Energy Analysis of Polymer Electrolyte Membrane Fuel Cell

Khuvendra Yadav, Vivek Kumar, Sandeep Jain, Rupesh Kumar, and Prayag Tiwari

Abstract**—** Fuel cells are one of the cleanest and most efficient technologies for generating electricity. Since there is no combustion, there are none of the pollutants commonly produced by boilers and furnaces. For systems designed to consume hydrogen directly, the only products are electricity, water and heat. This paper provides a specific numerical analysis of PEM fuel cell in context of heat transfer in consumption of hydrogen during process of fuel cell with different forms of energies and shows its performance and efficiency under test conditions. The potential application of PEM fuel cell can be used in automotive vehicle in low cost that gives high performance and high efficiency.

Keywords**—** Fuel cell, Energy analysis, Hydrogen, Electricity.

I. Introduction

THE use of fuel cells in both stationary and mobile power applications can offer significant advantages for the sustainable conversion of energy. Benefits arising from the use of fuel cells include efficiency and reliability, as well as economy, unique operating characteristics, planning flexibility and future development potential. By integrating the application of fuel cells, in series with renewable energy storage and production methods, sustainable energy requirements may be realized [11]. As a new technology, fuel cell and hydrogen have some safety concerns associated that has to be considered. Although some of the concerns rose are similar to those encountered with substances such as compressed or liquid natural gas (CNG or LNG) and technologies such as electrically powered vehicles, the combination of different technologies in new vehicles and the addition of new and unproven technology warrant special attention [12]. As a first stage responders should be informed of the potential risks of newly developed vehicles before they are commercialized, and measures should be put in place to minimize the hazards to the general population.

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II. Energy Contribution

Energy security is a major issue. Fossil fuel, particularly crude oil, is confined to a few areas of the world and continuity of supply is governed by political, economic and ecological factors. These factors conspire to force volatile, often high fuel prices while, at the same time, environmental policy is demanding a reduction in greenhouse gases and toxic emissions. A coherent energy strategy is required, addressing both energy supply and demand, taking account of the whole energy lifecycle including fuel production, transmission and distribution, and energy conversion, and the impact on energy equipment manufacturers and the end-users of energy systems [13]. In the short term, the aim should be to achieve higher energy efficiency and increased. In the long term, a hydrogen-based economy will have an impact on all these sectors. In view of technological developments, vehicle and component manufacturers, transport providers, the energy industry, and even householders are seriously looking at alternative energy sources and fuels and more efficient and cleaner technologies – especially hydrogen and hydrogen-powered fuel cells. In this document, the High Level Group highlights the potential of hydrogen-based energy systems globally, in the context of a broad energy and environment strategy. It then proposes research structures and actions necessary for their development and market deployment [14]. The introduction of fuel cells into the transportation sector will increase fuel efficiency, decrease foreign oil dependency, and become an important strategy/technology to mitigate climate change. As fuel cell vehicles begin to operate on fuels from natural gas or gasoline, greenhouse gas emissions will be reduced by 50%. In the future, the combination of high efficiency fuel cells and fuels from renewable energy sources would nearly eliminate greenhouse gas emissions. The early transition to lower carbon-based fuels will begin to create cleaner air and a stronger national energy security.

III. Fuel Cell And Sustainable DEVELOPMENT -Go Green

Sustainable development is one of those often used, but seldom defined, phrases. According to the United Nations, it is meeting the needs of the present without compromising the ability of future generations to meet their own needs. Attaining sustainable development doesn't mean that growth must stop; it does mean that environmental limits do exist because of the limited ability of the biosphere to deal with the wastes from human activities. This is one of the greatest challenges we face today a challenge that can only be met by

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responsibly developing and using technologies that will protect our environment for everyone. Today's innovations in fuel cell technology are addressing local, national, and global environmental needs. The decision to become involved with bringing these innovations into our daily lives is a strategic career opportunity and a smart thing to do. The winners will be those people who are ahead of the crowd. Innovative solutions can be an important competitive plus over half of the threat to our climate disappears if we use energy in ways that save money. In general, it's far cheaper to be efficient and save fuel than burn fuel. Fuel cells offer an opportunity for innovation [13]. Helping to make fuel cells be a part of the solution might be a challenge that's too exciting to ignore. A fuel cell by definition is an electrical cell, which unlike storage cells can be continuously fed with a fuel so that the electrical power output is sustained indefinitely (Connihan, 1981). They convert hydrogen, or hydrogen-containing fuels, directly into electrical energy plus heat through the electrochemical reaction of hydrogen and oxygen into water. The process is that of electrolysis in reverse.

