SUSTAINABLE METHODOLOGY FOR THE USE OF FUEL CELLS IN DATA CENTERS

by

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To my parents, Brother, Professor and friends

Parameswari and Balasubramanian, Akkineswaran, Dr.Dereje Agonafer,

Sandeep Patil and Divya Sakthivel

I am here and I could do this only because of you all

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ABSTRACT

SUSTAINABLE METHODOLOGY FOR THE USE OF FUEL CELLS IN DATA CENTERS

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Data centers have become the lynchpin of the modern economy – from the small to medium-sized organizations, to the enterprise data centers that operates American corporations and the server farms that operate cloud-computing services accommodated by Facebook, Amazon, Google, and others. The booming of cloud storage, extensive data analysis, e-commerce, and internet traffic is also making data centers one of the rapidly growing clients of electricity in developed countries, and one of the key drivers in the construction of new power plants. Key researches are carried out for sustainable development of power usage in data centers. Fuel cells have gone forth as one of the rapidly growing substitute power sources over the period of time. Whereas the 19^{th} century was the century of the steam engine and the 20^{th} century was the century of the internal combustion engine, it is potential that the 21^{st} century will be the century of the fuel cell. The fuel cell is changing the human view of producing power itself. Fuel cells can use hydrogen as a fuel, giving out cleaner, sustainable electrical power for the world. In this research, a fuel cell is designed that can potentially provide power for a rack of servers as a primary power source.

Fuel cell parameters are calculated using various thermodynamic and mathematical equations. Hydrogen (fuel) supply is needed continuously for the fuel cell to work endlessly. Solar energy is utilized to produce hydrogen at a higher rate than the need of fuel cell. ZnO/Zn water-splitting thermochemical cycle is developed in order to satisfy the objectives.

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INTRODUCTION

1.1 The history of fuel cells

“Father of Fuel Cells”, Sir William Grove, a british lawyer and amateur scientist was the first person to discover fuel cells in 1839. He observed current flowing between two electrodes when he suspended the connection between battery and electrolyser accidentally in an electrolysis experiment. During this process he watched hydrogen and oxygen getting exhausted with the flow of current and named this device as ‘Gas Battery’ [fig 1.1]. Later on, he developed his battery consisting of Platinum electrodes inside test tube containing hydrogen and oxygen immersed in sulphuric acid. Several gas batteries were connected in series to generate higher voltage and it was termed as ‘Gas Chain’ [fig 1.1] by Sir William in 1842. He faced electrode corrosion problems in the later part of the development of Fuel Cells.

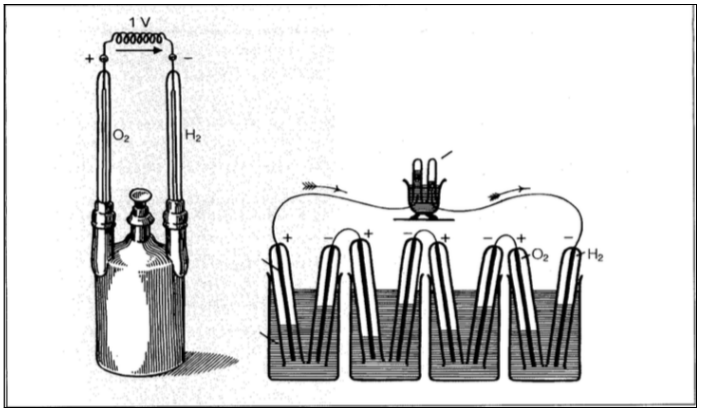


Figure 1.1. Groves gas battery and gas chain (Image: Fuel cell [1]).

In 1950, a chemical engineer from the University of Cambridge, Francis Bacon produced the first practical fuel cell. It used an alkaline electrolyte (molten KOH) in order to eliminate corrosion caused by sulphuric acid. Electrodes were coated with porous sintered nickel powder to increase the contact area between the electrodes, the gases and the electrolyte. It resulted in higher voltage generation.

1.2 Fuel cells for NASA

In the 1960's, International Fuel Cells in Windsor, Connecticut, USA, developed a fuel cell power plant for the Apollo Spacecraft. Fuel cell produces several times of energy compared to the conventional batteries which helped in generating electricity and supply drinking water for the astronauts on their voyage to the moon. It provided 1.5 kW of uninterrupted electric power. In 1970's , a more powerful alkaline fuel cell for NASA's space shuttle orbiter was developed. It used 3 fuel cell power plants to meet the electrical needs. Cryogenic tanks were used to fuel hydrogen and oxygen to the power plants . It had the capacity of supplying 12 kW of electric power continuously and 16 kW for short duration. Space shuttle orbiter proved to be one of the greatest advancement over fuel cell by producing 10 times the power from a similar sized package. Fuel cells stood out highly reliable in space missions and continued to accomplish over 106 missions and clogged up over 82 hours of operation. [Internet source : NASA]

NASA Glenn research center is the focal point for NASA's fuel cell research and development. They are conducting research on proton-exchange membrane fuel cells(PEMFC), regenerative fuel cell (RFC) and solid-oxide fuel cells (SOFC). PEMFC was first used in Gemini Mission which proved to be more powerful, lighter, safer, simpler to operate and more reliable. It even produced electric supply for space suits, airplanes and uninhabited air vehicles and reusable launch vehicles.

Figure 1.2. Short and Long stacks of PEMFC for different power needs (Image: www.nasa.gov).

One of the uninhabited air vehicles was Mars Flyer [fig 1.3] which used PEM fuel cell technology. NASA Glenn's fuel cell research could lead to new flight capabilities, electric power for long-term human exploration beyond earth orbit, more efficient cars and trucks and a cleaner environment.

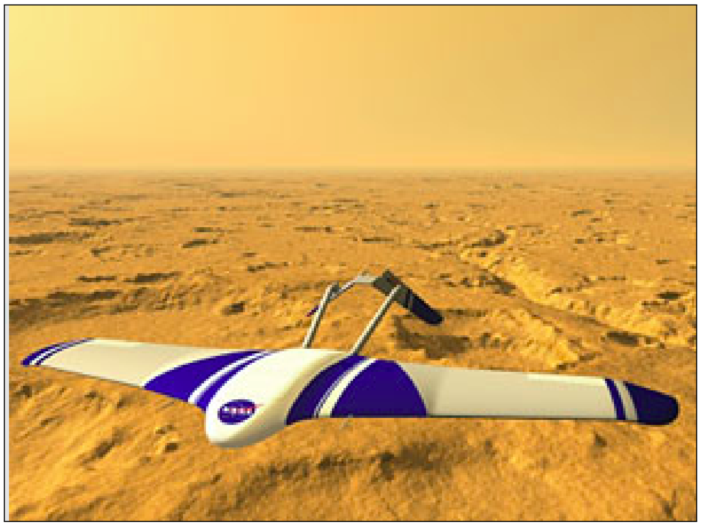


Figure 1.3. Mars flyer powered by PEMFC (Image: www.nasa.gov).

1.3 Fuel cells applications

NECAR 5 was the latest prototype fuel cell automobile developed by Daimlerchrysler in 2000. It was powered by liquid methanol which gets converted into hydrogen with a use of onboard fuel processor. It's efficiency proved to be high measuring twice that of the internal combustion engines. It has a top speed of 150km/hr with a power output of 100hp. It has very low emission levels and smooth compare to electric vehicles. Later fuel cells started getting implemented into buses, heavy duty trucks and cars produced by all major manufacturers [fig 1.4].

Fuel cell powerplants for residential and industrial applications were developed to aid the backup power. In case of a power outage fuel cells eliminated lead acid battery and diesel generators for uninterrupted power supply (UPS). With majority of developing countries increase in power demand , fuel cell came to rescue the power needs with lower pollution rates and higher efficiency.

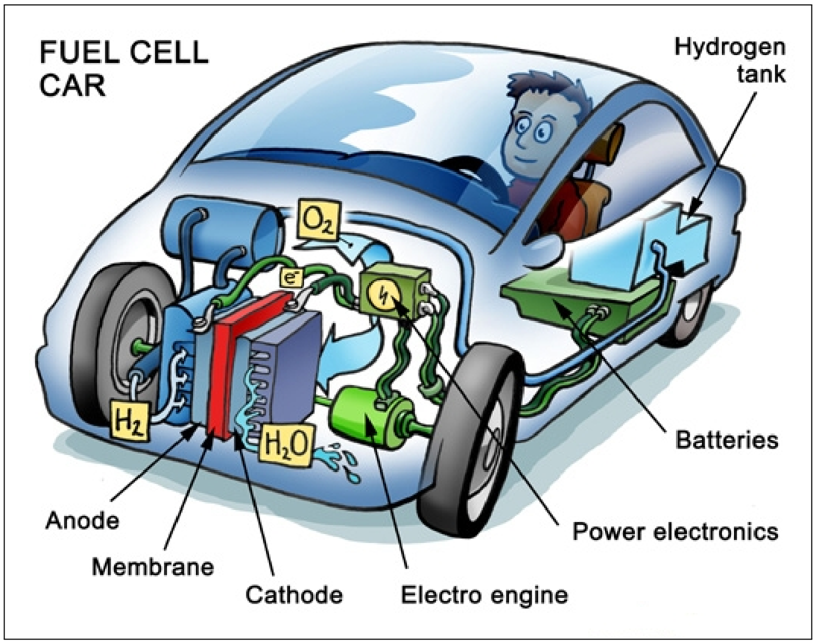


Figure 1.4. Fuel cells in automobiles (Image: Wikipedia).

