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Operating Conditioning Analysis of an Open-Cathode Proton Exchange Membrane (PEM) Fuel Cell

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Abstract: *The PEM fuel cell is a device that generates electricity by electrochemical reaction between hydrogen fuel and oxygen in the fuel cell stack. PEM fuel cell consists of an anode (hydrogen supply), a cathode (oxygen supply) and an electrolyte that allow charges move between the two positions of the fuel cell. The only product being developed after the reaction is water (H_2O) and heat as the waste which does not emit greenhouse gasses. The performance of fuel cell affected by numerous parameters. This study is restricted to cathode parameters that affect fuel cell performance. At the anode side, the reactant is not going through any changes. Experiments with variation in air velocity (0.5 lpm, 0.75 lpm and 1.0 lpm), temperature (20^oC and 35^oC) and relative humidity (50%, 60%, and 70%) have been carried out. The experiments results are presented in the form of fuel cell stack power output over time, which demonstrate the impacts of the various air condition on the execution of the PEM fuel cell. In this study, the experimental analysis shows that with variation of air conditions, it gives different fuel cell performance behavior. The optimized power output of the experiment was observed at an ambient temperature of 20^oC with 50% relative humidity and 1.0 lpm flow rates.*

Keywords: *air-breathing PEM fuel cell, fuel cell performance, air conditioning variations*

1. Introduction

There are various types of fuel cell had been developed and each of them has its own distinctive power output limit. The performance of fuel cell is affected by numerous parameters. In order to improve the performance of fuel cell, it is essential to understand and learn these basic working principles of open cathode of PEM fuel cell and how these parametric effects on the fuel cell. Broad of sources that related to the PEM fuel cell being studied to understand the working principle of PEM fuel cell. The objective of this chapter is to appraise recent progress that is being associated with the basic principle of PEM fuel cell and the parameter that affect the performance of PEM fuel cell at the cathode side. In addition, all things that can affect the performance of the fuel cell are also discussed.

The velocity of an air has significant influence on the performance of fuel cell. Passive air breathing fuel cell does not utilize the use of auxiliary component to flow the air to the cathode side, but instead the air be provided to cathode by natural convection due to different temperature gradient between the fuel cell stack and the ambient. To increase the velocity of air in the cathode region, an auxiliary component such fan is needed to force the air. Involving auxiliary component to fuel cell changing the fuel cell characteristic of passive air breathing fuel cell to force air breathing fuel cell. A Lot of previous study of many research claims that increasing the velocity of air to cathode region side increasing the fuel cell stack performance, in other words the force air breathing is better than passive air breathing fuel cell [1-3]. Stack temperature and rate of reaction in the fuel cell increase when fuel cell stack operates at high current load. Forced air is being introduced to help absorb and carry the heat that is being generated from fuel cell operation as well, helping to increase the air concentration at the cathode catalyst layer [2]. On the other hand, higher air flow helping in water management in the stacks. Electrochemical reaction cause water accumulates at the cathode side attribute from electro-osmotic drag, air

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being forced to cathode side help to carry away the water, thereby avoiding the occurrence of floods at the cathode side [5] [6]. However, the air supply to cathode side must not over accelerate due to water removes rate is linearly proportional to the air velocity. When water removed from the cell is higher than the amount of water generated, the membrane will suffer from dryness resulting in a relatively high-cell ohmic resistance and inferior in fuel cell stack performance [4] [5]. Moreover, over accelerate air will reduce the average temperature of the stack, causing a decrease in the chemical reaction rate [1] [3].

