell operation temperature and pressure.

2- Determine the appropriate model constant such as current density with the help of charts.

3- Specify the general constants.

4- Write down the Nernst voltage code on Matlab and calculate.

5- Write down the Ohmic loss code on Matlab and calculate.

6- Write down the Concentration loss code on Matlab and calculate.

7- Write down the Activation loss code on Matlab and calculate.

8- Write down the Output voltage code on Matlab and calculate. Create a plot with show the different temperatures effect on the output voltage.

9- Write down the Ohmic loss code on Matlab and calculate

10- Write down the Electrical output for one fuel cell code on Matlab and calculate. Create a plot with show the different temperatures effect on the electrical output.

11- Calculate the electrical output requirement of the ships and specify the stack number of the fuel cell.

12- Calculate and observe the effect of temperature on our model.

13- Calculate and observe the effect of pressure on our model.

6. RESULTS

6.1. The Effect of Temperature

Effect on Energy Output: The curve of output voltage is affecting by the terms that can be change due to temperatures increases or decreases. The operating temperature of the fuel cell has a direct effect on the energy output. It directly increases the energy produced by the fuel cell depending on the Nernst equation. The temperature also has an effect on losses. While it causes the concentration loss to increase, it reduces the activation loss but it has no effect on ohmic loss. However, since ohmic loss is affected by current density and total internal resistance, increasing or decreasing the temperature has no effect on ohmic loss. As it can be seen on the figure, it has a positive effect on the fuel cell energy as it reduces the activation loss, which is the biggest loss in the energy produced by the fuel cell. It was observed that the temperature increase had a positive effect on the power output.
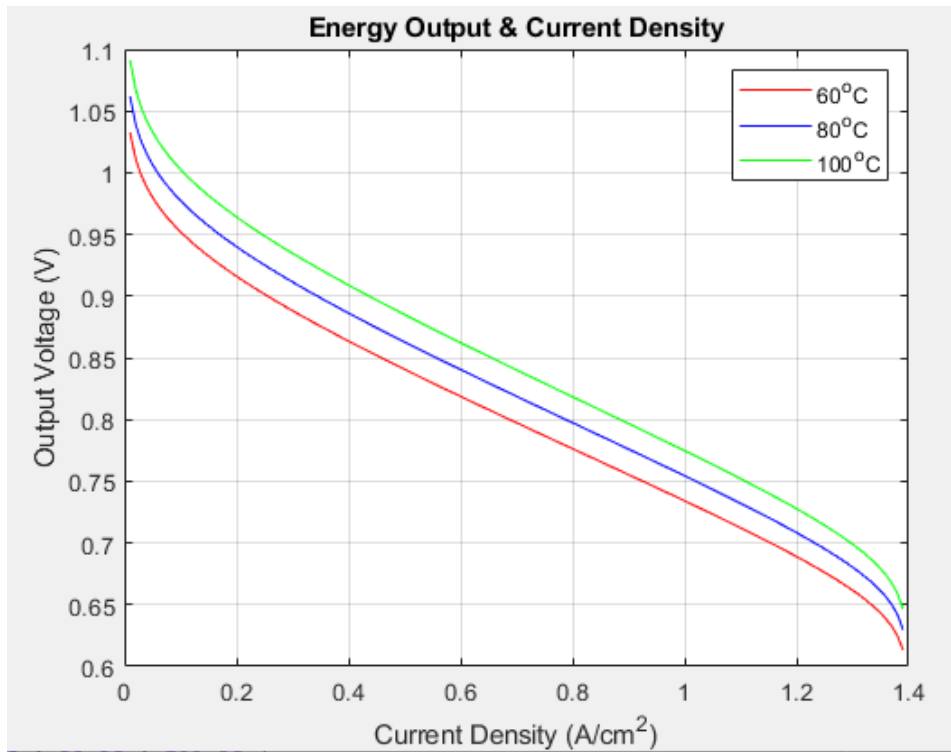

Figure 3 BAŞLIK

Effect On Electrical Output: Electrical power increases proportionally with current density and output voltage. As can be seen in the figure, electrical power has a high increase rate up to where the current density is $1.2\ A/cm^2$, but after that level, its increase has come to a standstill and even started to decrease due to the increase in losses especially due to mass transfer losses. The temperature change did not have much effect on the electrical power,