1.4 Fuel cell stacking

Multiple unit cells are connected in series via electrically conductive interconnects to achieve the required voltage and power output level for the application. The different stacking arrangements that have been developed are described below:

1.4.1 Planar-bipolar stacking

Most of the fuel cell stack follows the planar bipolar design. In this, individual unit cells are electrically connected with interconnects. The interconnects becomes a separator plate with two different functions :

- It provides electrical series connection between adjacent cells.
- It acts as a gas barrier to separate fuel and oxidant of adjacent cells.

In this stack, air and fuel flow are perpendicular to each other when there is a crossflow arrangement. Its manifold run through the unit cells. Manifolds do not penetrate the unit cells but are integrated in the interconnects.

1.4.2 Stacks with tubular cells

Tubular cell stacks are mainly developed for high temperature fuel cells. It has a significant advantage in sealing and structural integrity of cells. It can be used for high power density and short current paths. These cell arrays can be connected in either series or in parallel [1].

1.5 Fuel cell system

A fuel cell system is designed using several subsystems and components to make it function precisely. These subsystem and components are called balance of plants. This balance of plant creates specific operating conditions and requirements of individual operating conditions and requirements for a fuel cell system. Some of the purposes of balance of plant are listed below:

- Fuel Preparation
- Air Supply
- Thermal Management
- Water Management
- Electric Power Conditioning Equipment

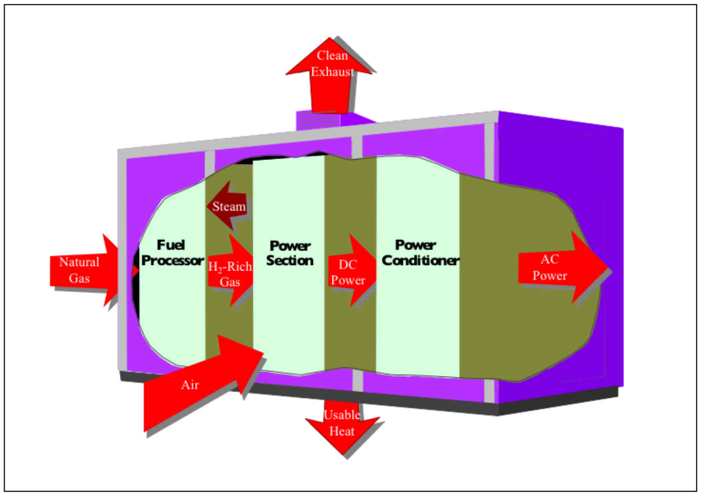
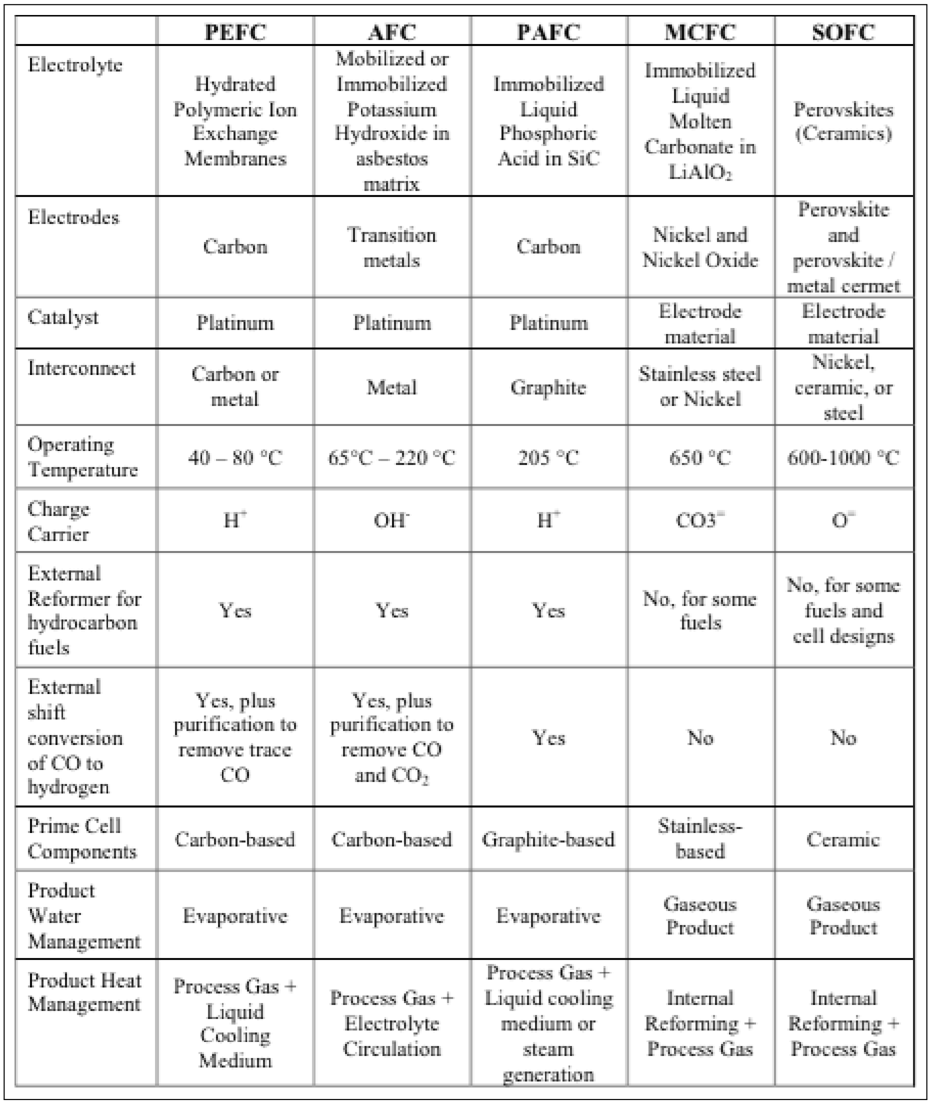


Figure 1.5. Fuel cell power plant (Image: FChandbook 7,NTEL).

Fuel Cell powerplants generally consist of a fuel processing system that supplies highly pure fuel to the cell stack, cell stack utilize the rich gas and air and gives out DC power with the expulsion of clean exhaust and usable heat. DC power is converted into usable AC power using power conditioning system.

1.6 Types of fuel cell

There are different fuel cells in variety of stages of development. Classification of fuel cell is generally done on the basis of type of electrolyte used in the cell. These electrolytes are decided depending upon the operating temperature range [2]. The different types of fuel cell are as listed in the figure 1.6



	PEFC	AFC	PAFC	MCFC	SOFC
Electrolyte	Hydrated Polymeric Ion Exchange Membranes	Mobilized or Immobilized Potassium Hydroxide in asbestos matrix	Immobilized Liquid Phosphoric Acid in SiC	Immobilized Liquid Molten Carbonate in $LiAlO_2$	Perovskites (Ceramics)
Electrodes	Carbon	Transition metals	Carbon	Nickel and Nickel Oxide	Perovskite and perovskite / metal cermet
Catalyst	Platinum	Platinum	Platinum	Electrode material	Electrode material
Interconnect	Carbon or metal	Metal	Graphite	Stainless steel or Nickel	Nickel, ceramic, or steel
Operating Temperature	40 – 80 °C	65°C – 220 °C	205 °C	650 °C	600-1000 °C
Charge Carrier	H^+	OH^-	H^+	$CO3^{=}$	$O^{=}$
External Reformer for hydrocarbon fuels	Yes	Yes	Yes	No, for some fuels	No, for some fuels and cell designs
External shift conversion of CO to hydrogen	Yes, plus purification to remove trace CO	Yes, plus purification to remove CO and CO_2	Yes	No	No
Prime Cell Components	Carbon-based	Carbon-based	Graphite-based	Stainless-based	Ceramic
Product Water Management	Evaporative	Evaporative	Evaporative	Gaseous Product	Gaseous Product
Product Heat Management	Process Gas + Liquid Cooling Medium	Process Gas + Electrolyte Circulation	Process Gas + Liquid cooling medium or steam generation	Internal Reforming + Process Gas	Internal Reforming + Process Gas

Figure 1.6. Types of fuel cell (Image: FChandbook 7,NTEL).