Operating temperature gives significant effect on the electrochemical reaction and transport of water that will determine the performance of PEM fuel cell. Many previous studies claim that increasing operating temperature will give a positive impact to the fuel cell performance [7]. The heat generated from the fuel cell dominate from electrochemical reaction which include the entropic heat and irreversible heat. Another source of fuel cell heat originates from the ohmic resistances and heat from the condensation of water vapor [8]. When an electrochemical reaction occurs, there is involving the transport of charges. The transportation of charges produce heat in the cells and the temperature of fuel cell rises [9]. Electro-osmotic drag causes protons moving through the membrane layer and concurrently draw water molecules from the anode to the cathode and result in water accumulation at cathode side. A fuel cell rises temperature will help water evaporation process, hence flooding does not happen at the cathode which enhances the mass transfer restriction and diminishes the ohmic losses [10]. However, the operating temperature must not exceed 100^{o}C which is a critical temperature for proton exchange membrane [2]. Proton exchange membrane might impose thermal stress and tend to dehydrate when operate at critical temperature resulted in an increase of membrane resistance, which deteriorates the membrane conductivity and leads to a severe voltage loss [1] [9]. Moreover, the thermal stress shorter the fuel cell lifetime stemming from cracks and pinholes of the membrane and gas diffusion layer (GDL) [13]. The ideal working temperature range for the PEM fuel cell is typically from 60^{o}C to 80^{o}C [9]. At [11] work, the water removal due to evaporation and water generation rate due to reaction balance at 60^{o}C. Too low operating temperature will decrease the electrochemical reaction rate and increase the ohmic resistance [12].

Humidity level of air can lead to the performance of fuel cell stack. The cell performance can be adversely affected by both drying out and flooding. The humidity level of the fuel cell at the anode and cathode are essential to be at right [14] [16]. The membrane exchange assembly (MEA) is highly depending on the water content. Too dry at the inlet will cause the membrane to dry out and too wet will cause the membrane to be flooding thus decreasing the fuel cell performance [15]. In circumstances of dry membrane, water content in the membrane is not sufficiently humidified and will cause abatement in proton conductivity and, consequently, increase the ohmic losses and ionic resistance which immediately reduces the performance of fuel cell [14] [16]. Previous study made by [10] state that the performance of fuel cell stack is better with higher relative humidity. In contrast, too wet of membrane also will lead to problem. Excessively wet will cause the buttresses in the electrodes and thus the concentration of the reactants will be low in the catalyst sites. The flooding at the electrode will lead to reduction of active surface area (ECSA) and the results is the lower power output [14]. Y. Wang postulated that flooding at the cathode side will cause the back diffusion which mean the water is moving from cathode to anode. To prevent flooding, it is the best to ensure that the rate of water generate is below the rate of water removal. Humidity and temperature are interrelated to each other and give significant effect on the performance of fuel cell. It is advocated that the fitting relative humidity to operate the stack would be higher than 55% relative humidity, but below 100% relative humidity [11].

2. Equipment Setup

2.1. Test Bench Component

A schematic diagram of the arrangement of the experimental apparatus used in this study is shown in the Fig I. The organization consists of gas supply system, fan system, HVAC system and humidifying system. The gas supply system is installed at the anode side of the fuel cell stack while the fan system, HVAC system and humidifying system is installed to the plenum system. The aim of the plenum system is used to vary the air condition that enters the cathode side of the fuel cell stack. The test subject of this experiment study is the Horizon H-1000XP PEM fuel cell stack consists of 50 individual cells that can produce 1kW of power from Horizon Fuel Cell Technologies. This fuel cell stack system comes with a controller box that will control all peripheral components. The features of the controller box are to control hydrogen supply and shut off, control stack temperature and purge rate, monitoring stack current and voltage, as well as protects stack from possible failures (like stack low voltage, over current, over temperature). The active region of fuel cell stack size is 26.4 x 20.3 cm^2 and it self-humidified and air-cooled. Pure hydrogen (99.997%) with fixed 0.5bar pressure is supplied to the anode inlet of the fuel cell stack. For experimental purposes, stack mounted with plenum that was made early to be able to change air conditions, including velocity, temperature and relative humidity. The fuel cell stack is connected to an electronic load bank and set up to 10A load for all experiments. For the recording of the experimental data, data logger is used to automatically record the air condition along the plenum and at the same time read the voltage output from the fuel cell stack.