especially up to 1 A/cm^2 current density. Since the temperature does not have a direct effect on the electrical power and positively affects the energy output, the temperature change also has a positive effect on the electrical power in high current density regions.
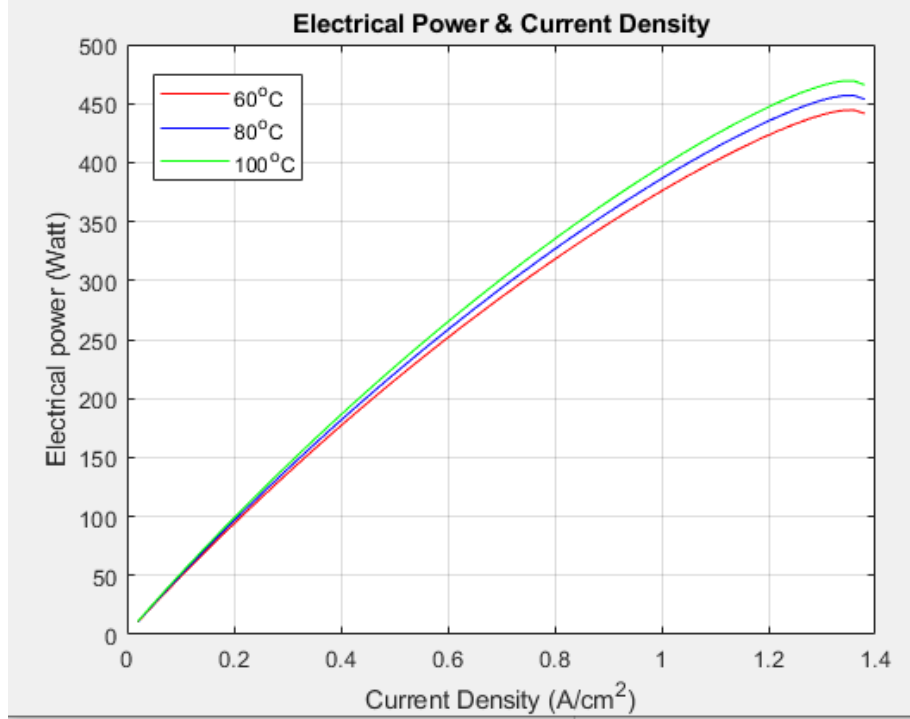

Figure 4 BAŞLIK

1.1. Effect of Pressure

Effect on Energy Output: The graph is shaped non-linearly due to factors that do not increase or decrease smoothly, especially in low (0-0.3 A/cm^2) and high current density (1.2-1.4 A/cm^2) regions. It can be seen from the graph that the pressure increase has a positive effect on the output voltage. The increase in the pressure value, unlike the temperature, is not close to each other at all values, while the increase was less when passing from 1 atm pressure to 3 atm pressure, while the increase was higher when passing from 3 atm to 5 atm.
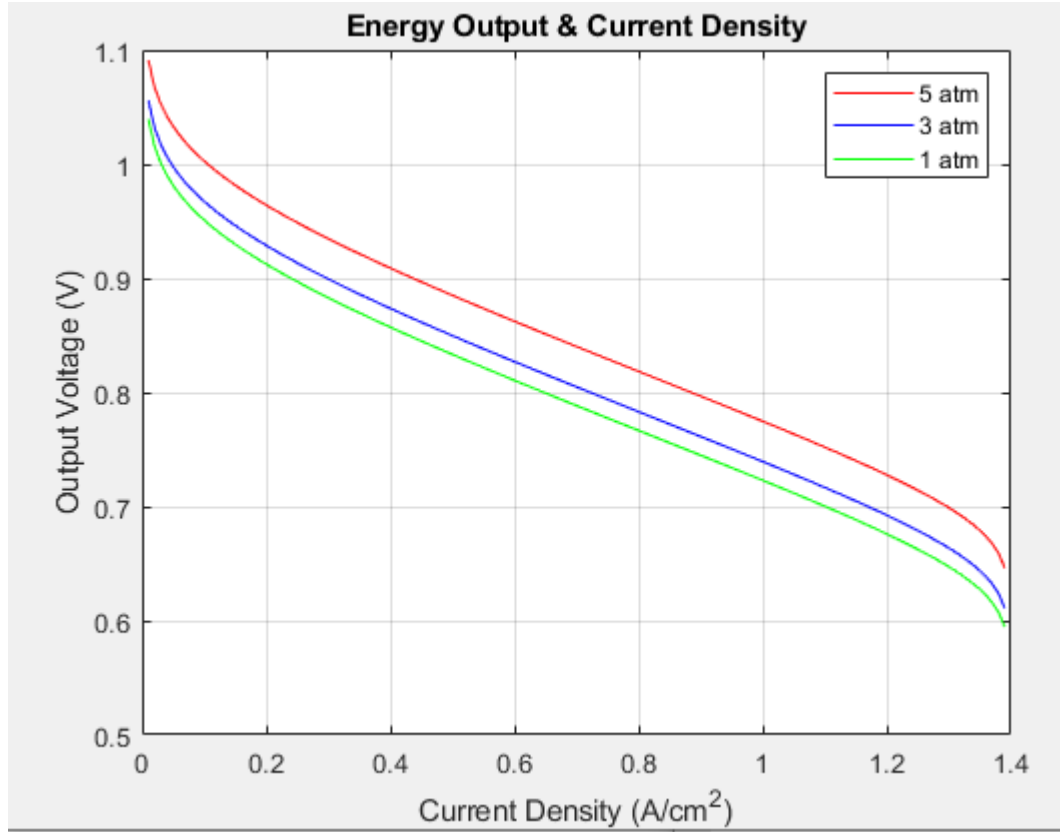
Figure 5 BAŞLIK