1.6.1 Polymer electrolyte membrane fuel cell

The electrolyte in this fuel cell is an ion exchange membrane i.e. an excellent proton conductor. It has very minimal corrosion problems due to only water existing inside the cell. It consist of carbon electrodes with platinum electro-catalyst that are used for both anode and cathode and with either carbon or metal interconnects. It is critical to manage the water content in the membrane for higher efficiency. The fuel cell should never exceed the given operating conditions [3].

- Advantages:
    - It has high resistance to gas crossover.
    - It operates on low temperature.
    - It requires minimum components to design its control system.
- Disadvantages:
    - Difficult thermal management system due to low and narrow operating temperature range.
    - Water management is another challenge.

1.7 Data Centers

Data centers are primarily large group of networked computer servers owned by large private and government organizations for the storage, processing, or distribution of large amounts of data. In 1960's, large mainframes which were equal to a size of a room served the purpose of data center. Development started in a rapid pace over all the data centers across the world. US being the leading developers, Intel released world's first commercial microprocessor in 1971. USA started disaster recovery plans with the utilization of data centers. It ensured that none of the disasters affect the business operations and top secret files. IBM started the initiative of clubbing old microcomputers in a room for increased storage space and processing speed and to be called as data centers. Many companies started building very large facilities to provide businesses with a range of answers for systems deployment and operation.

Figure 1.7. Modern day data center (Image: businessfacilities.com).

As of 2007, the average data center consumes as much energy as 25,000 houses. 5.75 million new servers are installed in every fiscal year. Government data centers count has gone up from 432 in 1999 to 1100+ today. 1.5 % of US energy is consumed by data centers and increases with the rate of 10 % every year. With the increase in data centers have come exponentially over the period of time, Power needs have been increased [4]. There are lots of researches carried over in all the sectors to cut the cost of running data centers. Developing sustainable methodologies in the data center sector have become a crucial part of the future research goals for a greener environment and low cost run data center.

1.8 Photochemical water splitting process

Electrochemical concepts are being applied successfully to microheterogenous systems that are made to convert and store visible light energy. This mimics the principle of photosynthetic bacteria that utilizes sulphides as electron donors for splitting hydrogen and oxygen from water particles. Generation of hydrogen by the visible light from cheap and readily available sources is a high priority subject in solar energy research. From using solar energy to power the electrolysis process to the use of semiconductors exposed to solar energy to generate hydrogen has been a epitome of renewable energy researches.

In this research, we will concentrate on the principle of generating hydrogen using ZnO/Zn plates for photochemical water splitting process

1.9 Aim of Research

1.9.1 Aim

The aim is to mathematically model a fuel cell stack that can power a rack of server and create a sustainable methodology to supply hydrogen (fuel) to the fuel cell uninterruptedly.

1.9.2 Objectives

- Compute the mathematical model of a fuel cell stack.
- Generate a fuel cell stack model in Simulink
- Validate the fuel cell stack.
- Develop a sustainable method of using solar energy to generate fuel for the fuel cell.

CHAPTER 2

FUEL CELL STACK MODEL

2.1 Server Specifications

We proceed with the rack of “HP Proliant DL 160 G5” servers used in UTA Data center lab to conduct this research. Electrical specifications of this server has been listed as follows:

Input requirements for one server

- Rated Voltage : 90 - 140 VAC
  180 - 264 VAC
- Rated I/P current : 3.6 A @ 230 VAC
  7.31 A @ 115 VAC
- Rated I/P frequency : 47 - 63 Hz
- Rated I/P Power : 855 W (@100 VAC)
  840.72 W (@200 VAC)

2.2 Rack Level Calculations

The specification of a single server has been listed in the previous section and total electric power required by the server needs to be calculated. [5]

- One rack contains 27 servers arranged in nine row and three column fashion.
- Rated I/P Current : 7.31 A × 27 = 197.37 A
- Rate Volatage: 115 VAC

2.3 H_2/O_2 Electrochemical device

In an H_2/O_2 electrochemical device hydrogen is oxidized by oxygen to water in an exothermic reaction:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O_{(g)} \quad \Delta_r H < 0 \tag{2.1}$$

The reaction enthalpy $\Delta_r H$ is equal to the enthalpy of water formation $\Delta_f H$. The energy content of any fuel is called heating value . The heating value of hydrogen is equal to the absolute value of the reaction enthalpy.

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O_{(g)} \quad \Delta_f H_{H_2O_{(g)}} = LHV = 241.84\frac{kJ}{mol} \tag{2.2}$$

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O_{(l)} \quad \Delta_f H_{H_2O_{(l)}} = HHV = 284.506\frac{kJ}{mol} \tag{2.3}$$

All thermodynamic potentials are dependant on temperature and pressure. Here we take the fuel cell temperature and pressure as given below [6]:

- Temperature = 340 K
- Pressure = 10 bar

The electromotive force(EMF) or reversible open cell voltage (OCV) E^0 of any electrochemical device is defined as:

$$E^0 = \frac{\Delta G}{n.F} \tag{2.4}$$

So we obtain the corresponding EMF as:

$$E_g^0 = \frac{-\Delta_f H_{H_2O_{(g)}}}{2F} = 1.184V \quad E_l^0 = \frac{-\Delta_f H_{H_2O_{(l)}}}{2F} = 1.193V \tag{2.5}$$

The thermal cell voltage of the fuel cell which are voltage equivalent to the enthalpy are:

$$E_{LHV}^0 = \frac{LHV}{2F} = 1.253V \quad E_{HHV}^0 = \frac{HHV}{2F} = 1.474V \tag{2.6}$$

2.4 Reactant feed and consumption

The reactants H_2 and O_2 are used inside the fuel cell stack by the electrochemical reaction. The molar flows of reactant consumptions are calculated using Faradays law:

$$n_{H_2} = \frac{I.N}{2F} = 0.2192\frac{mol}{sec} \tag{2.7}$$

$$n_{O_2} = \frac{I.N}{4F} = 0.1096\frac{mol}{sec} \tag{2.8}$$

The amount of reactant consumption of fuel cell is always less than the amount of reactant feed [7]. The ratio between the reactant feed and reactant consumption should always be more than one. This ratio is termed as stoichiometry(λ) (eqn 2.9) .

$$\lambda = \frac{n_{feed}}{n_{consumed}} \tag{2.9}$$

Whenever a electric power supplying device is designed, the current drawn by the source should be at the 70% of its total working capacity. We consider the current needed by server as the actual requirement and design a fuel cell which can function at its 70% capcaity to satisfy the electric power needs of a rack.

- Actual current requirement = 197.37 A
- Safety current requirement = 281.95 A

The stoichiometric ratios of cathode and anode are taken as following for higher efficiency and higher output:

- $\lambda_{anode} = 1.3$
- $\lambda_{cathode} = 1.8$

The reactant feed for the air and hydrogen into the fuel stack are calculated with the following equations:

$$n_{H_2,feed} = n_{H_2}.\lambda_{anode} = \frac{I.N}{2F}.\lambda_{anode} = 0.2849\frac{mol}{sec} \tag{2.10}$$

$$n_{air,feed} = \frac{n_{O_2}}{x_{O_2}}.\lambda_{cathode} = \frac{I.N}{4F.x_{O_2}}.\lambda_{cathode} = 0.9394\frac{mol}{sec} \tag{2.11}$$

The molar flows of unconverted reactants at the exhaust of the stack are given as :

$$n_{H_2,out} = n_{H_2,feed} - n_{H_2} = 0.0657\frac{mol}{sec} \tag{2.12}$$

$$n_{H_2,out} = n_{air,feed} - n_{O_2} = 0.8298\frac{mol}{sec} \tag{2.13}$$

The mass flow of reactants is calculated with the help of molar flow as demonstrated below:

$$m_{H_2,feed} = n_{H_2,feed} \times M_{H_2} = 0.5743\frac{g}{sec} \tag{2.14}$$

$$m_{air,feed} = n_{air,feed} \times M_{air} = 27.21\frac{g}{sec} \tag{2.15}$$

The dry mass gas flow at stack cathode and molar gas volume into the fuel cell stack are calculated as:

$$m_{cathode,out} = m_{air,feed} - m_{O_2,consumed} = 24.64\frac{g}{sec} \tag{2.16}$$

$$V = V_{omol} \times n_{H_2} = 2201.76 l/hr \tag{2.17}$$

Water molar flow and mass flow outlet from the stack is:

$$n_{H_2O,Prod} = n_{H_2} = 0.2192\frac{mol}{sec} \tag{2.18}$$

$$m_{H_2O,Prod} = n_{H_2}.M_{H_2O} = 3.9489\frac{g}{sec} \tag{2.19}$$

2.5 Hydrogen energy and power

Hydrogen is a chemical energy carrier with a specific energy density. This is calculated with specific set of equations and termed as mass specific chemical energy.