Overall reaction:

$$2H_2\ (gas) + O_2\,(gas) \quad \rightarrow \quad 2H_2O\ Energy$$

Because hydrogen and oxygen gases are electrochemically converted into water, fuel cells have many advantages over heat engines. These include: high efficiency, virtually silent operation and, if hydrogen is the fuel, there are no pollutant emissions. If the hydrogen is produced from renewable energy sources, then the electrical power produced can be truly sustainable. The two principle reactions in the burning of any hydrocarbon fuel are the formation of water and carbon dioxide. As the hydrogen content in a fuel increases, the formation of water becomes more significant, resulting in proportionally lower emissions of carbon dioxide [14]. As fuel use has developed through time, the percentage of hydrogen content in the fuels has increased. It seems a natural progression that the fuel of the future will be 100% hydrogen.

IV. Basic of Fuel Cell

Although fuel cells have been around since 1839, it took 120 years until NASA demonstrated some of their potential applications in providing power during space flight. As a result of these successes, in the 1960s, industry began to recognize the commercial potential of fuel cells, but encountered technical barriers and high investment costs fuel cells were not economically competitive with existing energy technologies. Since 1984, the Office of Transportation Technologies at the U.S. Department of Energy has been supporting research and development of fuel cell technology, and as a result, hundreds of companies around the world are now working towards making fuel cell technology pay off. Just as in the commercialization of the electric light bulb nearly one hundred years ago, today's companies are being driven by technical, economic, and social forces such as high Performance characteristics, reliability, durability, low cost, and environmental benefits. A fuel cell is an electrochemical energy Conversion device. It is two to three times more efficient than an internal combustion engine in converting fuel to power. A fuel cell produces electricity, water, heat using fuel and oxygen in the air. Water is the only emission when hydrogen is the fuel. As hydrogen flows into the fuel cell on the anode side, a platinum catalyst facilitates the separation of the hydrogen gas into electrons and protons (hydrogen ions). The hydrogen ions pass through the membrane (the center of the fuel cell) and, again with the help of a platinum catalyst, combine with oxygen and electrons on the cathode side, producing water. The electrons, which cannot pass through the membrane, flow from the anode to the cathode through an external circuit containing a motor or other electric load, which consumes the power generated by the cell. The voltage from one single cell is about 0.7 volts – just about enough for a light bulb – much less a car. When the cells are stacked in series, the operating voltage increases to 0.7 volts multiplied to the number of cells stacked.

