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Design and Analysis of A PEM Fuel Cell Suitable for Use in Electric Planes

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ABSTRACT: After many years of innocent but adverse developments, we have grown to become aware of the detrimental activities we do to the environment. With activists and news feeds constantly petitioning our consciences of global warming and other adverse outcomes of our day-to-day activities, the only sensible thing is to answer to the call of groaning nature. Many companies and individuals have taken the initiative to counter the damages we have done to our world experiencing a slow death by embarking into intensive research. As one step leads to the next, research birthed innovative ideas that proved successful to the transport industry and many other sectors awakening to the call. In this paper, a MATLAB dynamic simulation of a general PEM fuel cell to outline the losses associated with it is performed. The fuel cell is analyzed in the ANSYS environment to establish optimum working conditions of the fuel cell when variations in temperature and pressure are subjected to.

KEYWORDS: PEM fuel cell, , all-electric aircraft, losses, optimum working conditions

I. INTRODUCTION

Efficiency is what defines an engineer operating in any field. Our role is to engineer substantial solutions into the world at large at the most optimum and economical offer. Many engineering branches have shown their virility in efficacy by developing machinery and gadgets that are eco-friendly yet desirable. However, due to many constraints, the aviation industry though very powerful has since shown a lag in this race to produce environmentally friendly aircrafts. Speed, comfort, size, and greater flight performances have been achieved, but the key achievement, which is to zero out on harmful emissions has not yet been fully attained. Therefore, to be a part of such substantial movements, the aviation industry has embarked on projects that reduce, if not eradicate all pollutions emitted into the atmosphere. Figures have it that the aviation industry contributes 12% of the worlds air pollution yearly but this value is sadly rising by the day. This may appear to be a trifling figure, but the industry is on a success toll regardless of any hiccups due to various economic reasons. Gas turbine aircrafts do not only emit waste gases that eat away the ozone layer, but they are noisy to passengers on board and to people busy on the ground.

According to Facts and Figures, to counter the environmental problems arising from gas turbine pollution, leading aircraft giants have come up with designs to reduce emissions from the engines. Rolls Royce, with RionaArmesmith as its chief project engineer of Hybrid Electric Propulsion, has managed to be a successful team member alongside Airbus and Siemens in the development of the E-Fan X. It was expected to be in full operation by last year in 2020 (*This speculation held truth before the pandemic hit*). A conceptual BWB aircraft by Boeing that is more fuel efficient due to a reduced wetted area has been thrown on the table. Many other aspiring and successful companies have proposed many conducive designs; however, this does not help speed up the reduction of CO₂ being dumped into the dying atmosphere. China alone, with the myriads of people that ubicate within its borders has a recorded increase in international flights as stated by Wang et al. [1]. Redesigning gas turbine powered aircrafts without removing the gas turbines themselves merely adds to the damage as there is an estimated growth in the number of flights locally and internationally as a result of the research of Harrison et al. [2].

Other than batteries for substituting gas turbine engines, the next best solution that is establishing its presence in the electric plane field is the hydrogen fuel cell, particularly the PEM fuel cell. Finding its application well recognized in the transport industry of all modes of travel, the PEM fuel cell reacts hydrogen (H₂) and oxygen (O₂) together to have water and electricity resulting as the products. To give substantial impetus to the output voltage and power of the remarkable technology, several units have to be coagulated into a single stack. A stand-alone fuel cell cannot power any sort of component as the output voltage ranges between 0.6 and 0.7V. To acquire optimum operating conditions of the fuel cell for maximum aircraft performance, all possible conditions are varied from and analyzed.

II. RELATED WORK

In this work, a one-dimensional and three-dimensional numerical simulation were done and juxtaposed against tentative data obtained in a PEM fuel cell [3]. This paper gives an unequivocal review of how models play an imperative role in the development of fuel cell as this develops an understanding of the effect of different limits on the cell performance allowing for the enhancement of fuel cells systems. In [4], the author weighs the merits and de-merits in the states of hydrogen containment when presented for fuel to the aircraft which illuminates the setbacks enthroned to the use of hydrogen whichever state of operation chosen. Liquid hydrogen usurps authority in terms of the state of fuel used for the suggested electric plane designed. In [5] it is stressed out that the relatively small energy density of the present battery technologies dominating the market are adequate to build operable electric cars, but not fitting for electric aircraft. Because of the narrow pool of energy available on-board, an increment to percent in efficiency can give substantial increase in range and flight time, hence the advancement of more efficient propulsion systems and motors is as imperative as the advancement of battery technologies. This not only holds true for batteries but for fuel cell systems.

III. METHODOLOGY

MATLAB MODELLING

The active model of the fuel cell takes into thought the disparity in the fuel cell output voltage due to changes in the fuel cell current [6]. Because the fuel cell connects to a load, which in our case is a motor, there will be changes in the current that will ineluctably ensue.