- Mass specific chemical energy calculated by HHV

$$W_{H_2,HHV} = \frac{HHV}{M} \tag{2.20}$$

$$W_{H_2,HHV} = 39.1\frac{kWh}{Kg} \tag{2.21}$$

- Mass specific chemical energy calculated by LHV

$$W_{H_2,LHV} = \frac{LHV}{M} \tag{2.22}$$

$$W_{H_2,LHV} = 33.32\frac{kWh}{Kg} \tag{2.23}$$

- Chemical power of hydrogen flow is found out by the following equation:

$$P_{H_2,HHV} = HHV.n_{H_2} \tag{2.24}$$

$$P_{H_2,HHV} = 62.65kW \tag{2.25}$$

- Chemical power of hydrogen consumed in stack :

$$P_{H_2,HHVconsumed} = 1.481V.N.I \tag{2.26}$$

$$P_{H_2,HHVconsumed} = 62.63kW \tag{2.27}$$

- Chemical power of hydrogen feed:

$$P_{H_2,HHVfeed} = 1.481V.N.I.\lambda_{anode} \tag{2.28}$$

$$P_{H_2,HHVfeed} = 81.42kW \tag{2.29}$$

2.6 Fuel cell stack power

Fuel cell stack power is defined as the total power generated by the fuel cell considering all its input factors [8] [9].

- Electric stack power is the product of stack voltage and stack load.

$$P_{el} = AveCell.N.I \tag{2.30}$$

$$P_{el} = 32.37kW \tag{2.31}$$

- Thermal stack power is the part of the consumed chemical power which is not converted into electric power:

$$P_{therm} = P_{H_2,HHV} - P_{el} \tag{2.32}$$

$$P_{therm} = 30.25kW \tag{2.33}$$

2.7 Fuel cell efficiencies

Efficiency can be defined as the ratio of power output to the power input. Efficiency can be calculated using HHV and LHV. When efficiency is calculated at LHV, you get higher efficiency values but neglecting all higher temperature factors which is not feasible for implementation. We go forward in this research by calculating the efficiencies using HHV values. Efficiencies are one of the major equations calculated in every experiment as it determines the feasibility of product into real life products. We go ahead with calculating different efficiencies for the fuel cell as follows:

- Thermodynamic efficiency: It is the ratio between enthalphy and gibbs free enthlpy of any electrochemical device.

$$\eta_{el,TD,HHV} = \frac{E_l^0}{E_{HHV}^0} \tag{2.34}$$

$$\eta_{el,TD,HHV} = 83.1\% \tag{2.35}$$

- Electric efficiency: It is the ratio between electric stack power to the chemical power of the hydrogen consumed in stack.

$$\eta_{el} = \frac{P_{el}}{P_{fuel,consumed}} \tag{2.36}$$

$$\eta_{el,HHV} = \frac{AveCell}{1.481V} \tag{2.37}$$

$$\eta_{el,HHV} = 51.7\% \tag{2.38}$$

- Fuel electric efficiency: The fuel electric efficiency is the ratio of stack electric gross power to the fuel feed power.

$$\eta_{fuel,el,HHV} = \frac{AveCell}{1.481V.\lambda_{anode}} \tag{2.39}$$

$$\eta_{fuel,el,HHV} = 39.78\% \tag{2.40}$$

- Voltage efficiency: It is the ratio between average and reversible cell voltage.

$$\eta_{voltage} = \frac{AveCell}{E^0} \tag{2.41}$$

$$\eta_{voltage} = 51.72\% \tag{2.42}$$

- Thermal efficiency: It can be calculated according to the electric efficiency and can be calculated based on HHV.

$$\eta_{therm,HHV} = \frac{1.481V - AveCell}{1.481V} \tag{2.43}$$

$$\eta_{therm,HHV} = 48.28\% \tag{2.44}$$

CHAPTER 3

SOLAR THERMAL ZnO/Zn WATER-SPLITTING THERMOCHEMICAL CYCLE

3.1 Principle

Solar energy has become the most feasible renewable energy to harness for efficient utilization. With the day-to-day increasing needs, alternate forms of energy has played a great role in filling the needs. This process is the effective application of the renewable energy to convert the heat energy into a chemical energy. It involves the understanding of a two-step zinc oxide thermochemical water-splitting cycle to produce hydrogen [10].

3.2 Working

- Step 1: This step occurs in a transport tube that can conduct very high temperatures. The primary purpose of the tube is to dissociate zinc oxide inside them. These tubes will be heated using the solar thermal energy collected using a field of heliostats and concentrators. Zinc oxide dissociation [eq 3.1] is known to be a quick reactions under favorable conditions. This has the disadvantage of reverse-reaction inside the tube itself. Eventually the rate of dissociation is limited and Zn is obtained in a constant rate lower than the rate of dissociation.

  $$ZnO \rightarrow Zn + \frac{1}{2}O_2 \tag{3.1}$$

- Step 2: The zinc obtained in eq 3.1 is utilized in this reaction to generate hydrogen. Zinc powder is exposed to steam in a thermogravimetric analyzer and a transport tube reactor. This step can be driven to completion given enough time for zinc oxide to reside back. This step gives zinc oxide (eq3.2) and hydrogen as residue in which hdrogen is taken as the by-product that can be used as fuel for the fuel cell and zinc oxide is again sent into transport tubes for further reactions.

$$Zn + H_2O \rightarrow ZnO + H_2 \tag{3.2}$$

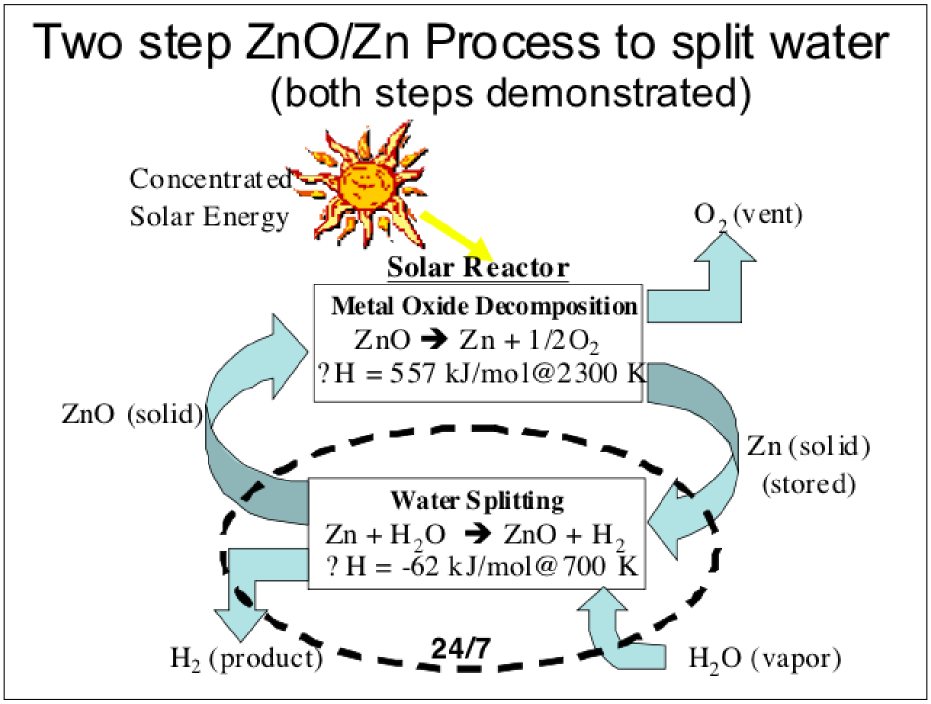


Figure 3.1. Solar thermal water-splitting thermochemical cycle (Image: NREL).

With the reaction containing two different gases, hydrogen and oxygen as their by products, it can be claimed that these both can interact to form explosive mixtures. This claim can be totally neglected as these gases are evolved in two different steps. They are obtained in different reactions in two different chambers. Solar energy can be stored overnight in the chemical bonds of solids. Production of hydrogen can be continuous and can be operated by the hydrolysis reaction so that the solar reduced oxides are used up over the night.

3.3 Strengths of ZnO/Zn cycle

- It occurs in two steps in a simple manner involving high temperature endothermic reaction (eq3.1) followed by an exothermic reaction (eq3.2) at a low temperature(400^{o}C).
- Zinc metal powder is used to store solar energy inside a storage tank padded with inert gas. The quantity of zinc metal powder increases when on-sun driving reaction (eq3.1) and decreases during off-sun hours when reaction 3.2 occurs.
- Zinc is one of the highly abundant, non-toxic and inexpensive material compared to all redox reaction elements. This can be obtained in large quantities for such process.