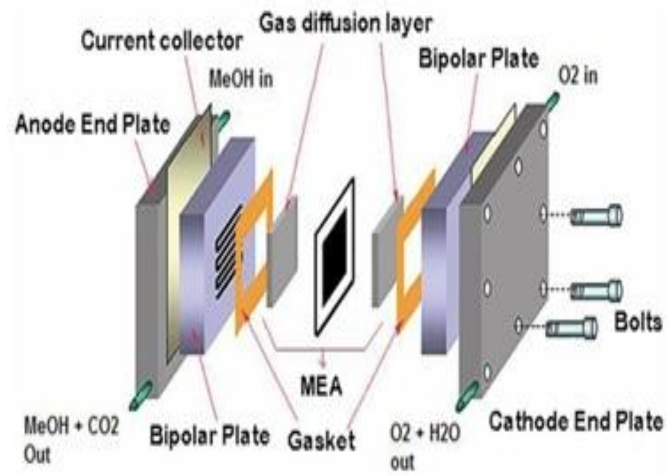

Fig. 1 General assembly of fuel cell

V. Polymer Electrolyte Membrane Fuel Cell

An ordinary electrolyte is a substance that dissociates into positively charged and negatively charged ions in the presence of water, thereby making the water solution electrically conducting. The electrolyte in a polymer electrolyte membrane fuel cell is a type of plastic, a polymer, and is usually referred to as a membrane. The appearance of the electrolyte varies depending upon the manufacturer, but the most prevalent membrane, Nafion produced by DuPont, resembles the plastic wrap used for sealing foods. Typically, the membrane material is more substantial than common plastic wrap, varying in thickness from 50 to 175 microns. To put this in perspective, consider that a piece of normal writing paper has a thickness of about 25 microns. Thus polymer electrolyte membranes have thicknesses comparable to that of 2 to 7 pieces of paper. In an operating fuel cell, the membrane is well humidified so that the electrolyte looks like a moist piece of thick plastic wrap [9]. Polymer electrolyte membranes are somewhat unusual electrolytes in that, in the presence of water, which the membrane readily absorbs, the negative ions are rigidly held within their structure. Only the positive ions contained within the membrane are mobile and are free to carry positive charge through the membrane. In polymer electrolyte membrane fuel cells these positive ions are hydrogen ions, or protons, hence the term Ð proton exchange membrane. Movement of the hydrogen ions through the membrane, in one direction only, from anode to cathode, is essential to fuel cell operation [11]. Without this movement of ionic charge within the fuel cell, the circuit defined by cell, wires, and load remains open, and no current would flow. Because their structure is based on a Teflon backbone, polymer electrolyte membranes are relatively strong, stable substances. Although thin, a polymer electrolyte membrane is an effective gas separator. It can keep the hydrogen fuel separate from the oxidant air, a feature essential to the efficient operation of a fuel cell. Although ionic conductors electrons, polymer electrolyte membranes does not conduct electrons the organic nature of the polymer electrolyte membrane structure makes them electronic insulators, another feature essential to fuel cell operation. As electrons cannot move through the membrane, the electrons produced at one side of the cell must travel, through an external wire, to the other side of the cell to complete the circuit. It is in their route through the circuitry external to the fuel cell that the electrons provide electrical power to run a car or a power plant.

VI. Working of Pem Fuel Cell

Hydrogen enters the anode side of the fuel cell. At the same time Oxygen is applied to the cathode side. The hydrogen protons pass through PEM (Proton Exchange Membrane) while the electrons of the hydrogen cannot penetrate the membrane. The PEM is the electrolyte that passes the protons but not the electrons.

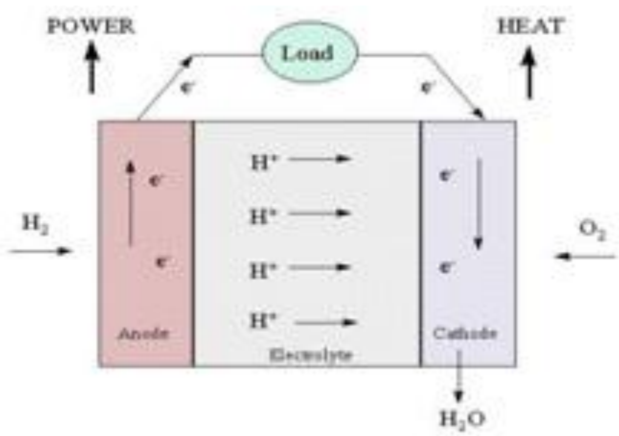

Fig. 2 Working stage of a Proton Exchange Membrane Fuel Cell

The electrons seeking the least path of resistance will flow from the anode of the fuel cell through an electrical circuit to power electrical devices or loads and return to the fuel cell via the cathode. The electrons will join with the hydrogen and oxygen within the cell to form a water molecule which is the water vapor byproduct of the fuel cell [10]. In reality billions of water molecules are produced. This rapid combination of elements also creates heat. A PEM fuel cell has an average operational temperature of 80 degrees C or 176 degrees F. The combining of hydrogen and oxygen elements creates free electrons which is the desired energy output- electricity.