2.2. Fan System

Fan system is employed to increase the velocity of air that enter the cathode of the fuel cell stacks. This fuel cell stack comes with four built-in fans to remove the heat generate by forced convection and also provides oxygen supply to the cathode region. The fan automatically works with the assistance of the controller box. In an effort to control the air velocity, according to specific air conditions, the fan wires connected to the controller box were renovated and it has been connected to the variable DC supply. Fan speed varies with the increase of input voltage to the fan, vice versa. At the cathode outlet, an instrument which is named as an anemometer were installed to offer a velocity reading in units of m/s.

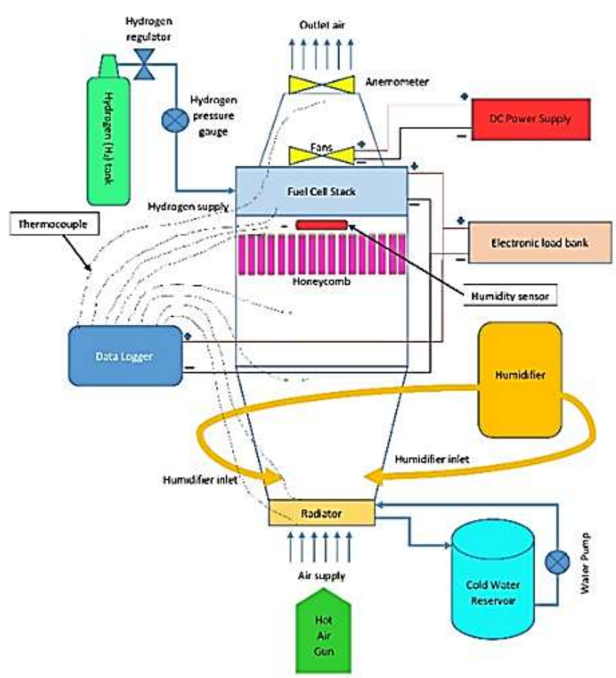

Fig. 1: Fuel cell test bench facilities

2.3. HVAC System

HVAC system provides the heating and cooling of air temperature along the plenum. To heat the air to required air condition, hot air gun is placed at the front of intake plenum pointing to cathode fuel cell stack. The electrical heating element inside the gun can be controlled to required temperature and maximum temperature up to 600^{o}C. The air cooling process is using the radiator that place at the forepart of the intake plenum. Ice and water fill in a pail, once water cool, the water is pumped to the radiator all while the air pass through the radiator is cooled by convection process.

2.4. Humidifying System

There are many types of humidifier on the market, but for this experiment the ultrasonic humidifiers are being chosen to humidify the air in the cathode region at ambient pressure. Ultrasonic humidifier creates mist from the ultrasonic frequency that vibrate the metal diaphragm, by the way of cavitation the water is split into ultra-fine vapor mist. At that point is, no heating element involve like other type of humidifier which mean the temperature of the air are not being interrupted. The relative humidity inside the building is approximately 50%. Relative humidity of air can be determined for maximum up to 80%. Before the experiment start, relative humidity of air was adjusted to achieve desired point. The relative humidity of air needs to be maintained within ±5^{o}C of the target humidity level at desired temperature and velocity for a period of 1 hour. Because of relative humidity and temperature are correlated, a minor alteration in temperature will affect the relative humidity level, so the temperature needs to be kept as stable as possible.

2.5. Electronic Data Collection Devices

All data are being gathered using the GRAPHTEC GL200A data logger that offers 10 isolated channels and allowing PC control. The data logger able to collect voltage, temperature, humidity, pulse and logic data. Channel 1 to 7 is set to capture temperature along the plenum using the thermocouple wire, while channel 9 is used to capture the relative humidity level of the air using humidity sensor and channel 10 is used to capture voltage output from the fuel cell stack using copper wire. Sampling data are being set up to maximum values which is 100ms for each data capture for 1 hour period for each experiment conducted. All information read by data logger is transferred to a PC and been converted into electronic spreadsheet using Excel application. From the spreadsheet, all these data are then being used to plot the graph power versus time in defining the power output distribution.