<u>Effect on Electrical Power</u>: Electrical power output is proportional to output voltage and current density. As a result, when pressure increases electrical power increases. As can be seen in the figure, electrical power has a high increase rate up to where the current density is 1.2 A/cm^2, but after that level, its increase has come to a standstill and even started to decrease due to the increase in losses especially due to mass transfer losses. As in the energy output graph, the difference between 1 atm pressure and 3 atm pressure is less at high current density values, while it is higher between 3 atm pressure and 5 atm pressure.
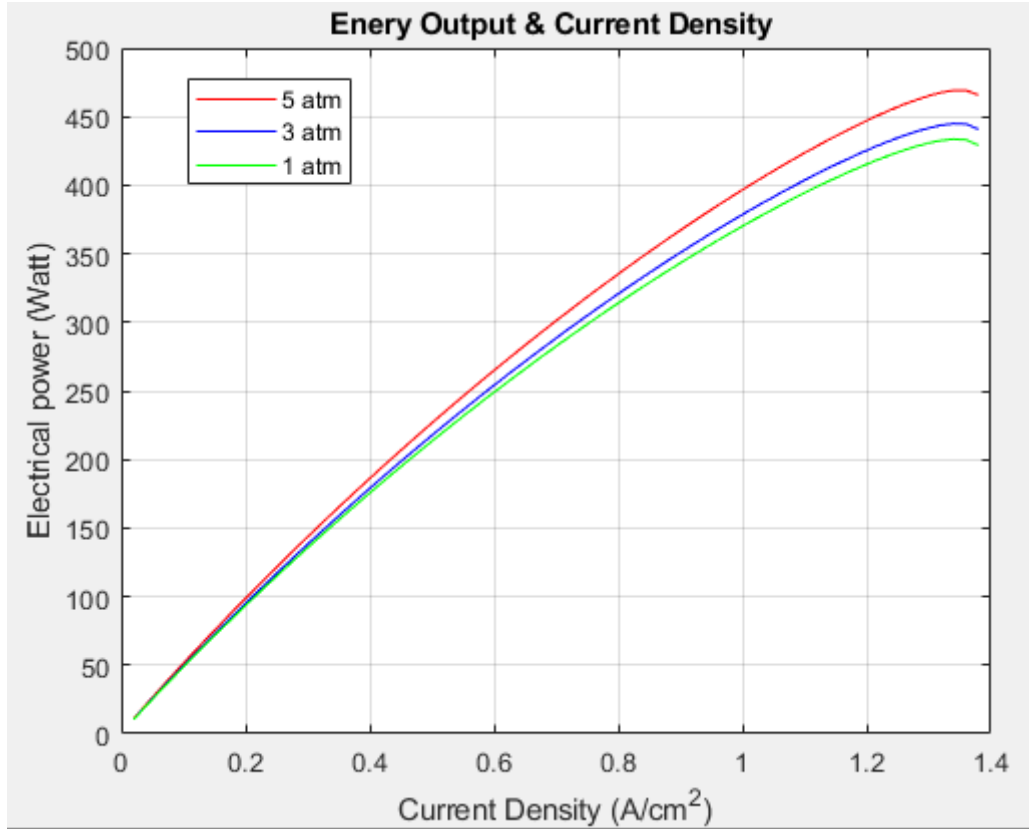
Figure 6 BAŞLIK

Effect of Pressure Coefficient: When the effect of the pressure coefficient, which was used as a constant (0.75) while operating the system, was examined by expanding the range, it was observed that the increase in the pressure coefficient had a positive effect on the energy output and was highly affected by the temperature as shown in the figure. Also, by increasing the pressure coefficient used in the system, the power output of the system will increase. The system used while observing the pressure coefficient difference, all the factors except pressure coefficient assumed constant.
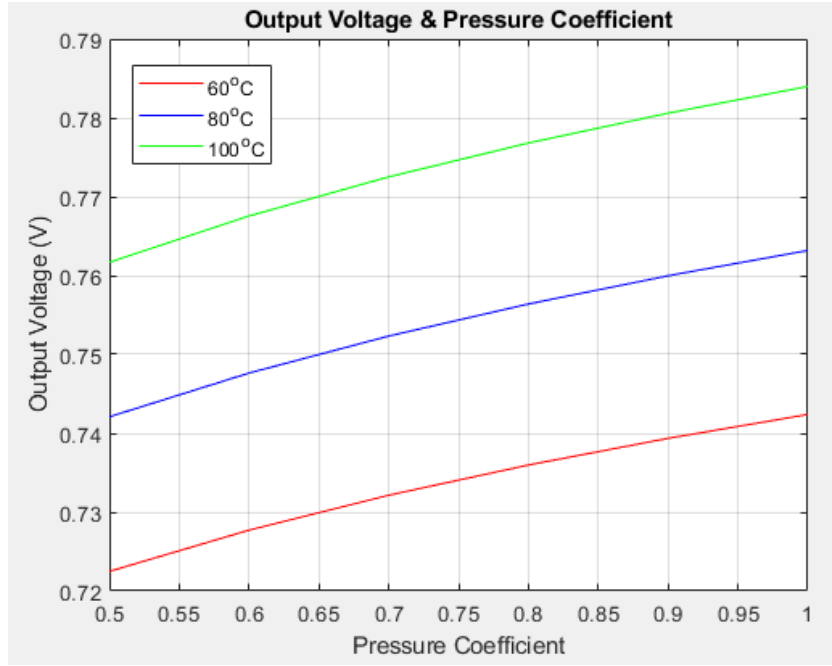
Figure 7 BAŞLIK

