THERMAL MANAGEMENT OF HIGH TEMPERATURE POLYMER ELECTROLYTE MEMBRANE FUEL CELLS BY USING FLATTENED HEAT PIPES

by

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High temperature polymer electrolyte membrane fuel cell is a clean energy conversion device that generates electricity directly from the electrochemical reaction. Since the working temperature is about 160 °C, the heating and cooling mechanisms are critical factors to maintain the optimal working condition and prevent the cell from degradation. Simulation models of high temperature polymer electrolyte membrane fuel cell were built for investigating the temperature distribution on the working area of fuel cells and temperature gradient across the stack. The ordinary method of heating by using heating pads and cooling by applying forced convection air was compared with the heat pipe heating and cooling technique. The results showed that heat pipe provided a more uniform temperature distribution and current density across the fuel cells stack. The temperature gradient of 0.214 °C per cell during heating and 0.054 °C per cell during cooling processes were observed. Meanwhile, only 0.44 mA/cm^2 *per cell of current density gradient was found.*

Key words: *high temperature polymer electrolyte membrane fuel cell, fuel cell, heat pipes, thermal management*

Introduction

The high temperature polymer electrolyte membrane fuel cell (HT-PEMFC) is an attractive energy conversion device since the characters of no GHG emissions, quiet operation, and compactness. By raising the working temperature to higher than 120 °C, the HT-PEMFC has surpassed the low temperature polymer electrolyte membrane fuel cell (LT-PEMFC) in many ways, such as no need of water management since the polybenzimidazoles based membrane used phosphoric acid as the conductive medium, ability to tolerate 30000 ppm CO content in the fuel, hence release the requirement of CO cleaner [1, 2]. The higher operating temperature not only contributes to the higher rate of electrochemical reactions, but also reduces the ohmic resistance [3, 4].

A suitable heating mechanism is a critical factor to optimize the performance of a HT-PEMFC. The stack needs to be heat up until it reaches the default temperature before supplying hydrogen and air. The heat energy must be properly supplied to prevent temperature gradient in each component from damaging bipolar plates and causing performance degradation of stack [5]. Various heating techniques have been investigated by research

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groups. Singdeo *et al.* [6] simulated the air heating, ohmic heating and liquid coolant heating for fuel cells. They observed that the air heating technique provides the fast start-up time with less energy consumption at temperatures around 120 °C. The similar result was present by Andreasen and Kaer [7], the HT-PEMFC stack was heated up by 160 °C hot air. This technique shows more homogeneous heat distribution than the direct heating by external electrical heaters.

The cooling mechanism for fuel cells must effectively removes the generated heat to prevent hotspots on components and to maintain working temperature within a proper range. Two cooling techniques are commonly used to uphold the working temperature of HT-PEMFC stack, *i.e.* liquid cooling and air cooling techniques. The liquid cooling technique performs a better heat removing rate since the transferred medium with higher heat capacity and thermal conductivity, but the leaking problem of the liquid system is the most irritated issue must be solved. The downsides of liquid cooling technique are using the complicated system with parasitic power consumption from pump, flow meter, pressure sensor, valve, *etc.* Bujlo *et al.* [8] conducted an external oil cooling system to maintain the working temperature of a 48 cells HT-PEMFC stack. The operating temperature was stably controlled at 120-160 °C and the reformer gas was fed as the reactant fuel. Song *et al.* [9] established a water pumpless cooling system for 1 kWe HT-PEMFC stack, the operating temperature was successfully controlled at 150 °C by only using the phase-change latent heat of water. Supra *et al.* [10] applied a thermal oil cooling system in a 1 kWe HT-PEMFC stack, the cell temperature was controlled at 180 °C with the current density of 450 mA/cm^2 and cell voltage of 0.5 V.