Now, the output voltage of PEM fuel cell is given by the following equation,

$$V_{stack} = n * (E_{ernst} - (\text{losses in the fuel cell})) \quad (2.1)$$

Where:

n = the number of stacks designated for the fuel cell

E_{ernst} : The Nernst equation affords a relationship between the cell potential of an electrochemical cell, temperature, the standard cell potential and the reaction quotient. Even under non-standard conditions, with the Nernst equation the cell potentials of electrochemical cells can be determined [7][8]. The equation was introduced by a German chemist Walther Hermann Nernst. It is given by,

$$E_{ernst} = E^{\circ} - \frac{RT}{2F} (\ln PH_2 + 0.5 \ln PO_2) \quad (2.2)$$

Losses in the fuel cell

Fuel cells experience 3 chief losses, namely, ohmic losses, concentration voltage losses and lastly, activation losses.

Ohmic Losses:

Ohmic losses occur due to the impedance to the flow of ions in the electrolyte and impedance to the flow of electrons through the electrically conductive fuel cell elements. It is given by,

$$V_{ohm} = I_{fc} * (R_p + R_e) \quad (2.3)$$

Where,

R_e = resistance by the membrane to the flow of electrons and it is given by,

$$R_e = \rho * \left(\frac{l}{A} \right) \quad (2.4)$$

$$\rho = 181.6 * \left\{ \frac{\left(\left(1 + 0.03 * j + 0.062 * j^2 \right) * \left(\frac{T}{303} \right)^2 \right)}{\left((14 - 0.634 - 3 * j) * e^{(4.18 * \left(\frac{T}{303} \right))} \right)} \right\} \quad (2.5)$$

R_p = resistance of the membrane to the flow of protons. R_p is a constant or fixed value.

Concentration Losses: When the electrode limits current production of a species mass transfer losses are said to occur. They occur generally at high current densities due to limited mass transfer of chemical species by diffusion to the



electrode. They are represented by the following equation,

$$V_{conc} = -B \cdot \ln\left(1 - \left(\frac{j}{j_{max}}\right)\right) \tag{2.6}$$

Activation losses: These are caused by the slowness of the reactions taking place on the electrode surface. The voltage decreases somewhat due to the electrochemical reaction kinetics. They are represented by,

$$V_a = -1 \cdot (\alpha_1 + \alpha_2 \cdot T + \alpha_3 \cdot T \cdot \ln PO + \alpha_4 \cdot T \cdot \ln I_{fc}) \tag{2.7}$$

Where,

$$CO = \frac{PO}{5.08 \cdot 10^6 \cdot e^{-498/T}} \tag{2.8}$$

Current density is given by the formula:

$$j = \frac{I_{fc}}{A} \tag{2.9}$$

Ansys modelling

Anode collector: Each cell consists of a membrane-electrode assembly situated between an anode flow plate and a cathode flow plate. Usually, the first face includes an electrically conductive layer disposed on substrate of the printed circuit board to serve as stack current collector electrode.

Anode Flow Channel: To properly control the water transport system in the fuel cell is an essential step. Fuel cells, through humidification are made to be saturated with the rightful amounts of water to achieve d function properly and effectively. However, due to water generation in the fuel cell, the membrane can get water-logged. This is where the flow channels come into play. These help to manage the water content of the fuel cell as leaving the membrane drenched in water merely leads to a poor functioning fuel cell.

Anode Gas Diffusion Layer [9]: The GDLs situates outside the catalyst layers and enable the transport of reactants into the catalyst layer, as well as elimination of product water. Each GDL is typically comprised of a sheet of carbon paper in which the carbon fibers are partly coated with polytetrafluoroethylene (PTFE). Gases diffuse speedily through the openings in the GDL. These openings are kept open by the aquaphobic PTFE, which prevents unnecessary water build-up. In myriads of cases, the inner surface of the GDL is covered with a thin layer of high-surface-area carbon mixed with PTFE, called the microporous layer. The microporous layer can help regulate the balance between water retention (needed to sustain membrane conductivity) and water release (needed to keep the openings open so hydrogen and oxygen can diffuse into the electrodes).