In the study based on 1 hydrogen fuel cell, it was observed that the fuel cell produced 386.267 watts of electrical power with a constant current density of 1 A/cm^2 and a temperature of 80 ℃ and a ship energy requirement is assumed to be 0.7 megawatt. As a result, 2000 fuel cells will be sufficient to meet the energy needs of the ship. As can be seen from the graph below, there is an inversely proportional relationship between efficiency and current density because when current density increases, mass transfer loss increases.
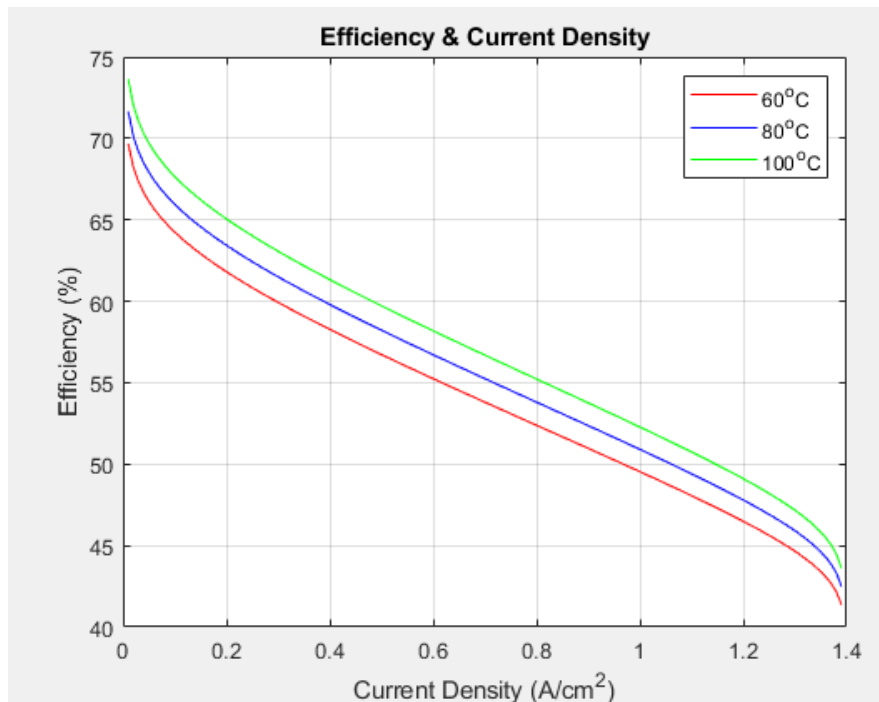
BAŞLIK

CONCLUSIONS

In this thesis, a PEM fuel cell is modeled. The factors that most affect the fuel cell performance outputs were defined and their effects were examined. The performance is reflected primarily in the PEM fuel cell output voltage, electrical power output and efficiencies. As a result, the main conclusions are as follows:

- There is a direct proportionality between the operating temperature and pressure of the fuel cell and the fuel cell performance.

- In cases where high electrical energy is needed, it is considered more appropriate to use the fuel cell at high pressure and temperature.

- It has been seen that there is an inverse ratio between current density and efficiency, but an optimal current density selection will be correct since there is also a direct ratio between current density and output energy.

- When the total area to be used for the fuel cell is calculated, it has been seen that the use of fuel cells is suitable for the ship. Although it is not preferred in the short term due to its high installation cost, it has been observed that this negativity turns into a positivity in the long term.

- Total efficiency value calculated according to the second law of thermodynamics is better with both higher temperatures and higher pressures.

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REFERANSLAR KISMINI GELİŞTİRİN BU KADAR REFERANS KABUL EDİLMEZ.