3.4 Challenges of ZnO/Zn cycle

- The reverse reaction in the step 1 prevents the conversion of reaction. Alternative process of quenching zinc using a gas before it reacts with oxygen is an expensive process and might result in increase in particle size which in turn reduces the reaction rate.
- The heliostat/multiple tower need to be designed to concentrate the solar power by 7000X to reach the temperature of 1800^{o}C
- It may be possible to develop a high temperature, O_2 transport membrane for use within the reactor, but this is especially difficult due to the presence of Zn vapor.

3.5 Process flowchart

The entire process flowchart of the solar thermal water-splitting thermochemical cycle is described in the figure 3.5. This chart gives an entire breakdown of hydrogen generation using this process.

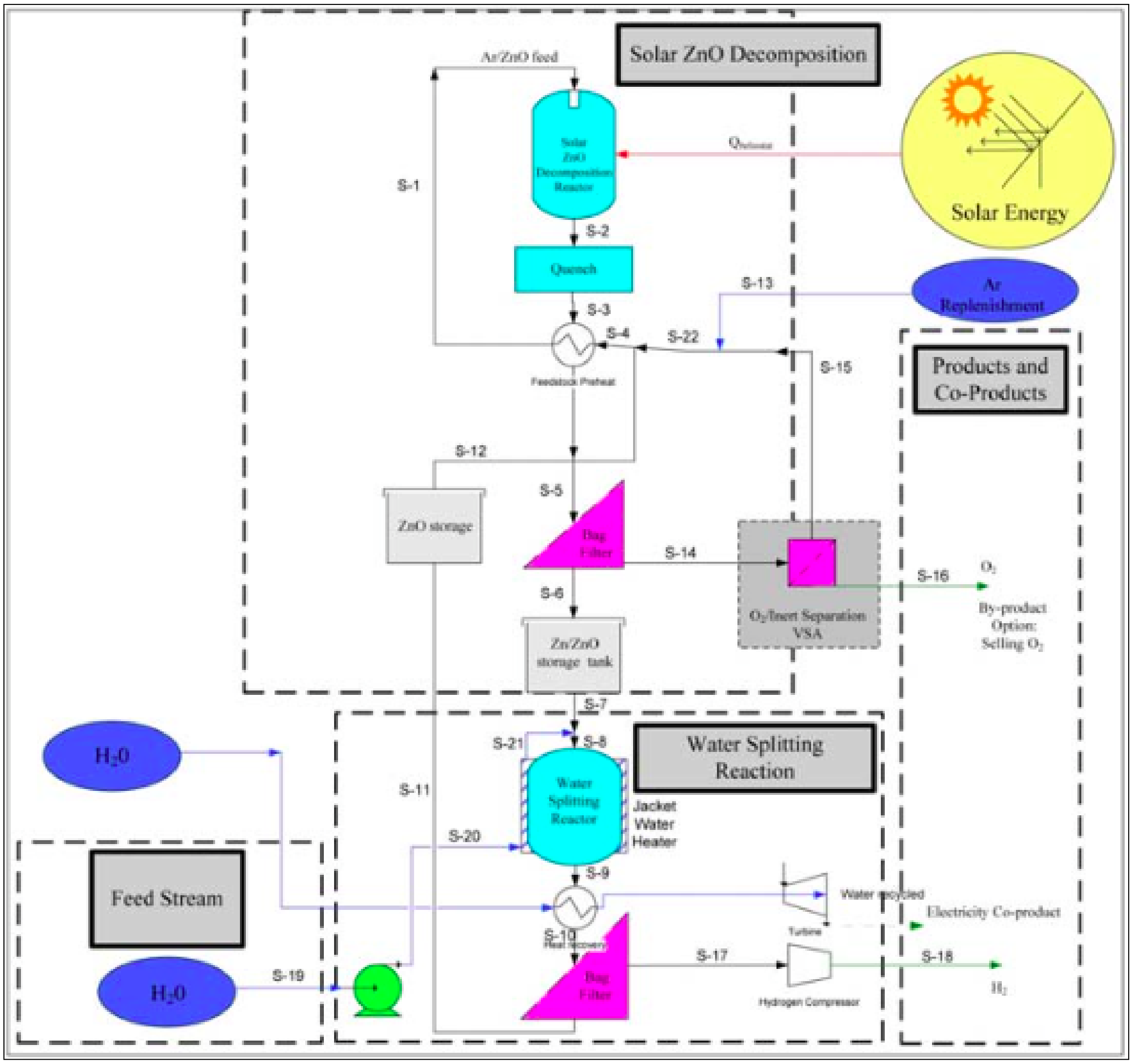


Figure 3.2. Process flowchart (Image: NREL).

This solar thermal ZnO/Zn water-splitting thermochemical cycle will be a resource for producing hydrogen that will be utilized as the fuel for the PEM fuel cell. This setup is capable of generating 100000 Kg of H_2/day. It can supply fuel to a fuel cell that can be operated to effectively power a data center with several racks of server. Power consumption cost can be down by huge amount. This process is still in developmental stages by National Renewable Energy Laboratory and has been proposed as one of the efficient ways to produce hydrogen.

In this research, fuel cell utilization in data centers as primary power source is supported by the continuous fuel supply by the solar thermal ZnO/Zn water-splitting thermochemical cycle. Solar thermal process can support the fuel cell effectively in order to keep the data center functioning uninterruptedly.

CHAPTER 4

VALIDATION OF FUEL CELL STACK MODEL

4.1 Validation methodology

Validation of a fuel cell is the degree to which the numerical values computed using thermodynamic and mathematical formulas corresponds to the simulated values. Fuel cell stack model is verified computationally using SIMULINK in MATLAB. Mathematically computed values are given as input in pre-defined fuel cell stack model in SIMULINK and its parameters are checked in it's output. Detailed fuel cell model is generated utilizing the known parameters and graphs are generated for flow rates and voltage output [11].

4.2 Modelling a fuel cell stack using SIMULINK

SIMULINK consists of a set of pre-defined library with several sections. In the electric drive/extra sources section, generic hydrogen fuel cell stack model can be found.

Generic hydrogen fuel cell block is then utilized to gives various inputs as determined

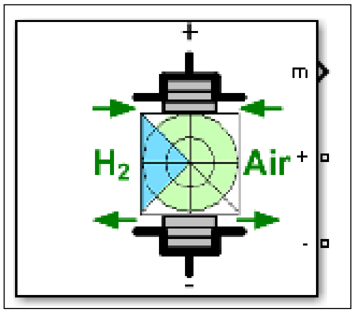
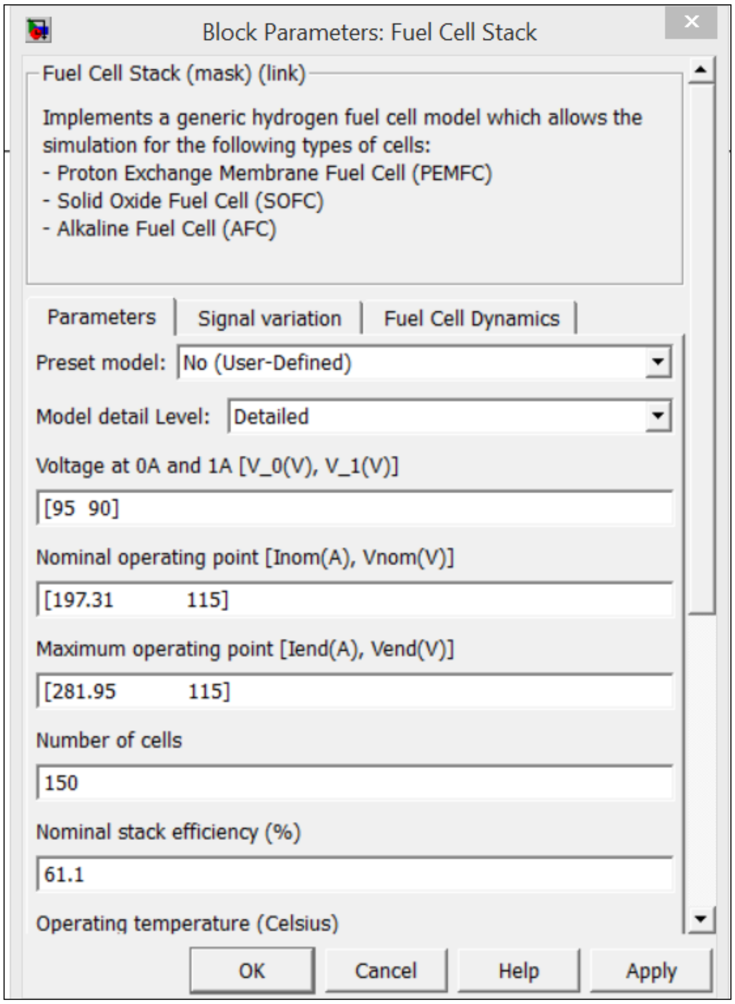


Figure 4.1. Generic hydrogen fuel cell block.

using mathematical calculation. Figure4.1 is the fuel cell block as determined by the SIMULINK. This gives a general conception of the input and output of the fuel cell.