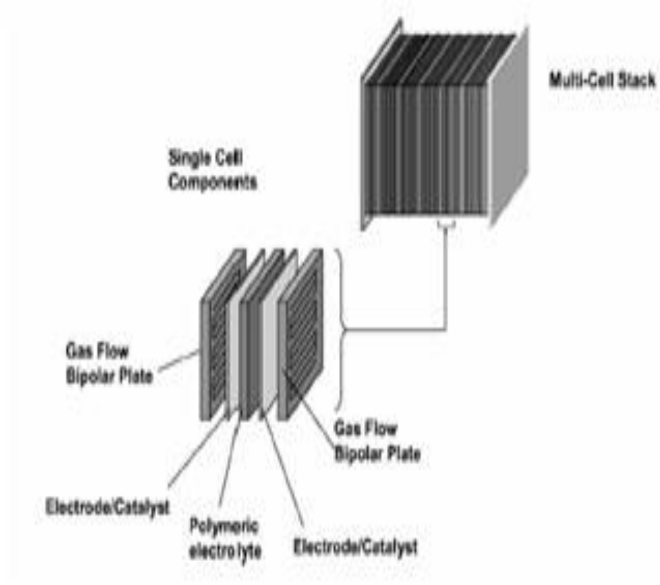

Fig. 3 Schematic of a PEM fuel cell stack

VII. Mathematical formulation of Pem Fuel Cell

In PEM fuel cell various types of mathematical calculation and analysis are involved [1], [2], [3], [4], [5], [6], [7], [8]. In this section the important parameters based calculation is depicted:

Conservation of mass

$$\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=Sm \tag{1}$$

Momentum transport

$$\begin{aligned} u\frac{\partial(\rho u)}{\partial x}+v\frac{\partial(\rho u)}{\partial y}+w\frac{\partial(\rho u)}{\partial z} \\ &=\frac{\partial p}{\partial y}+\frac{\partial}{\partial x}\left(\mu\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu\frac{\partial u}{\partial y}\right) \\ &+\frac{\partial}{\partial z}\left(\mu\frac{\partial u}{\partial z}\right)+spxu\frac{\partial(\rho v)}{\partial x}+v\frac{\partial(\rho v)}{\partial y} \\ &+w\frac{\partial(\rho v)}{\partial z} \\ &=\frac{\partial p}{\partial y}+\frac{\partial}{\partial x}\left(\mu\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu\frac{\partial v}{\partial y}\right) \\ &+\frac{\partial}{\partial z}\left(\mu\frac{\partial v}{\partial z}\right)+spy\,u\frac{\partial(\rho w)}{\partial x}+v\frac{\partial(\rho w)}{\partial y} \\ &+w\frac{\partial(\rho w)}{\partial z} \\ &=\frac{\partial p}{\partial y}+\frac{\partial}{\partial x}\left(\mu\frac{\partial w}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu\frac{\partial w}{\partial y}\right) \\ &+\frac{\partial}{\partial z}\left(\mu\frac{\partial w}{\partial z}\right)+spz \end{aligned} \tag{2}$$

Hydrogen transport anode side

$$u\frac{\partial(\rho mH_2)}{\partial x}+v\frac{\partial(\rho mH_2)}{\partial y}+w\frac{\partial(\rho mH_2)}{\partial z} = \left(\mu\frac{\partial(Jx,H_2)}{\partial x}\right)+\left(\mu\frac{\partial(Jy,H_2)}{\partial y}\right) + \left(\mu\frac{\partial(Jz,H_2)}{\partial z}\right)+sH_2 \qquad \dots(3)$$

Water vapor transport

$$u\frac{\partial(\rho mwv)}{\partial x}+v\frac{\partial(\rho mwv)}{\partial y}+w\frac{\partial(\rho mwv)}{\partial z} = \left(\mu\frac{\partial(Jx,wv)}{\partial x}\right)+\left(\mu\frac{\partial(Jy,wv)}{\partial y}\right) + \left(\mu\frac{\partial(Jz,wv)}{\partial z}\right)+s_{wvp}+s_{awve} + s_{cwve} \qquad \dots(4)$$

Water liquid transport

$$u\frac{\partial(\rho mwl)}{\partial x}+v\frac{\partial(\rho mwl)}{\partial y}+w\frac{\partial(\rho mwl)}{\partial z} = \left(\mu\frac{\partial(Jx,wl)}{\partial x}\right)+\left(\mu\frac{\partial(Jy,wl)}{\partial y}\right) + \left(\mu\frac{\partial(Jz,wl)}{\partial z}\right)+s_{wlp} \qquad \dots(5)$$