Air cooling, a relatively simpler and cheaper technique could be applied to the HT-PEMFC stack as well. The fans or compressors are used to supply air higher than the stoichiometric ratio to remove the generated heat from fuel cells stack. Andreasen *et al.* [11] applied the air cooling system to 1 kWe fuel cell-battery in a small electric vehicle. An axial blower was used to both control stack temperature and supply the air-fuel, the result proved 180 °C operating temperature can be stably controlled. A thermal management strategy of air cooling system for 1 kWe HT-PEMFC stack was modelled by Reddy and Jayanti [12]. The air stoichiometric factor of 10 was required to control the cell temperature at 200 °C, but a high temperature gradient of 50 °C was observed within the cell.

The heat pipe is one of the most efficient passive heat transfer devices. It basically consists of three components, container (sealed and vacuum), wick structure and working fluid. The liquid working fluid is vaporized at the evaporator section. Then, vapour phase fluid carry the latent heat and flows to condenser section. At the condenser section, the heat is released out and the vapour condense to liquid phase. The condensed working fluid returns to the evaporator section through the wick structure by capillary force. The thermal conductivity of heat pipe is approximately 500 times higher than a solid copper rod [13]. It had been applied to many applications, *e.g.* microelectronics device, laptop, solar cell, *etc.* Zhou *et al.* [14] applied ultra-thin flattened heat pipe to electronic devices. The results showed that the maximum heat transport capacity of 24 W was achieved by 1.1 mm flattened heat pipe. For fuel cell applications, Oro and Bazzo [15] applied triangular cross-section heat pipes to a PEMFC cooling system. The results showed that a set of heat pipes able to dissipate heat up to 12 W. Sun and Zheng [16] studied the thermal management of PEMFC, they announced that heat pipes are feasible to use in fuel cell cooling system since heat pipe provides compact structure and high thermal efficiency. Vasiliev and Vasiliev [17] considered using heat pipe spreader to improve the efficiency of fuel cells. They suggested applying the micro-heat pipe to the fuel cells stack under 100 W. While, the over 100 W fuel cells stack could be responded by pulsating heat pipe or loop heat pipes. Shirzadi *et al.* [18] investigated the cooling system of LT-PEMFC by using the heat pipes with 4 mm diameter and 170 mm long. The result showed that the operating temperature of 20 W fuel cells stack could be controlled by using three miniature heat pipes.

An uniform temperature distribution in the fuel cells stack could avoid local hotspots which might damage the structural components and increase the membrane degradation rate [12]. A low temperature gradient also leads to a higher mean operating temperature of stack, results in a faster chemical reaction and better performance [19, 20]. Due to the characters of high heat transfer rate and bidirectional heat delivery, heat pipes were applied to a 1 kWe fuel cells stack for both cooling and heating processes in this study. A stack model was built to investigate the thermal distribution on the working area and the temperature gradient across the fuel cells stack. The results were compared to the ordinary heating/cooling processes by using heating pads and air cooling technique.

Physical design and theoretical analysis

In this study, the design of 1 kWe HT-PEMFC stack refers to the experimental stacks developed by Advent Technologies S.A. [21] and Bujlo *et al.* [8]. Hydrogen and air were supplied to the stack with flow rates of 0.84 m^3/hr and 4 m^3/hr, respectively. The working area of stack investigated by the latter research group was 96 cm^2, and the power density reached 250 mW/cm^2 by using hydrogen and air as the reactants. Therefore, the stack model was presumed to contain 40 cells with 100 cm^2 working area, hydrogen and air were supplied and operating temperature was 160 °C in all study cases.

Stack design

Figure 1(a) shows a fuel cells stack adopting an ordinary heating and cooling method. Two 200 W heating pads are attached on the end plates of stack, an ordinary bipolar plate without cooling channel design is shown in fig. 2(a). The cooling channels can be found in figs. 1(c) and 2(b). On both sides of bipolar plate, 10×10 cm^2 flow field patterns are constructed to distribute the fuel and air.

Another stack equipped with copper heat pipes is shown in figs. 1(b) and 1(d). The flattened heat pipes are inserted into the special bipolar plates which are installed every four cells in the stack, the special bipolar plates is the bipolar plate with the cooling channels. A small heating pad is mounted to the outer ends of three heat pipes as show in fig. 2(c). For each special bipolar plate, 12 heat pipes are inserted into the core zone. The sizes of heat pipe are 185 mm in length and 2 mm in thickness, the thermal conductivity is assumed as 7000 W/mK for both heating and cooling processes.