APPENDICES

Molar Enthalpy of Formation of Various Substances

Substance	Formula	M [kg/kmol]	hfo [kJ/kmol]
Carbon	$C(s)$	12.001	0
Hydrogen	$H_2(g)$	2.016	0
Nitrogen	$N_2(g)$	28.012	0
Oxygen	$O_2(g)$	32	0
Carbon monoxide	$CO(g)$	28.013	-110,530
Carbon dioxide	$CO_2(g)$	44.001	-393,520
Water Vapor	$H_2O(g)$	18.016	-241,820
Water	$H_2O(l)$	18.016	-285,820
Hydrogen peroxide	$H_2O_2(g)$	34.016	-136,310
Ammonia	$NH_3(g)$	17.03	-46,190
Methane	$CH_4(g)$	16.043	-74,850
Acetylene	$C_2H_2(g)$	26.038	226,730
Ethylene	$C_2H_4(g)$	24.034	52,280
Ethane	$C_2H_6(g)$	30.07	-84,680
Propylene	$C_3H_6(g)$	42.051	20,410
Propane	$C_3H_8(g)$	44.097	-103,850
n-Butane	$C_4H_{10}(g)$	58.123	-126,150
Benzene	$C_6H_6(g)$	78.114	82,930
n-Octane	$C_8H_{18}(g)$	114.231	-208,450
n-Octane	$C_8H_{18}(l)$	114.231	-249,950
n-Dodecane	$C_{12}H_{26}(g)$	170.22	-291,010
Methyl alcohol	$CH_3OH(g)$	32.043	-200,670
Methyl alcohol	$CH_3OH(l)$	32.043	-238,660
Ethyl alcohol	$C_2H_5OH(g)$	46.069	-235,310
Ethyl alcohol	$C_2H_5OH(l)$	46.069	-277,690
Oxygen	$O(g)$	16	249,190
Hydrogen	$H(g)$	1.008	218,000
Nitrogen	$N(g)$	14.006	472,650
Hydroxyl	$OH(g)$	17.008	39,460

Adapted from TEST (The Expert System for Thermodynamics) <www.thermofluids.net> by S.Bhattacharjee, San Diego State University

Figure 9

```
%%Nerns't Equaiton%%
clear all;
clc;
A=512; %fuel cell area
n=2000; %number of cells in 1 stack
F=96485; %Faraday's constant Coulombs/electron-mol
delta_g=-237340;
T=353.15;
R=8.3145; %Universal gas constant(Jmol^-1K^-1)
p_h2=2./3.;
p_o2=1./3.;
p_h2o=1; %When liquid water is produced in a fuel cell
Nernst=-(delta_g/(2*F))+(((R*T)/(2*F))*log((p_h2*p_o2)/p_h2o))

%%Ohmic Loss%%
i=1.0; %current density acm^-2
r_i=0.15; %total internal resistance ohmcm^2
v_ohmic=i*r_i

%%Concentration Loss%%
R=8.3145; %Universal gas constant
i_L=1.4; %Acm^-2;
V_conc=(R*T)./(2*F)*log((i_L./(i_L-i)))

%%Activation Loss%%
i_0_ref=3.0e-9;
a_c=2400;
L_c=0.4; %mgPtcm^-2
gamma=0.75;
E_c=66000; %Jmol^-1
p=2./3*10^5;
p_ref=101.325.*10^3;
T_ref=298.15;
alpha=1;
i_0=i_0_ref*a_c*L_c.*((p/p_ref).*(gamma))*exp((-E_c/(R*T)*(1-(T/T_ref))));
V_act=((R*T)./(alpha*F))*log(i./i_0)

%Vout%
Vout= Nernst-(v_ohmic+V_conc+V_act)


% Watt Output %
Wout=Vout.*A.*n.*i
```

```matlab
%%Nerns't Equaiton%%
clear all;
clc;
F=96485; %Faraday's constant Coulombs/electron-mol
delta_g=-237340;
T=333.15;
R=8.3145; %Universal gas constant(Jmol^-1K^-1)
p_h2=2./3.;
p_o2=1./3.;
p_h2o=1; %When liquid water is produced in a fuel cell
Nernst=(-(delta_g./(2.*F))+(((R.*T)./(2.*F))).*log((p_h2.*p_o2)./p_h2o))