IV. EXPERIMENTAL RESULTS

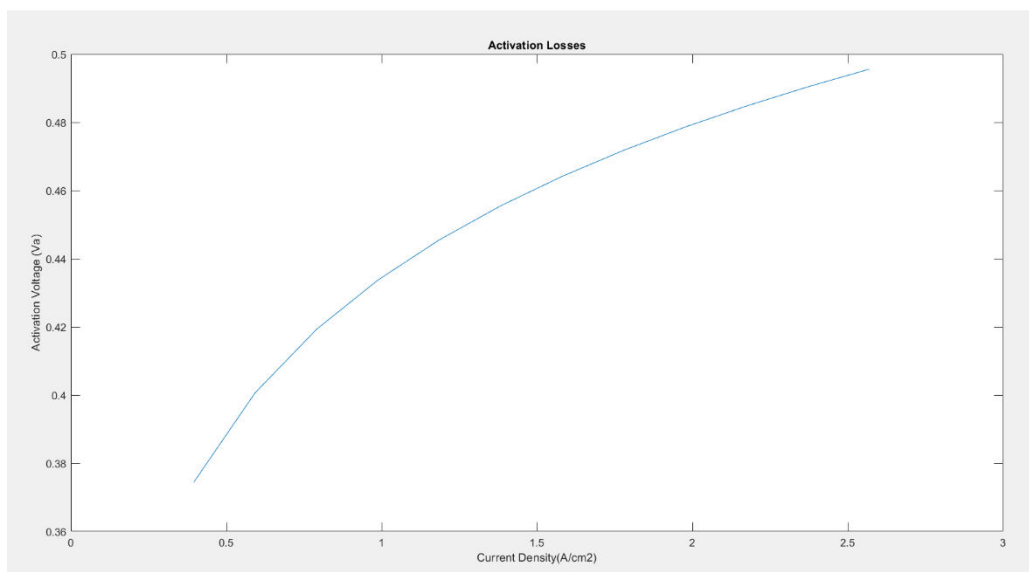


Figure 1 Graph obtained after our assumed values of E⁰ and I_{fc} were used

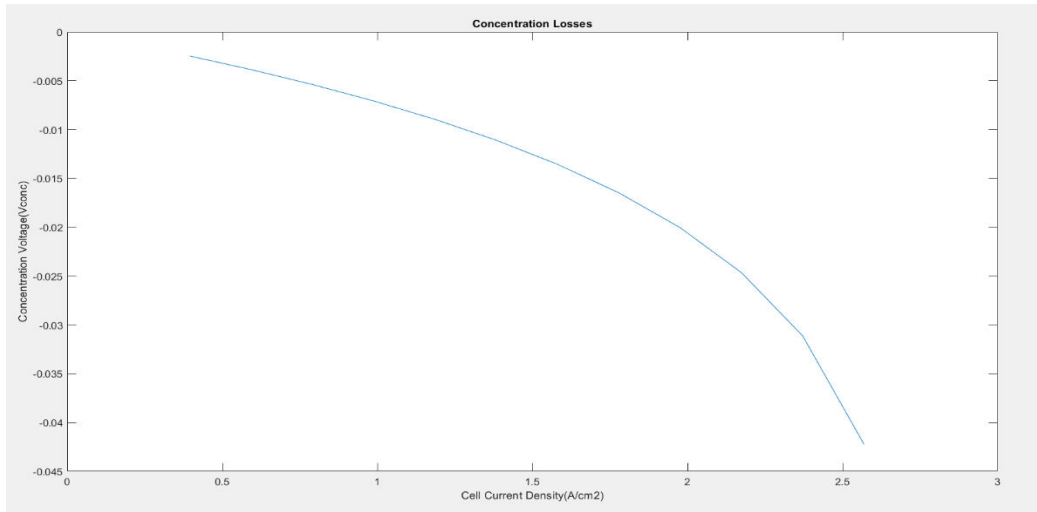


Figure 2 Extent of concentration losses when current density is subjected to changes

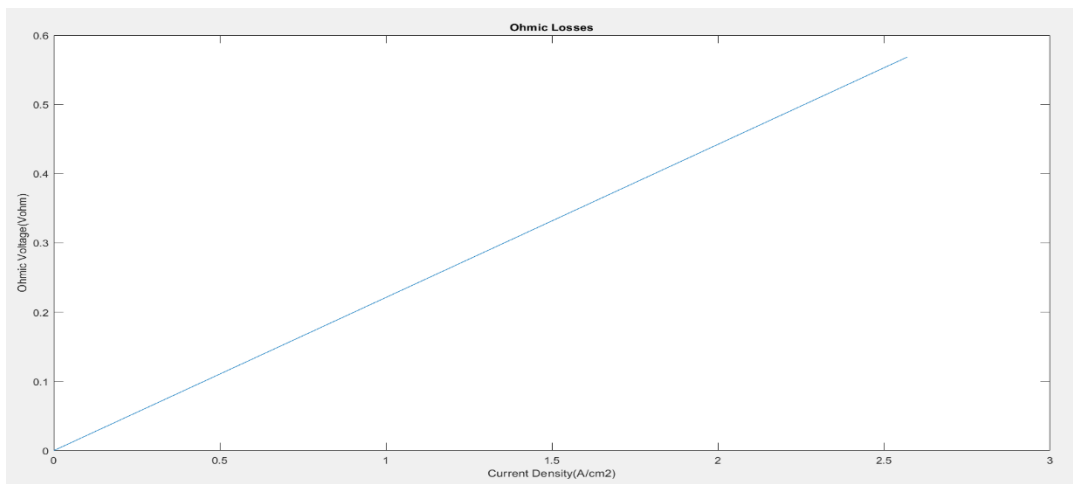


Figure 3 Plot from MATLAB showing the relationship between the Ohmic losses and the current density