Model setup

Heating procedure

The ordinary heating technique and the heat pipes heating technique were investigated with two slightly different stack models. For the ordinary heating technique, the heat energy is generated from the heaters and directly transferred from both end plates to the middle of stack by conduction. As for the heat pipes heating, the small heating pads are the heat sources, the flattened heat pipes deliver the heat energy from the heating pad to the core of stack. The heat energy of both techniques are controlled by a DC power supply.

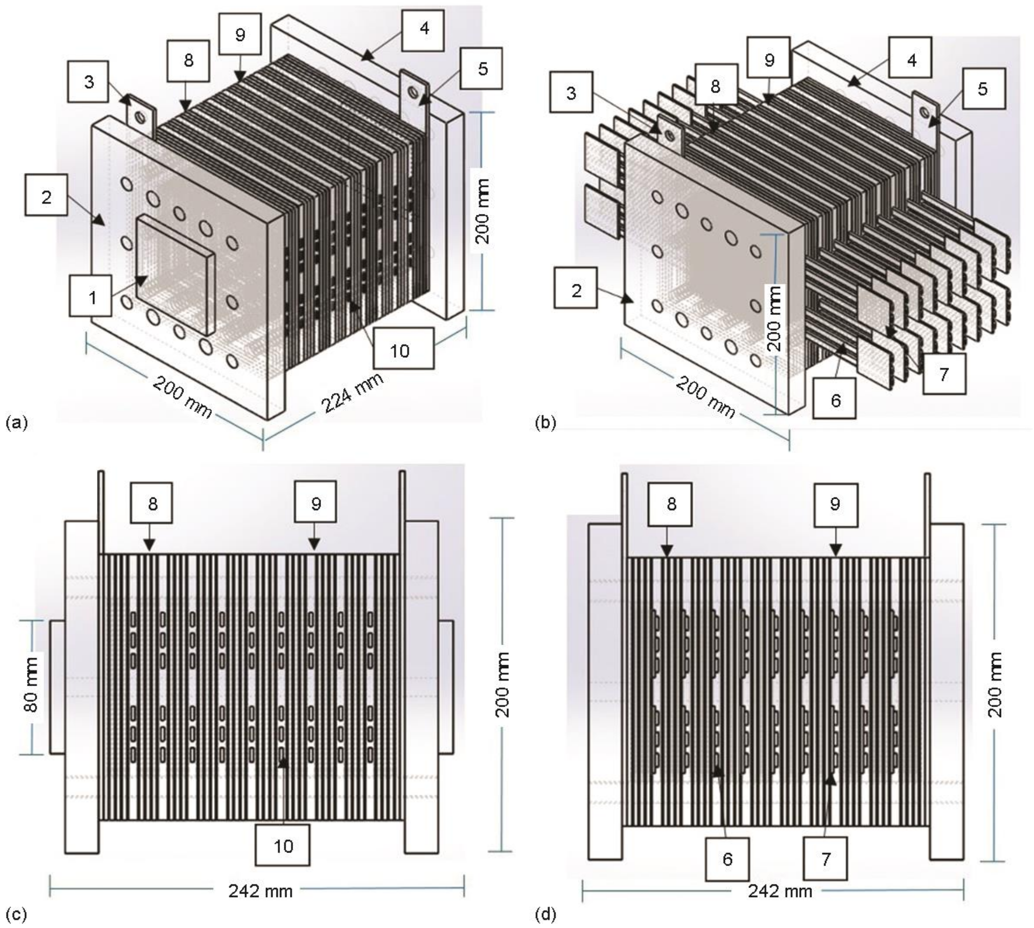


Figure 1. The comparison between model of ordinary stack and the heat pipe stack; (a) ordinary stack, (b) heat pipes stack, (c) side view of ordinary stack, and (d) side view of heat pipe stack; *1 – heating pad, 2, 4 – end plates, 3, 5 – current collector plates, 6 – copper heat pipe, 7 – small heating pad, 8 – bipolar plate, 9 – special bipolar plate, and 10 – cooling channel*