%%Ohmic Loss%%
i=0:0.01:1.4; %current density acm^-2
r_i=0.15; %total internal resistance ohmcm^2
v_ohmic=i*r_i

%%Concentration Loss%%
R=8.3145; %Universal gas constant
i_L=1.4; %Acm^-2;
V_conc=((R.*T)./(2*F))*log((i_L./(i_L-i)))

%%Activation Loss%%
i_0_ref=3.0e-9;
a_c=2400;
L_c=0.4; %mgPtcm^-2
gamma=0.75;
E_c=66000; %Jmol^-1
p=2./3*10^5;
p_ref=101.325.*10^3;
T_ref=298.15;
alpha=1;
i_0=(i_0_ref.*a_c.*L_c.*((p/p_ref).*(gamma))).*exp((-E_c./(R.*T).*(1-(T./T_ref))));
V_act=(((R.*T)./(alpha.*F))).*log(i./i_0)

%Vout%
Vout_1= Nernst-(v_ohmic+V_conc+V_act)
```

```matlab
%%Nerns't Equaiton%%
F=96485; %Faraday's constant Coulombs/electron-mol
delta_g=-237340;
T=353.15;
R=8.3145; %Universal gas constant(Jmol^-1K^-1)
p_h2=2./3.;
p_o2=1./3.;
p_h2o=1; %When liquid water is produced in a fuel cell
Nernst=(-(delta_g./(2.*F))+(((R.*T)./(2.*F))).*log((p_h2.*p_o2)./p_h2o))

%%Ohmic Loss%%
i=0:0.01:1.4; %current density acm^-2
r_i=0.15; %total internal resistance ohmcm^2
v_ohmic=i*r_i

%%Concentration Loss%%
R=8.3145; %Universal gas constant
i_L=1.4; %Acm^-2;
V_conc=((R.*T)./(2*F))*log((i_L./(i_L-i)))

%%Activation Loss%%
i_0_ref=3.0e-9;
a_c=2400;
L_c=0.4; %mgPtcm^-2
gamma=0.75;
E_c=66000; %Jmol^-1
p=2./3*10^5;
p_ref=101.325.*10^3;
T_ref=298.15;
alpha=1;
i_0=(i_0_ref.*a_c.*L_c.*((p/p_ref).*(gamma))).*exp((-E_c./(R.*T).*(1-(T./T_ref)))));
V_act=(((R.*T)./(alpha.*F))).*log(i./i_0)

%Vout%
Vout_2= Nernst-(v_ohmic+V_conc+V_act)
```

```matlab
%%Nerns't Equaiton%%
F=96485; %Faraday's constant Coulombs/electron-mol
delta_g=-237340;
T=373.15;
R=8.3145; %Universal gas constant(Jmol^-1K^-1)
p_h2=2./3.;
p_o2=1./3.;
p_h2o=1; %When liquid water is produced in a fuel cell
Nernst=(-(delta_g./(2.*F))+(((R.*T)./(2.*F))).*log((p_h2.*p_o2)./p_h2o))

%%Ohmic Loss%%
i=0:0.01:1.4; %current density acm^-2
r_i=0.15; %total internal resistance ohmcm^2
v_ohmic=i*r_i

%%Concentration Loss%%
R=8.3145; %Universal gas constant
i_L=1.4; %Acm^-2;
V_conc=((R.*T)./(2*F)).*log((i_L./(i_L-i)))

%%Activation Loss%%
i_0_ref=3.0e-9;
a_c=2400;
L_c=0.4; %mgPtcm^-2
gamma=0.75;
E_c=66000; %Jmol^-1
p=2./3*10^5;
p_ref=101.325.*10^3;
T_ref=298.15;
alpha=1;
i_0=(i_0_ref.*a_c.*L_c.*((p/p_ref).*(gamma))).*exp((-E_c./(R.*T).*(1-(T./T_ref)))));
V_act=(((R.*T)./(alpha.*F))).*log(i./i_0)

%Vout%
Vout_3= Nernst-(v_ohmic+V_conc+V_act)

plot(i,Vout_1,'r',i,Vout_2,'b',i,Vout_3,'g')
title ('Energy Output & Current Density')
xlabel('Current Density (A/cm^2)')
ylabel('Output Voltage (V)')
legend('60^oC','80^oC','100^oC')
grid on
```