Fuel cell parameters are calculated in chapter 2 and values are utilized to use the fuel cell block for its validation. Voltage, efficiency,flow rate, operating temperature, current output and pressure values are given in the “Block Parameters: Fuel Cell Stack” dialogue box. Figure 4.2 and 4.3 shows the dialogue box and values given as input to generate a detailed model.



Block Parameters: Fuel Cell Stack

Fuel Cell Stack (mask) (link)

Implements a generic hydrogen fuel cell model which allows the simulation for the following types of cells:
- Proton Exchange Membrane Fuel Cell (PEMFC)
- Solid Oxide Fuel Cell (SOFC)
- Alkaline Fuel Cell (AFC)

Preset model: No (User-Defined)

Model detail Level: Detailed

Voltage at 0A and 1A [V_0(V), V_1(V)]: [95 90]

Nominal operating point [Inom(A), Vnom(V)]: [197.31 115]

Maximum operating point [Iend(A), Vend(V)]: [281.95 115]

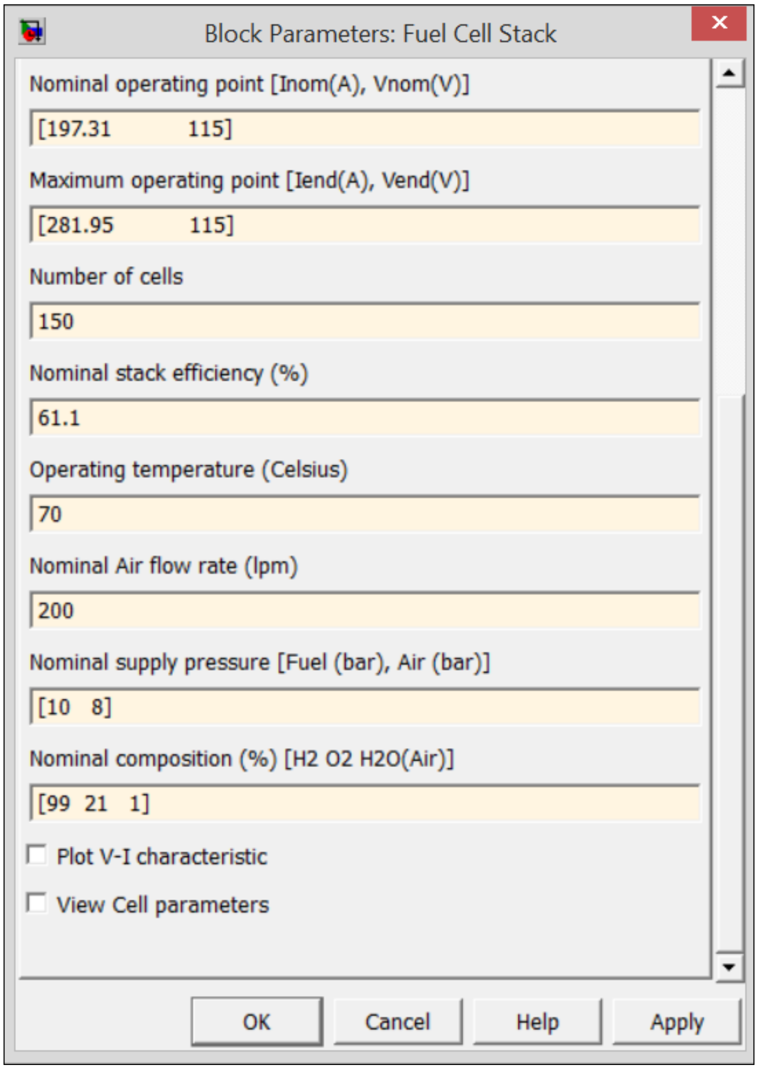
Number of cells: 150

Nominal stack efficiency (%): 61.1

Operating temperature (Celsius)

Figure 4.2. Fuel cell block paramters I/P 1.

It gives us an option of generating the V-I charcateristic plot and the resultant cell parameters in detail. By checking in the box in the dialogue paramenters, The resultant V-I characteristics is obtained as in figure 4.4.



Nominal operating point [Inom(A), Vnom(V)]
[197.31 115]
Maximum operating point [Iend(A), Vend(V)]
[281.95 115]
Number of cells
150
Nominal stack efficiency (%)
61.1
Operating temperature (Celsius)
70
Nominal Air flow rate (lpm)
200
Nominal supply pressure [Fuel (bar), Air (bar)]
[10 8]
Nominal composition (%) [H2 O2 H2O(Air)]
[99 21 1]
☐ Plot V-I characteristic
☐ View Cell parameters

Figure 4.3. Fuel cell block paramters I/P 2.

V-I characteristics also generate the plot between the current and power which determines the power capacity of fuel cell at its maximum current delivering capacity.

It validates the power calculated using the mathematical model.

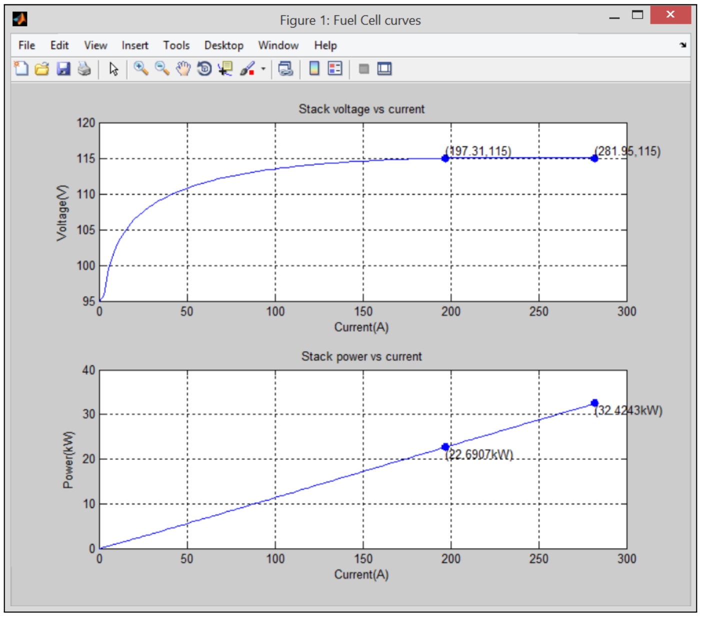
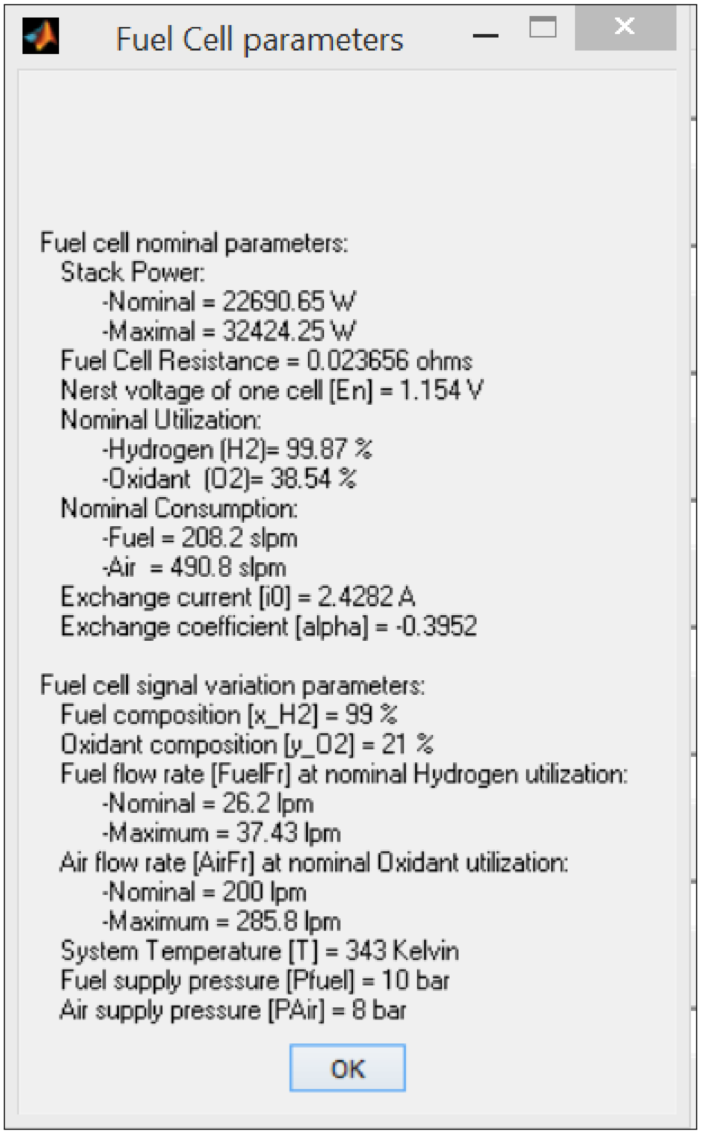


Figure 4.4. V-I characteristics.