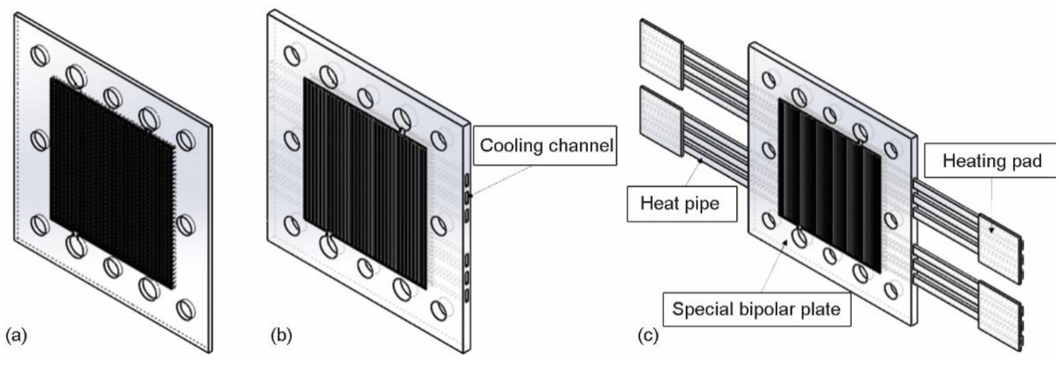


Figure 2. Detail of bipolar plate; (a) ordinary bipolar plate, (b) special bipolar plate, and (c) special bipolar plate mounted with 12 heat pipes and four heating pads

Cooling procedure

The membrane electrode assemblies (MEA) in both stack models were considered as constant heat sources during the cooling procedure. For the ordinary air cooling technique, the same model of fig. 1(a) was used to simulate the results of temperature distribution across the fuel cells stack, which is the same model in the heating process but the heat sources have been changed to MEA. The forced convection air was blown through the cooling channels to bring out the generated heat energy. The heat removal rate by forced convection air, according to calculation, was set to 57.4 W/m^2 for keeping the operation temperature of stack at 160 °C. With the heat pipes cooling technique, the generated heat energy was transferred from MEA to ambient air via the flattened heat pipes by conduction. The position of the heat pipes and special bipolar plates can be found in figs. 1(b) and 1(d).

The temperature distribution on the working area and temperature gradient across the fuel cells stack were investigated and compared. The temperature difference between the first and the 20th cell was especially concerned, which presented the temperature gradient across the fuel cells stack. All stack models in this study were built by a computer-aided design program SOLIDWORKS and simulation results were obtained from the computer-aided engineering software ANSYS™.

Thermal load estimation

The current density i of the HT-PEMFC stack is calculated by:

$$i = \frac{P_e}{nV_c} \tag{1}$$

where P_e [W] is the power of the stack, n – the number of cells, and V_c [V] – the electric potential of voltage. Referring to the results of previous works by other researchers [22-24], the current densities were 0.65, 0.7, and 0.95 A/cm^2, hence the modelled stack was designed to work at current density of 0.5 A/cm^2 to reach 0.5 V cell voltage.

Not only electricity, but also heat and water are the by-products from the electrochemical reactions of HT-PEMFC. The heat energy is generated and released out from MEA during the operation. In this study, the by-product heat was assumed as a homogeneous heat source emitted from MEA. The heat production of the HT-PEMFC stack can be calculated:

$$Q_{\text{production}} = P_e\left(\frac{1.25}{V_c} - 1\right) \tag{2}$$

The calculated heat production was 0.375 W/cm^2, similar with the generated heat used as the constant heat source in the models by other research groups [25, 26].