3. Results

The results of the experiment are analyzed based on two different air inlet temperatures; at 20^{0}C and 35^{0}C. At both temperatures the flow rates are varied at 0.5 lpm, 0.75 lpm and 1.0 lpm meanwhile the humidity is varied at 50 percent, 60 percent and 70 percent. The polarization data were collected within one hour. The hydrogen condition is maintained at 25^{0}C without humidification. Figure 2 shows the power variation produced by the fuel cell at air inlet condition of 35^{0}C. The highest power recorded for each humidification condition at 0.5 lpm is 376.93W (70% RH), 373.25 W (60% RH) and 367.24 W (50% RH) as in Fig. 2(a). Meanwhile, at 0.75 lpm the highest power recorded is 375.60 W (70% RH), 375.73 W (60% RH) and 377.39W (50% RH) as in Fig. 2 (b) and at 1.0 lpm the highest power is 378.42 W (70% RH), 378.42 W (60% RH) and 378.64 W (50% RH) as in Fig. 2 (c). Based on the results, the largest flow rates of 1.0 lpm generates higher power compared to 0.75 lpm and 0.5 lpm as occurs at 50 percent relative humidity. The lowest power generates occurs at smallest flow rates 0.5 lpm recorded value of 346.58 W (50% RH).

Figure 3 shows the power variation produced by the fuel cell at air inlet condition at 20^{0}C. The highest power recorded for each humidification condition at 0.5 lpm is 386.40 W (70% RH), 382.79 W (60% RH), and 378.66 W (50% RH) as in Fig. 3 (a). Meanwhile, at 0.75 lpm the highest power recorded is 370.52 W (70% RH), 376.44 (60% RH) and 379.51 W (50% RH) as in Fig. 3 (b) and at 1.0 lpm the highest power recorded is 372.13W

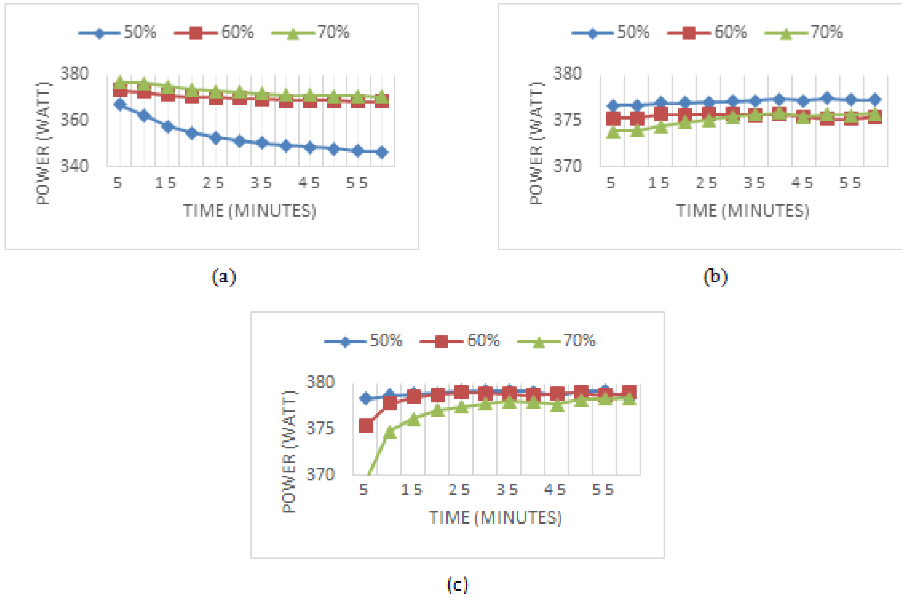

Fig. 2: Air inlet temperature at 35^{0}C with flow rates of (a) 0.5 lpm, (b) 0.75 lpm and (c) 1.0 lpm

(70% RH), 372.13 W (60% RH) and 385.43 W (50% RH) as in Fig. 3 (c). Based on the results, the smallest flow rates of 0.5 lpm generates relatively higher power compared to the air inlet at 0.75 lpm and 1.0 lpm. The lowest power generates produced by fuel cell occurs when air inlet is conditioned at 1.0 lpm with value of 356.57 W (70% RH).