33

```matlab
%Electrical Output
A=512; %area of fuel cell cm^2
n=1; %stack number
Wout1=Vout_1.*A.*n.*i
Wout2=Vout_2.*A.*n.*i
Wout3=Vout_3.*A.*n.*i

plot(i,Wout1,'r',i,Wout2,'b',i,Wout3,'g')
title('Electrical Power for 1 Cell ')
xlabel('Current Density (A/cm^2)')
ylabel('Electrical power (Watt)')
legend('60^oC','80^oC','100^oC')
grid on
```

```matlab
%%Nerns't Equaiton%%
clear all;
clc;
F=96485; %Faraday's constant Coulombs/electron-mol
delta_g=-237340;
T=373.15;
R=8.3145; %Universal gas constant(Jmol^-1K^-1)
p_h2=2./3.;
p_o2=1./3.;
p_h2o=1; %When liquid water is produced in a fuel cell
Nernst=(-(delta_g./(2.*F))+(((R.*T)./(2.*F))).*log((p_h2.*p_o2)./p_h2o))

%%Ohmic Loss%%
i=0:0.01:1.4; %current density acm^-2
r_i=0.15; %total internal resistance ohmcm^2
v_ohmic=i*r_i;

%%Concentration Loss%%
R=8.3145; %Universal gas constant
i_L=1.4; %Acm^-2;
V_conc=((R.*T)./(2*F))*log((i_L./(i_L-i)))

%%Activation Loss%%
i_0_ref=3.0e-9;
a_c=2400;
L_c=0.4; %mgPtcm^-2
gamma=0.75;
E_c=66000; %Jmol^-1
p=2./3*10^5;
p_ref=101.325.*10^3;
T_ref=298.15;
alpha=1;
i_0=(i_0_ref.*a_c.*L_c.*((p/p_ref).*(gamma))).*exp((-E_c./(R.*T).*(1-(T./T_ref))));
V_act=(((R.*T)./(alpha.*F))).*log(i./i_0)

%Vout%
Vout_1= Nernst-(v_ohmic+V_conc+V_act)
```

```matlab
%%Nerns't Equaiton%%
F=96485; %Faraday's constant Coulombs/electron-mol
delta_g=-237340;
T=373.15;
R=8.3145; %Universal gas constant(Jmol^-1K^-1)
p_h2=2./3.;
p_o2=1./3.;
p_h2o=1; %When liquid water is produced in a fuel cell
Nernst=(-(delta_g./(2.*F))+(((R.*T)./(2.*F))).*log((p_h2.*p_o2)./p_h2o))

%%Ohmic Loss%%
i=0:0.01:1.4; %current density acm^-2
r_i=0.15; %total internal resistance ohmcm^2
v_ohmic=i*r_i

%%Concentration Loss%%
R=8.3145; %Universal gas constant
i_L=1.4; %Acm^-2;
V_conc=((R.*T)./(2*F))*log((i_L./(i_L-i)))

%%Activation Loss%%
i_0_ref=3.0e-9;
a_c=2400;
L_c=0.4; %mgPtcm^-2
gamma=0.75;
E_c=66000; %Jmol^-1
p=2./3*10^5;
p_ref=303.975.*10^3;
T_ref=298.15;
alpha=1;
i_0=(i_0_ref.*a_c.*L_c.*((p/p_ref).*(gamma))).*exp((-E_c./(R.*T).*(1-(T./T_ref))));
V_act=(((R.*T)./(alpha.*F))).*log(i./i_0)
```

```matlab
%%Nerns't Equaiton%%
F=96485; %Faraday's constant Coulombs/electron-mol
delta_g=-237340;
T=373.15;
R=8.3145; %Universal gas constant(Jmol^-1K^-1)
p_h2=2./3.;
p_o2=1./3.;
p_h2o=1; %When liquid water is produced in a fuel cell
Nernst=(-(delta_g./(2.*F))+(((R.*T)./(2.*F))).*log((p_h2.*p_o2)./p_h2o))

%%Ohmic Loss%%
i=0:0.01:1.4; %current density acm^-2
r_i=0.15; %total internal resistance ohmcm^2
v_ohmic=i*r_i

%%Concentration Loss%%
R=8.3145; %Universal gas constant
i_L=1.4; %Acm^-2;
V_conc=((R.*T)./(2*F)).*log((i_L./(i_L-i)))

%%Activation Loss%%
i_0_ref=3.0e-9;
a_c=2400;
L_c=0.4; %mgPtcm^-2
gamma=0.75;
E_c=66000; %Jmol^-1
p=2./3*10^5;
p_ref=506.625.*10^3;
T_ref=298.15;
alpha=1;
i_0=(i_0_ref.*a_c.*L_c.*((p/p_ref).*(gamma))).*exp((-E_c./(R.*T).*(1-(T./T_ref)))));
V_act=(((R.*T)./(alpha.*F))).*log(i./i_0)

%Vout%
Vout_3= Nernst-(v_ohmic+V_conc+V_act)

plot(i,Vout_1,'r',i,Vout_2,'b',i,Vout_3,'g')
title ('Energy Output & Current Density')
xlabel('Current Density (A/cm^2)')
ylabel('Output Voltage (V)')
legend('5 atm','3 atm','1 atm')
grid on
```

```matlab
%%Nerns't Equaiton%%
clear all;
clc;
F=96485; %Faraday's constant Coulombs/electron-mol
delta_g=-237340;
T=373.15;
R=8.3145; %Universal gas constant(Jmol^-1K^-1)
p_h2=2./3.;
p_o2=1./3.;
p_h2o=1; %When liquid water is produced in a fuel cell
Nernst=(-(delta_g./(2.*F))+(((R.*T)./(2.*F))).*log((p_h2.*p_o2)./p_h2o))

%%Ohmic Loss%%
i=0:0.02:1.4; %current density acm^-2
r_i=0.15; %total internal resistance ohmcm^2
v_ohmic=i*r_i

%%Concentration Loss%%
R=8.3145; %Universal gas constant
i_L=1.4; %Acm^-2;
V_conc=((R.*T)./(2*F))*log((i_L./(i_L-i)))

%%Activation Loss%%
i_0_ref=3.0e-9;
a_c=2400;
L_c=0.4; %mgPtcm^-2
gamma=0.75;
E_c=66000; %Jmol^-1
p=2./3*10^5;
p_ref=101.325.*10^3;
T_ref=298.15;
alpha=1;
i_0=(i_0_ref.*a_c.*L_c.*((p/p_ref).*(gamma))).*exp((-E_c./(R.*T).*(1-(T./T_ref))));