Since the electricity of fuel cells is generated from the hydrogen oxidation reaction and oxygen reduction reaction inside the cells. Hydrogen and air are fed into the fuel cells stack at room temperature. Since the temperature difference between cell and reactants, the fuels will absorb heat from the stack. The heat loss from hydrogen and air heating can be calculated:

$$Q_{H_2} = \dot{m}_{H_2} c_{p,H_2} \Delta T \tag{3}$$

$$Q_{\text{air}} = \dot{m}_{\text{air}} c_{p,\text{air}} \Delta T \tag{4}$$

where $\dot{m}_{H_2}$ and $\dot{m}_{\text{air}}$ [kgs^{-1}] are the mass-flow rate of supplied hydrogen and air, respectively, c_{p,H_2} and $c_{p,\text{air}}$ [kJkg^{-1}K^{-1}] – the specific heat capacity of supplied hydrogen and air, respectively, and ΔT [K] – the temperature difference between the cell and inlet fuel. Water is a product from the fuel cells which is generated by the chemical reaction. The amount of produced water in the stack is:

$$\text{Water}_{\text{production}} = 9.34 \cdot 10^{-8} \frac{P_e}{V_c} \tag{5}$$

As mentioned, the working temperature of HT-PEMFC is about 160 °C which means that the produced water will absorb heat and vaporize to the steam form. The heat losses by latent heat of evaporation could be calculated by:

$$Q_{\text{evaporation}} = \dot{m}_{\text{water}} h_v \tag{6}$$

where $\dot{m}_{\text{water}}$ [kgs^{-1}] is the mass production rate of water during the chemical reaction and h_v [kJkg^{-1}] – the specific evaporation enthalpy for water.

The generated heat from fuel cells is absorbed by several processes. Therefore, the net amount of generated heat is concluded:

$$Q_{\text{net}} = Q_{\text{production}} - Q_{\text{H}_2} - Q_{\text{air}} - Q_{\text{evaporation}} \tag{7}$$

The net generated heat must be released from the stack to maintain the operating temperature. Therefore, in the cooling procedure, MEA is considered as a heat source in the model for both heat pipes cooling technique and the ordinary air cooling technique. The heat is uniformly distributed from the MEA to other components.

Results and discussions

The stack performance depends on the uniformity of temperature distribution on fuel cells. To avoid the heat spot occurring on the MEA, the heat energy across the whole stack must be evenly dispersed. The temperature distribution across the fuel cells stack was investigated by simulation. Results will be discussed in three different categories: heating process, cooling process, and effect of the temperature distribution on the electricity generation.

Heating process

The start-up process is an important period for operating a HT-PEMFC stack. As mentioned above, the working temperature of HT-PEMFC is about 160 °C. Therefore, the stack needs to be heat up to a certain temperature (typically over 120 °C) before feeding hydrogen and oxygen to the stack to prevent the membrane degradation. The stack consists of different material components. During the heating process, if the components unequally expand due to the temperature gradient, the crevices between components will be induced and eventually causes the fuels leakage. Besides, the temperature difference on each cell affects the cells performance as well.

For both the heat pipes heating technique and ordinary heating technique, the stack temperature was increased from the room temperature to a default steady-state condition. From figs. 3(a) and 3(b), the (maximum) temperatures of heaters, 202.15 °C and 244.37 °C can be observed respectively. Figures 3(c) and 3(d) show the longitudinal cross-section view of stack with temperature distribution contour across the fuel cells stack. The heat pipes heating technique kept the heat distribution uniformly across the stack. In contrast, the highest temperatures appeared on both ends of stack in the ordinary heating technique. Figure 3(e) presents temperature distribution across the fuel cells stack of two different heating techniques. The heat pipes heating technique showed a more uniform temperature distribution across the stack. It derived the highest temperature of 198.74 °C at the centre of the 20th cell. With the ordinary heating technique, the highest temperature of 212.78 °C was appeared on the first cell and 40th cell of the stack since they were close to the heating pad.