The fuel cell shows expected behavior when the air inlet flow condition is varied which is in this study the relation between air inlet flow rates induced and the humidity. The power is varied because of the fact that the proton ions transfer rate inside the membrane are highly depending on the membrane condition. PEM effectiveness is increased if it is operated in highly humidified condition. Meanwhile the flow rates represent the amount of reactants being delivered into the fuel cell. This is true, as shown in Fig. 2 (a) and 3 (a). At this

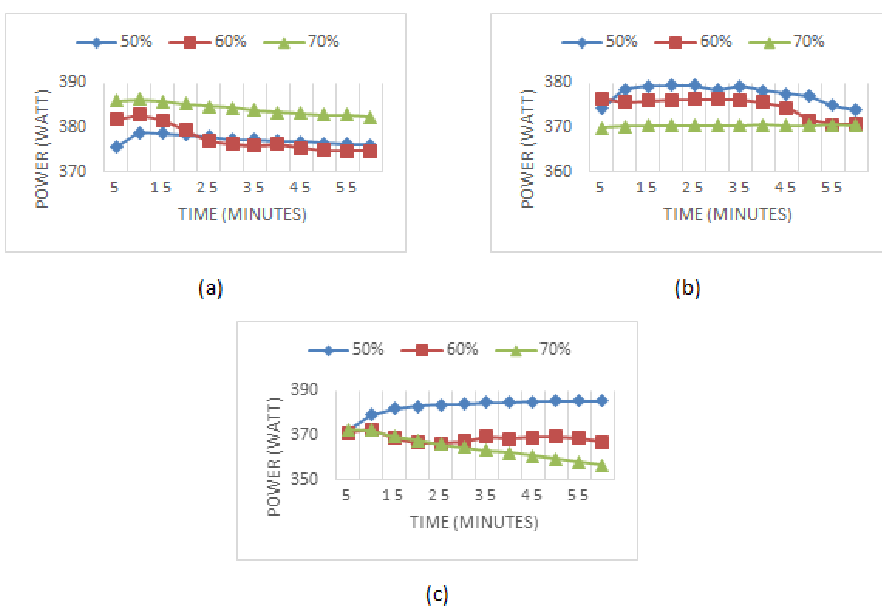

Fig. 3: Air inlet temperature at 20^{0}C with flow rates of (a) 0.5 lpm, (b) 0.75 lpm and (c) 1.0 lpm

condition, the flow rates introduced is the lowest which is 0.5 lpm only the temperature is varied which is 35^0C and 20^0C. Both graphs show the relative increase in power when higher humidification is introduced.This shows that the membrane response effectively when higher humidified air inlet condition is introduced. Within one hour, the graph of Fig. 2 (a) and Fig. 3 (a) shows decreasing of power between activation condition and end of the experiments; for example, at 35^0C the power is reduced from 376.93 W to 368.65 W for 70% RH meanwhile at 20^0C the power is also reduced from 386.40 W to 382.28 W for 70% RH. The reduction also occurs in all other 4 conditions. This phenomenon occurs due to the fact that, the air flow rates supplied does not able sustained the load given therefore leads to lower electrochemical reaction occurs especially for the last 10 mins of experiments. The largest reduction recorded is at 35^0C and 50% RH which is from 373.25W to 346.58 W shows membrane is in the driest condition because of air inlet operates at high temperature, low humidity and smallest flow rates.