Oxygen transport cathode side

$$u\frac{\partial(\rho mo_2)}{\partial x}+v\frac{\partial(\rho mo_2)}{\partial y}+w\frac{\partial(\rho mo_2)}{\partial z} = \left(\mu\frac{\partial(Jx,o_2)}{\partial x}\right)+\left(\mu\frac{\partial(Jy,o_2)}{\partial y}\right) + \left(\mu\frac{\partial(Jz,o_2)}{\partial z}\right)+s_{o_2} \qquad \dots(6)$$

Energy equation

$$u\frac{\partial(\rho u_h)}{\partial x}+v\frac{\partial(\rho v_h)}{\partial y}+w\frac{\partial(\rho w_h)}{\partial z} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + sh_p = sh_e \qquad \dots(7)$$

$$s_m = s_{H2}+s_{wvp}+s_{wlp}+s_{wve} \; at\; z=z_3$$

$$s_m = s_{o_2}+s_{wvp}+s_{wlp}+s_{wve} \; at\; z=z_2 \qquad ..(8)$$

$$spx=\frac{\mu u}{\beta x}$$

$$spy=\frac{\mu v}{\beta y}$$

$$spz=\frac{\mu w}{\beta z} \qquad \dots(9)$$

$$at\; z1\le z\le z2 \;and\; z3\le z\le z4$$

$$s_{h2}=\frac{-I(x,y)}{2F}M_{H2}A_{cv}\;\; At\; Z=Z3 \qquad \dots(10)$$

$$s_{wvp}=\frac{M_{H2o}\sum_{n\,of\,v}^{1}\frac{mass_{n\,of\,v}}{m_{\,n\,of\,z\,v}}}{\left(1-\frac{P_w^{sat}}{p}\right)}\left[\frac{P_{wv}^{sat}-P_{wv}}{P}\right]*C$$

$$at\; Z_0\le Z\le Z_s \qquad \dots(11)$$

$$S_{awve}=-\frac{\propto(x,y)}{F}I\,(x,y)H_2o\;A_{CV}\; at\; Z=Z_3 \qquad \dots(12)$$

$$S_{cwve}=\frac{1+2\propto(x,y)}{2F}I\,(x,y)H_2o\;A_{CV}\; at\; Z=Z_2 \qquad \dots(13)$$

$$S_{wlp}=-S_{wvp}\; at\; z_0\le z\le z_5 \qquad \dots(14)$$

$$S_{O2}=-\frac{I(x,y)}{4F}M_{O2}A_{cv}\;\; At\; Z=Z_2 \qquad \dots(15)$$

Heat source by electrochemical reactions

$$S_{he}=2.4E5*\left[\frac{1+2\propto(x,y)}{2F}I\,(x,y)M_{H2o}\,A_{CV}\right]Z=Z_2$$

$$-(I(x,y)V_{cell}A_{cv})_{Z=Z2}\; at\; Z=Z_8 \qquad \dots(16)$$

Heat source by phase change

$$S_{hp}=S_{wlp}*h_{fg}\; at\; z_0\le z\le z_5 \qquad \dots(17)$$

Diffusion mass flux of species *n* in ξ direction

$$J_{\xi,n}=\rho D_{\xi,n}\frac{\partial m_{K,n}}{\partial\xi} \qquad \dots(18)$$

Binary diffusion coefficient [10]

$$\frac{PD_{n,j}(x,y)}{(P_{c-n}^{*}P_{c-j})^{\frac{1}{3}}\,(T_{c-n}.T_{c-j})^{\frac{5}{12}}\left(\frac{1}{M_n}+\frac{1}{M_j}\right)\wedge 1/2} = 3.64\times10^{-8}\left(\frac{T_{(x,y)}}{\sqrt{T_{c-n.}T_{c-j}}}\right)\wedge 2.334 \qquad \dots(19)$$

$$\propto(x,y) = n_d(x,y) - \frac{F}{I(x,y)}D_w(x,y)\;\frac{\left(C_{wlc}(x,y)-C_{wla}(x,y)\right)}{t_m} \qquad ..(20)$$