Fuel cell parameters gives a detailed summary of input and output data of a hydrogen fuel cell stack with the provided input parameters. Values obtained in the figure 4.5 can be correlated with the mathematically computed values and verified.

4.3 Validation results

The set of I/P and O/P parameters gives an overview of the fuel cell stack model. Fuel cell stack model simulates the result with respect to the duration of operation. We take the value of 100000 seconds as the time duration get an approximate flow rate and voltage output.



```
Fuel cell nominal parameters:
   Stack Power:
         -Nominal = 22690.65 W
         -Maximal = 32424.25 W
   Fuel Cell Resistance = 0.023656 ohms
   Nerst voltage of one cell [En] = 1.154 V
   Nominal Utilization:
         -Hydrogen (H2)= 99.87 %
         -Oxidant  (O2)= 38.54 %
   Nominal Consumption:
         -Fuel = 208.2 slpm
         -Air  = 490.8 slpm
   Exchange current [i0] = 2.4282 A
   Exchange coefficient [alpha] = -0.3952

Fuel cell signal variation parameters:
   Fuel composition [x_H2] = 99 %
   Oxidant composition [y_O2] = 21 %
   Fuel flow rate [FuelFr] at nominal Hydrogen utilization:
         -Nominal = 26.2 lpm
         -Maximum = 37.43 lpm
   Air flow rate [AirFr] at nominal Oxidant utilization:
         -Nominal = 200 lpm
         -Maximum = 285.8 lpm
   System Temperature [T] = 343 Kelvin
   Fuel supply pressure [Pfuel] = 10 bar
   Air supply pressure [PAir] = 8 bar
```

Figure 4.5. Fuel cell paramters O/P.

We assign the input flow rate of fuel and air using the pre-determined parameters. Values are transformed into time varied equations and then given as input to the fuel cell. Temperature and pressure are assigned constant values at 70^{o}C and 10 bar respectively.

The output “m” is connected to a scope to generate the values of voltage and flow

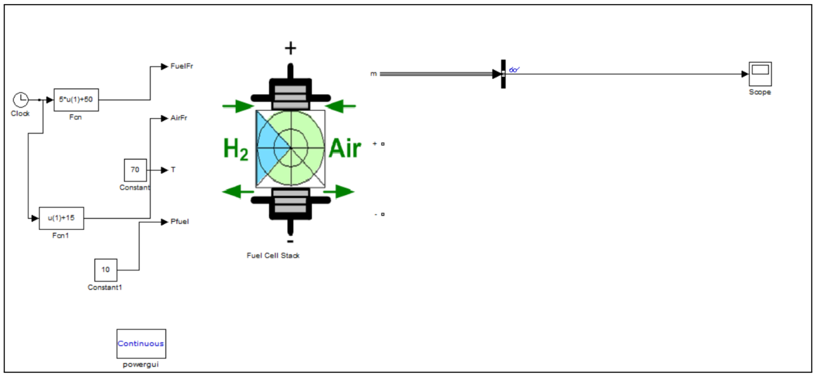


Figure 4.6. Fuel cell block with input and scope.

rates with respect to the time. Scope is used to generate plots in SIMULINK with respect to the time period in an accurate method.

Detailed fuel cell block shown here in figure 4.7 describes each possible output and input to a fuel cell. It is depicted as similar to a microprocessor pin diagram. Every output and input are marked on the figure over the arrows and all are directed to a bus operator which can store the values of every output obtained from fuel cell stack model.

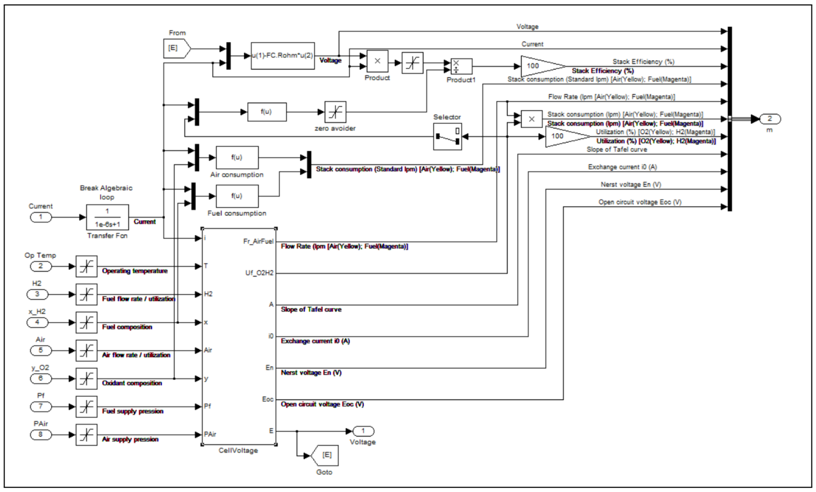


Figure 4.7. Detailed fuel cell block.

Fuel cell flow rate plot is obtained to discuss the relation between the fuel flow into the stack and time assuming the stack is producing constant power. It shows two lines , one of fuel and other of air constantly being supplied to the fuel cell . Figure 4.8 confirms the mathematical values of fuel flow rate are true for the constant power generation.

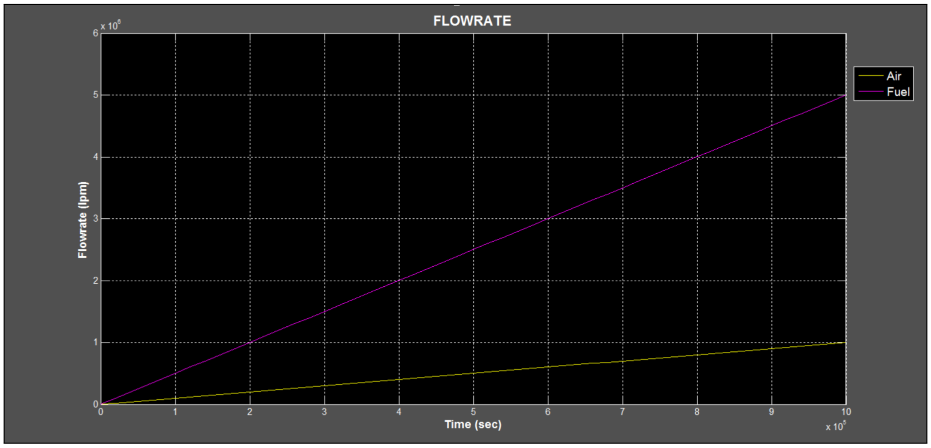


Figure 4.8. Flow rate vs Time.

Stack consumption is the plot generated between the fuel and air consumed by the stack with change in time. The value of stack consumption always differs from the value of fuel flow rate into the stack. This makes measuring stack consumption rate an essential factor. Figure 4.9 shows the constant fuel and air consumption by the stack. It is inferred from figure 4.8 and figure 4.9 that both the graph lines are identical, which proves that fuel flow rate is in exact ratio to the stack consumption rate with respect to the variable time. This validation proves our fuel cell stack model to be totally reliable and efficient to utilize.

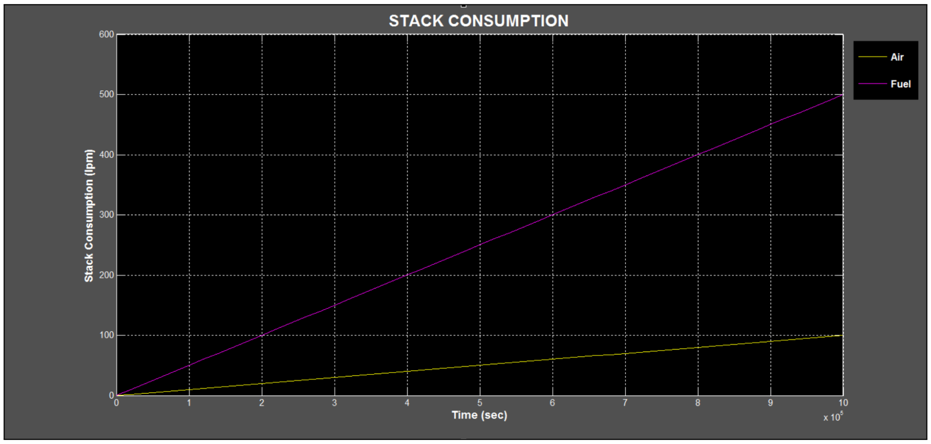


Figure 4.9. Stack consumption vs Time.