Fig. 2 (b), Fig. 2 (c), Fig. 3 (b) and Fig. 3 (d) represents the air flow rates at 0.75 lpm and 1.0 lpm shows different behavior compared to the graphs of 0.5 lpm. At all 4 graphs, the increase of air inlet humidity does not generate higher power. In this condition, higher flow rates cause the drying effect onto the PEM surfaces and the humidification introduced was not able to increase the PEM effectiveness. As an example, at 35^0C the power generated is 377.39W (50% RH), 375.73 W (60% RH) and 375.60 W (70% RH) and at 20^0C the power generated is 379.51 W (50% RH), 376.44 (60% RH) and 370.52 W (70% RH) for 0.75 lpm. Meanwhile, the graphs show quite different behavior if comparison is made between the air inlet condition at 35^0C and 20^0C for 0.75 lpm and 1.0 lpm within one hour of experiments. At 35^0C, Fig. 2 (b) and Fig. 2 (c), shows constant power increases is observed from the activation region until the end of the experiments. On the other hand, at 20^0C mix results is observed. The graph in Fig 3 (b) shows a relative increase of cell performance for almost 35 mins, however the power is reduced for the next 25 mins. This occurs at the humidified condition of 50% RH and 60% RH. At 70% RH almost constant power is observed between an hour of operation, however at a lower value. This shows that flooding occurs at all these three conditions and higher humidification severed the effect even more. Flooding is the phenomenon of liquid water blocks the active pore area of PEM thus reducing the cell performance. The liquid water came from two sources; from the electrochemical reaction of fuel cell by product and from external sources of inlet humidity condition. Due to high water vapor accumulation increases, the local pressure increase above the water vapor pressure resulting in liquid water formation. The fact that lower humidity value shows higher cell performance proves that the membrane active area is lessened by the existence of water formation. Meanwhile, at 1.0 lpm the increase of flow rates reduced the amount of flooding as faced by the fuel cell during air inlet introductions at 0.5 lpm conditions. The increase of flow rates able to remove the water from the fuel cell as observed from the exit duct of the fuel cell. At 60% RH and 70% RH the flow rates do not appear to have significant impact. However, at 50% RH, highest power is observed at 385.43 W and the graph plotted is constantly increases even after an hour of fuel cell operation showing balance flow rates and humidity relation.

4. Conclusion

As a conclusion, an experimental study had been performed to investigate the effect in variation of air condition at the cathode side on the performance of PEM fuel cell stack. Among the variation of air condition at cathode side of fuel cell stack were air temperature, air velocity and air relative humidity. Based from the experimental study, it can be found that variation of air condition had considerable effect on the fuel cell stack performance. Water, thermal and gas management are correlated and need to be well managed in order to achieve high and stable power output. From this study, the operating conditions that produced the best air condition that produced stable high power output over time achieved at 20^oC air temperature, 1 lpm air velocity with 50% air relative humidity. To undertake a study of the experiment, other probability that could affect performances such as cell orientation, cathode channel length, pressure at cathode side and others should be emphasized for next of study.

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6. References

[1] D.T. Santa Rosa, D.G. Pinto, V.S. Silva, R.A. Silva, C.M. Rangel. "High performance PEMFC stack with open-cathode at ambient pressure and temperature conditions". *International Journal of Hydrogen Energy*. vol. 32, pp. 4350 – 4357, 2007
http://dx.doi.org/10.1016/j.ijhydene.2007.05.042

[2] M. Tohidi, S.H. Mansouri, H. Amiri. "Effect of primary parameters on the performance of PEM fuel cell". *International Journal of Hydrogen Energy*. vol. 35, pp. 9338-9348, 2010.
http://dx.doi.org/10.1016/j.ijhydene.2010.03.112

[3] Barreras F, Lo´pez AM, Lozano A, Barranco JE. "Experimental study of the pressure drop in the cathode side of air-forced Open-cathode proton exchange membrane fuel cells". *International Journal of Hydrogen Energy*. vol. 36, pp. 7612-7620, 2011.
http://dx.doi.org/10.1016/j.ijhydene.2011.03.149