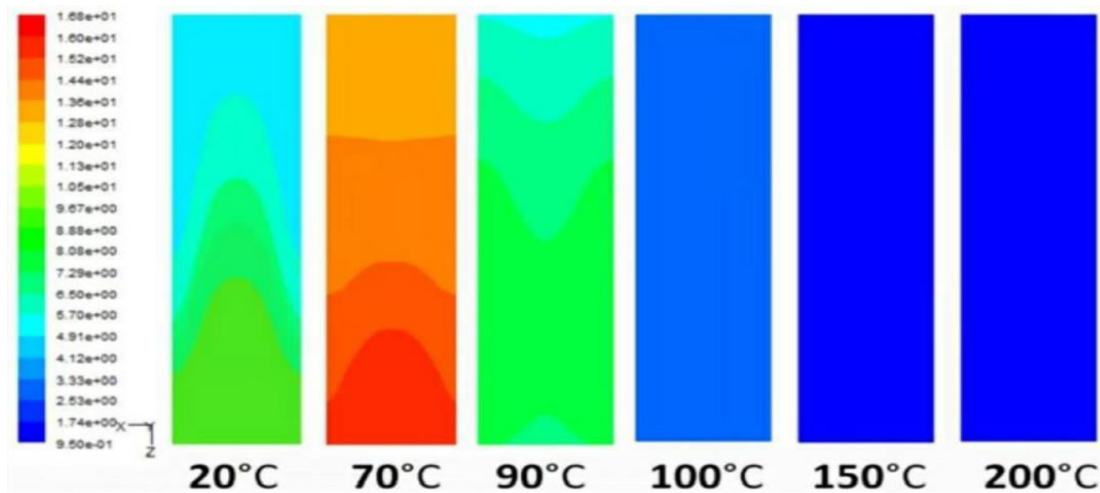


Figure 4 Temperature tests done on the fuel cell in ANSYS

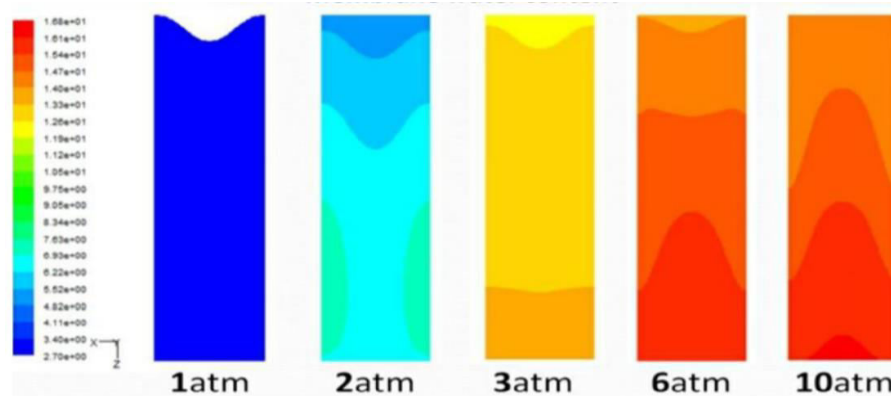


Figure 5: Water membrane content under a handful of operating pressures on atmosphere.

V. CONCLUSION

Performance of PEM fuel cell increases with the increase of operating temperature from 20°C to 70°C. Pertaining to the operating temperature range of 100-200 degree C, the water content at the membrane is heavily limited and inevitably decreases in protonic conductivity. The optimum performance of the fuel cell to be assigned is within the range of 60°C -70°C. With an increase in pressure, cell performance shoots up because the high -pressure values embellish both the fuel cell reaction kinetics and the mass transfer process. Focusing all our energy on only finding the right temperatures and pressure conditions will not result in the improvement of fuel cells and neither will it induce reception for full time use in all-electric aircrafts. Extensive research of better performing membrane materials and electrodes operating in the superlative range, will start a revolutionary growth in more fuel cell based all-electric aircrafts. Other factors that dissuade multitudes from implementing fuel cells into aircraft propulsion systems is the expenses that come along with the costly electrodes. Replacing the costly platinum electrodes for those made from the more pocket conscious cobalt without compromising any performance, will result in a peremptory to the debates on whether to embrace hydrogen technology or not for aircraft propulsion operations.

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