V_act=(((R.*T)./(alpha.*F))).*log(i./i_0)

%Vout%
Vout_1= Nernst-(v_ohmic+V_conc+V_act)
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L_c=0.4; %mgPtcm^-2
gamma=0.75;
E_c=66000; %Jmol^-1
p=2./3*10^5;
p_ref=303.675.*10^3;
T_ref=298.15;
alpha=1;
i_0=(i_0_ref.*a_c.*L_c.*((p/p_ref).*(gamma))).*exp((-E_c./(R.*T).*(1-(T./T_ref)))));
V_act=(((R.*T)./(alpha.*F))).*log(i./i_0)

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Vout_2= Nernst-(v_ohmic+V_conc+V_act)
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L_c=0.4; %mgPtcm^-2
gamma=0.75;
E_c=66000; %Jmol^-1
p=2./3*10^5;
p_ref=506.975.*10^3;
T_ref=298.15;
alpha=1;
i_0=(i_0_ref.*a_c.*L_c.*((p/p_ref).*(gamma))).*exp((-E_c./(R.*T).*(1-(T./T_ref))));
V_act=(((R.*T)./(alpha.*F))).*log(i./i_0)

%Vout%
Vout_3= Nernst-(v_ohmic+V_conc+V_act)

%Electrical Output
A=512; %area of fuel cell cm^2
n=1; %stack number
Wout1=Vout_1.*A.*n.*i
Wout2=Vout_2.*A.*n.*i
Wout3=Vout_3.*A.*n.*i


plot(i,Wout1,'r',i,Wout2,'b',i,Wout3,'g')
title('Enery Output & Current Density ')
xlabel('Current Density (A/cm^2)')
ylabel('Electrical power (Watt)')
legend('5 atm','3 atm','1 atm')
grid on
```

```matlab
%%Nernst Equaiton%%
clear all;
clc;
F=96485; %Faraday's constant Coulombs/electron-mol
delta_g=-237340;
T=333.15;
R=8.3145; %Universal gas constant(Jmol^-1K^-1)
p_h2=2./3.;
p_o2=1./3.;
p_h2o=1; %When liquid water is produced in a fuel cell
Nernst=(-(delta_g./(2.*F))+(((R.*T)./(2.*F))).*log((p_h2.*p_o2)./p_h2o))

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L_c=0.4; %mgPtcm^-2
gamma=0.5:0.1:1;
E_c=66000; %Jmol^-1
p=2./3*10^5;
p_ref=101.325.*10^3;
T_ref=298.15;
alpha=1;
i_0=(i_0_ref.*a_c.*L_c.*((p/p_ref).*(gamma))).*exp((-E_c./(R.*T).*(1-(T./T_ref))));
V_act=(((R.*T)./(alpha.*F))).*log(i./i_0)

%Vout%
Vout_1= Nernst-(v_ohmic+V_conc+V_act)
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delta_g=-237340;
T=353.15;
R=8.3145; %Universal gas constant(Jmol^-1K^-1)
p_h2=2./3.;
p_o2=1./3.;
p_h2o=1; %When liquid water is produced in a fuel cell
Nernst=(-(delta_g./(2.*F))+(((R.*T)./(2.*F))).*log((p_h2.*p_o2)./p_h2o))

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p=2./3*10^5;
p_ref=101.325.*10^3;
T_ref=298.15;
alpha=1;
i_0=(i_0_ref.*a_c.*L_c.*((p/p_ref).*(gamma))).*exp((-E_c./(R.*T).*(1-(T./T_ref)))));
V_act=(((R.*T)./(alpha.*F))).*log(i./i_0)

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V_act=(((R.*T)./(alpha.*F))).*log(i./i_0)

%Vout%
Vout_3= Nernst-(v_ohmic+V_conc+V_act)

plot(gamma,Vout_1,'r',gamma,Vout_2,'b',gamma,Vout_3,'g')
title ('Output Voltage & Pressure Coefficient')
xlabel('Pressure Coefficient')
ylabel('Output Voltage (V)')
legend('60^oC','80^oC','100^oC')
grid on
```

```matlab
%%Nerns't Equaiton%%
clear all;
clc;
F=96485; %Faraday's constant Coulombs/electron-mol
delta_g=-237340;
T=333.15;
R=8.3145; %Universal gas constant(Jmol^-1K^-1)
p_h2=2./3.;
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p_h2o=1; %When liquid water is produced in a fuel cell
Nernst=(-(delta_g./(2.*F))+(((R.*T)./(2.*F))).*log((p_h2.*p_o2)./p_h2o))

%%Ohmic Loss%%
i=0:0.01:1.4; %current density acm^-2
r_i=0.15; %total internal resistance ohmcm^2
v_ohmic=i*r_i

%%Concentration Loss%%
R=8.3145; %Universal gas constant
i_L=1.4; %Acm^-2;
V_conc=((R.*T)./(2*F))*log((i_L./(i_L-i)))

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p=2./3*10^5;
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T_ref=298.15;
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i_0=(i_0_ref.*a_c.*L_c.*((p/p_ref).*(gamma))).*exp((-E_c./(R.*T).*(1-(T./T_ref)))));
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V_act=(((R.*T)./(alpha.*F))).*log(i./i_0)

%Vout%
Vout_3= Nernst-(v_ohmic+V_conc+V_act)

%Efficiency
eff1=(Vout_1./(1.482))*100
eff2=(Vout_2./(1.482))*100
eff3=(Vout_3./(1.482))*100

plot(i,eff1,'r',i,eff2,'b',i,eff3,'g')
title ('Efficiency & Current Density')
xlabel('Current Density (A/cm^2)')
ylabel('Efficiency (%)')
legend('60^oC','80^oC','100^oC')
grid on
```