$$C_{wlc}=\frac{m_{wlc}\rho}{M_{H2O}}\; and\; C_{wla}=\frac{m_{awlp}}{M_{H2O}}$$

Net water transfer coefficient per proton

$$\lambda=0.043+17.81a_a-39.85a_a^2+36.0a_a^3;0<a_a\le1 \quad (21)$$

$$= 14 + 1.4(a_a - 1); 1 < a_a \le 3$$

Water content in the membrane

$$n_d = 0.0029\lambda^2 + 0.05\lambda - 3.4 \times 10^{-19} \quad \ldots(22)$$

Electro-osmotic drag coefficient

$$D_w = D_\lambda exp\left(2416\left(\frac{1}{303} - \frac{1}{T(x,y)}\right)\right); D_\lambda = 10^{-10}, \lambda < 2; D_\lambda = 10^{-10}\left(1 + 2(\lambda - 2)\right), 2 \le \lambda \le 3 \quad \ldots(23)$$

Water diffusion coefficient

$$D_\lambda = 10^{-10}\left(3 - 1.67(\lambda - 3)\right), 3 < \lambda < 4.5; D_\lambda = 1.25 \times 10^{-10}, \lambda \ge 4.5 \quad \ldots(24)$$

Water vapor concentration for anode and cathode surfaces of the MEA

$$C_{wk}(x,y) = \frac{\rho_m, dry}{M_m, dry}(0.043 + 17.8a_k^3 + 36.0a_k^3); a_k \le 1$$

$$= \frac{\rho_m, dry}{m_m, dry}\left(14 + 1.4(a_k - 1)\right); for\ a_k > 1\ where\ k = a\ or\ c$$

Water activity

$$a_k = \frac{X_{w,k}P(x,y)}{P_{w,k}^{sat}} \quad \ldots(25)$$

Local current density

$$I(x,y) = \frac{\sigma_m(x,y)}{t_m}\{V_{oc} - V_{cell} - \eta(x,y)\} \quad \ldots(26)$$

Local membrane conductivity

$$\sigma_m(x,y) = \left(0.00514\ \frac{M_m, dry}{\rho_m, dry}C_{wa}(x,y) = 0.00326\right).exp\left(1268\left(\frac{1}{303} - \frac{1}{T(x,y)}\right)\right)10^2 \quad \ldots(27)$$

Local over potential

$$\eta(x,y) = \frac{R_T(x,y)}{0.5F}ln\left[\frac{I(x,y)P(x,y)}{Io_{O2}\ P_{O2}\ (x,y)}\right] + \frac{RT(x,y)}{1.0F}ln\left[\frac{I(x,y)p(x,y)}{Io_{H2}\ P_{H2}(x,y)}\right] \quad \ldots(28)$$

Viscosity of mixture

$$m = \sum_n m_n\mu_n \quad \ldots(29)$$

VIII. Numerical Procedure for Heat Transfer in PEMFC

A control volume technique based on a commercial flow solver, FLUENT (version 4.48), is used to solve the coupled governing equations [6]. However, this software requires specification of the source terms for species transport equations, two-phase equations for water, and heat generation equations created by electrochemical reactions. The new subroutines are written to calculate the electrochemical and permeability for this simulation. Also, FLUENT requires a subroutine to account for the flux of protons and water across the membrane [5]. As mentioned earlier, Figure-2 illustrates the geometry of the fuel cell systems that is simulated in this work. It consists of two flow channels (upper is anode and lower is cathode) separated by diffusion layers and MEA. The flow path is 10 centimeters long in the axial direction and a 0.1 cm (height) ×0.08 cm (width) cross-section area for the flow channel. Both anode and cathode flow channels Are divided into 8×10×34 equally sized grid cells. Each diffusion layer has a Dimension of 0.05 cm (height) ×0.16 cm (width) ×10 cm (length) and is simulated with 8×16×34 equally sized grid cells. Fewer of those cells are in the graphite current Collector [6]. The transport of the water liquid, water vapor, and the protons are simulated. By source terms in control volumes in contact with the membrane then equation- 22 is used. The computation domain does not extend through the membrane. The heat source from the electrochemical reactions is included in the subroutine and it generates the heat from inside the membrane. Separate grid independence test was performed by increasing and decreasing the number of the grid cells.

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