[4] Wu JF, Galli S, Lagana I, Pozio A, Monteleone G, Yuan XZ, Martin J, Wanga HJ. "An air-cooled proton exchange membrane fuel cell with combined oxidant and coolant flow". *Journal of Power Sources*. vol. 188, pp. 199–204, 2008
http://dx.doi.org/10.1016/j.jpowsour.2008.11.078

[5] Yuan W, Tang Y, Pan MQ, Li ZT, Tang B. "Model prediction of effects of operating parameters on proton exchange membrane fuel cell performance". *Renewable Energy*. vol. 35, pp. 656–666, 2010.
http://dx.doi.org/10.1016/j.renene.2009.08.017

[6] Wen CY, Lin YS, Lu CH, Luo TW. "Thermal management of a proton exchange membrane fuel cell stack with pyrolytic graphite sheets and fans combined. International Journal of Hydrogen Energy". vol. 36, pp. 6082-6089, 2011.
http://dx.doi.org/10.1016/j.ijhydene.2011.02.052

[7] Wang L, Husar A, Zhou TH, Liu HT. "A parametric study of PEM fuel cell performances". *International Journal of Hydrogen Energy*. vol. 28, pp. 1263 – 1272, 2003.
http://dx.doi.org/10.1016/S0360-3199(02)00284-7

[8] Kandlikar SG, Lu ZJ. "Thermal management issues in a PEMFC stack – A brief review of current status". *Applied Thermal Engineering*. vol. 29, pp. 1276–1280, 2009.
http://dx.doi.org/10.1016/j.applthermaleng.2008.05.009

[9] Zhang JL, Xie Z, Zhang JJ, Tang YH, Song CJ, Navessin TC, Shi ZQ, Song D, Wang HJ, Wilkinson DP, Liu Z-S, Holdcroft S. "High temperature PEM fuel cells". *Journal of Power Sources*. vol. 160, pp. 872–891, 2006.
http://dx.doi.org/10.1016/j.jpowsour.2006.05.034

[10] Zhang JL, Tang YH, Song CJ, Cheng X, Zhang JJ, Wang HJ. "PEM fuel cells operated at 0% relative humidity in the temperature range of 23–120 ◦C". *Electrochimica Acta*. vol. 52, pp. 5095–5101, 2007.
http://dx.doi.org/10.1016/j.electacta.2007.02.002

[11] Fabian T, Posner JD, O'Hayre R, Cha SW, Eaton JK, Prinz FB, Santiago JG. "The role of ambient conditions on the performance of a planar, air-breathing hydrogen PEM fuel cell". *Journal of Power Source*. vol. 161, pp. 168–182, 2006.
http://dx.doi.org/10.1016/j.jpowsour.2006.03.054

[12] Ahn JW, Choe SY. "Coolant controls of a PEM fuel cell system". *Journal of Power Sources*. vol. 179, no. 1, pp. 252–264, 2008
http://dx.doi.org/10.1016/j.jpowsour.2007.12.066

[13] Maher A.R. Sadiq Al-Baghdadi. "A CFD study of hygro–thermal stresses distribution in PEM fuel cell during regular cell operation". *Renewable Energy*. vol. 34, pp. 674–682, 2009.
http://dx.doi.org/10.1016/j.renene.2008.05.023

[14] Schmittinger W, Vahidi A. "A review of the main parameters influencing long-term performance and durability of PEM fuel cells". Journal of Power Sources. vol. 180, no. 1, pp. 1-14, 2008.
http://dx.doi.org/10.1016/j.jpowsour.2008.01.070

[15] Andrej, D., Matej, G., Boštjan, P., Maja, A-K., Janko, P., Vladimir, J. "Detection of Flooding and Drying inside a PEM Fuel Cell Stack". *Journal of Mechanical Engineering*. vol. 59, no. 2, pp. 56-64, 2013

[16] G Hinds. "Performance and Durability of PEM Fuel Cells: A Review". NPL Report DEPC-MPE 002. 2004, pp. 25–42.