The results of the flow rate and stack consumption rate proves the mathematical model of the fuel cell to be accurate and efficient. After checking the input parameters, output parameter needs to be validated. Output voltage is plotted with respect to the time and we obtain the results as the constant value. It demonstrates that fuel cell can supply constant voltage with the calculated fuel flow rate at the given temperature and pressure. Figure 4.10 shows the straight line plot of voltage measured against time.

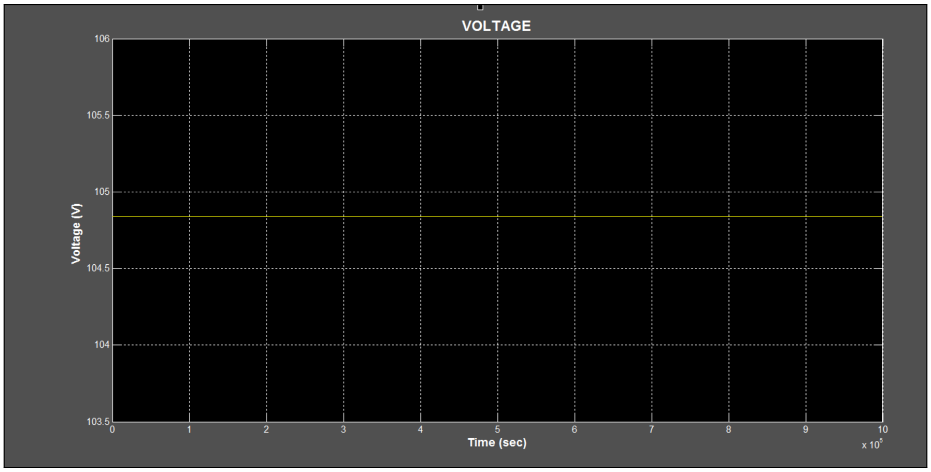


Figure 4.10. Voltage vs Time.

CHAPTER 5

RESULTS AND DISCUSSION

This research was conducted to design a fuel cell calculating all its input and output parameters with the given server power requirements. Taking into consideration, a rack from the university data center and meeting its requirements was a challenge. A hydrogen fuel cell was successfully designed using mathematical and thermodynamic calculations and the calculations were validated using SIMULINK model and plots [12].

Solar thermal ZnO/Zn water-splitting thermochemical cycle is used to generate hydrogen that can be utilized to supply the requirements of a fuel cell. This process takes place throughout the day in on-sun and off-sun conditions and facilitates in producing hydrogen continuously. Utilizing solar energy to produce hydrogen is a sustainable development towards fuel cell which proves this research objective

Starting with the design of fuel cell, it requires fuel supply to operate continuously. Hydrogen is used as a fuel and its input flow rate need to be determined. The chemical energy of hydrogen is converted into electrical energy inside the fuel cell. Fuel cell requires the optimum operating temperature and pressure for safe operation.

With these data's, fuel cell molar flow rate is determined using the output current, number of cells inside the stack and the faradays number. Table 5.1 shows the tabulated values of molar flows at input and output of fuel cell.

Table 5.1. Molar flow rates of reactants and products

Sr. No	Molar flow	Description	Results
1	n_{H_2}	Molar flow of hydrogen	$0.2192\ \frac{mol}{sec}$
2	n_{O_2}	Molar flow of oxygen	$0.1096\ \frac{mol}{sec}$
3	$n_{H_2 feed}$	Molar flow of hydrogen to the stack	$0.2849\ \frac{mol}{sec}$
4	$n_{airfeed}$	Molar flow of air to the stack	$0.9394\ \frac{mol}{sec}$
5	n_{airout}	Molar flow of air to the stack	$0.8298\ \frac{mol}{sec}$
6	n_{H_2Oprod}	Molar flow of water as product	$0.2192\ \frac{mol}{sec}$

Molar flow gives the values of flow rate of reactants and products in moles per unit time. Molar flow needs to be converted into mass flow for the understanding of regular standards and determining the fuel consumption rate. Mass flow is calculated for the fuel cell input and output and written down in table 5.2.

Table 5.2. Mass flow rates of reactants and products

Sr. No	Mass flow	Description	Results
1	$m_{H_2\ feed}$	Mass flow of hydrogen into the stack	$0.5743\ \frac{g}{sec}$
2	$m_{air\ feed}$	Mass flow of air into the stack	$27.21\ \frac{g}{sec}$
3	$m_{cathode\ out}$	Mass flow of cathode output	$24.6417\ \frac{g}{sec}$
4	$m_{H_2O\ prod}$	Mass flow of water outlet	$0.2192\ \frac{g}{sec}$
5	V	Volume flow of fuel	$2201.76\ \frac{l}{hr}$

Table 5.2 and 5.1 gives the detailed values of reactants and products flow rate. The chemical energy is now converted into electrical energy and the values are deter-

mined with the set of operations mentioned in chapter 2. Fuel cell stack power and hydrogen energy is calculated at different instances as tabulated in table 5.3.

Table 5.3. Hydrogen energy and fuel cell stack power

Sr. No	Energy and power	Description	Results
1	$W_{H_2\ HHV}$	Mass specific chemical energy at HHV	$39.1\ \frac{kWh}{kg}$
2	$W_{H_2\ LLV}$	Mass specific chemical energy at LHV	$33.32\ \frac{kWh}{kg}$
3	$P_{H_2\ HHV}$	Chemical power of hydrogen flow	62.65 kW
4	$P_{HHV\ consumed}$	Chemical power of hydrogen consumed	62.63 kW
5	$P_{H_2\ feed}$	Chemical power of hydrogen feed	81.42 kW
6	P_{el}	Electric stack power	32.37 kW
7	P_{therm}	Thermal stack power	30.25 kW

Fuel cell stack power has been determined and the whole structure to obtain it can be assumed to be the mathematical model of the fuel cell. A product is claimed to be valid only when efficiencies are within the stated limits. This research takes towards its final stage of design of fuel cells with the calculation of efficiencies. Thermodynamic, electric and voltage efficiencies are calculated and the results are as in table 5.4. It gives the feasibility of the operation of fuel cell towards the required data center.

Table 5.4. Fuel cell stack efficiencies

Sr. No	Efficiency	Description	Results
1	$\eta_{\ el\ TD\ HHV}$	Thermodynamic efficiency	83.1 %
2	$\eta_{\ el\ HHV}$	Electric efficiency	51.7 %
3	$\eta_{\ fuel\ el\ HHV}$	Fuel electric efficiency	39.78 %
4	$\eta_{\ Voltage}$	Voltage efficiency	51.72 %
5	$\eta_{\ therm}$	Thermal efficiency	37.15 %

Sustainable methodology for the use of fuel cell in data center has been demonstrated by designing a fuel cell that can genrate power for a rack of servers. Since the PEM fuel cells can be operated only by using hydrogen as fuel, solar thermal water-splitting method is implemented to generate hydrogen in order to supply fuel for the hydrogen fuel cell. This makes the whole process continuous and data center can be run without any maintenance window for a longer period of time. Utilization of fuel cells in data centers as primary power source will be of great substitute to the traditional electric power. This research could pave path for the increasing power demands across the world in data centers, Fuel cells will be a efficient alternative source in the future.

5.1 Future Scope

This research has given an outline to design a fuel cell that can power a server. Similar fuel cells with large number of stacks can be developed in order to supply power to the farm of data centers. When the size of data centers increase, The power requirement also increases and for higher number of racks, It is required to have design a higher temperature fuel cells. We have considered hydrogen fuel cell as the source of power, Various different fuel cells can be implemented depending upon the requirement and ambient conditions.

The increase in the size of data centers, increases the cost of operation and maintenance. Higher level control system and self maintained fuel cells can be designed with the extended research on the same topic. Solar thermo water-splitting method had been suggested as the sustainable methodology to generate hydrogen which in order produces electricity. It requires the continuous supply of zinc oxide powders to keep the cycle working constantly, efficient methods for the use of the metal can be determined in the future with the extensive research on this process.

This system has been designed and validated using mathematical and computational methodology, the next process in this research would be implementing these parameters to a fuel cell stack model into a physical state and test it in the laboratory. Manual testing in laboratories under certain safety conditions, It can be imlemented in commercial business and work as an alternative to the conventional electric power.

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BIOGRAPHICAL STATEMENT

Vignesh Balasubramanian earned his Bachelor of Engineering degree in Mechanical Engineering from Anna University, India in 2013. While pursuing his Masters of Science degree in Mechanical Engineering from University of Texas at Arlington, he conducted research in the development of sustainable methodologies for the economic consumption of fuel cells in data centers under the supervision of Dr. Dereje Agonafer. He has worked intensely on various research projects leading to university held data centers. He was awarded the Masters degree in May 2015.

He worked dynamically in various co-curriculum activities and also held a position as a vice-president for one of the largest registered student organizations in UTA.