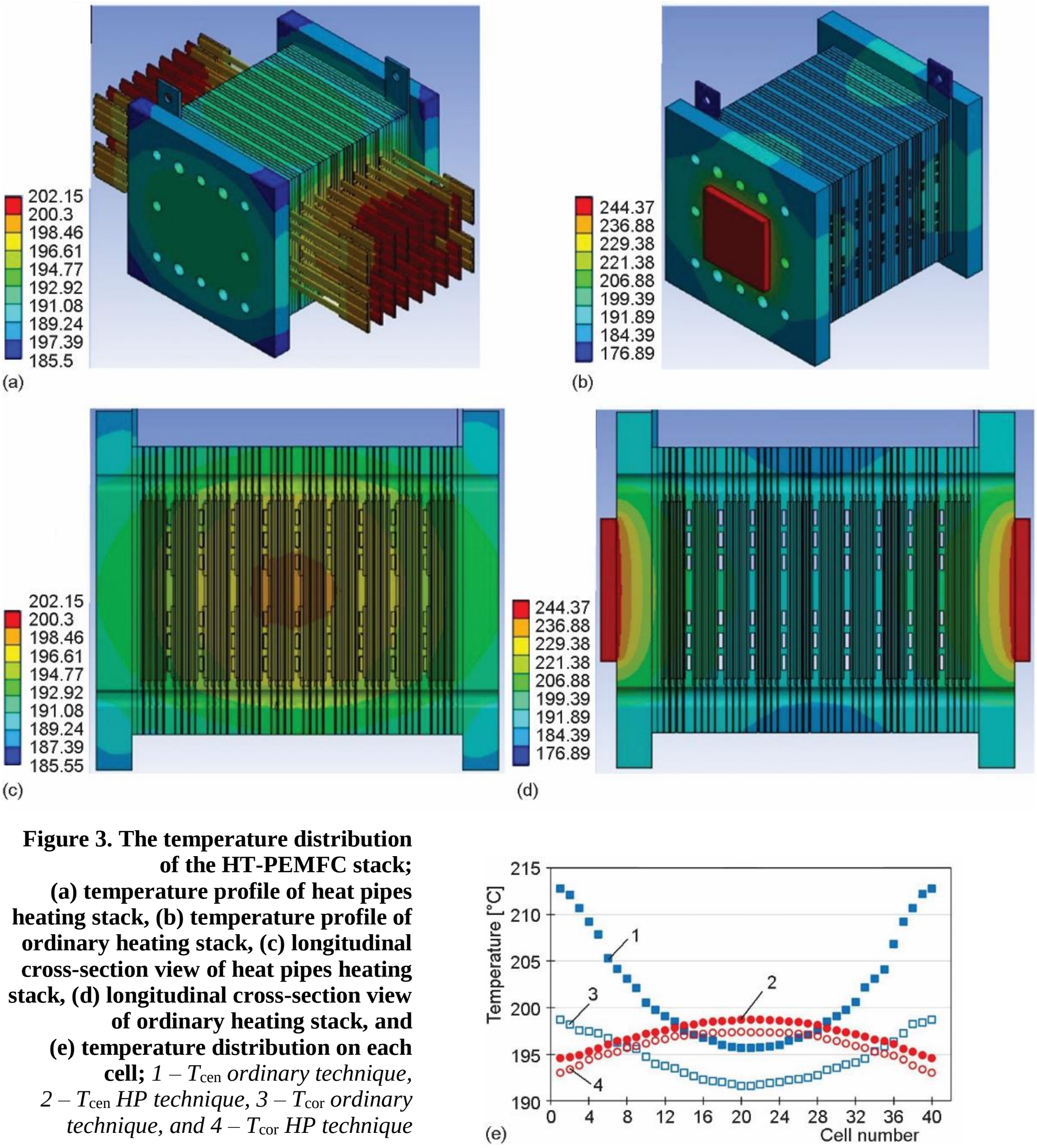


Figure 3. The temperature distribution of the HT-PEMFC stack; (a) temperature profile of heat pipes heating stack, (b) temperature profile of ordinary heating stack, (c) longitudinal cross-section view of heat pipes heating stack, (d) longitudinal cross-section view of ordinary heating stack, and (e) temperature distribution on each cell; *1 – T_{cen} ordinary technique, 2 – T_{cen} HP technique, 3 – T_{cor} ordinary technique, and 4 – T_{cor} HP technique*

The temperature distribution on working area was also explored. The temperatures on the centre and corner of working area for each cell are presented in fig. 3(e). The ordinary heating technique evinced the highest temperature difference on the first cell and 40th cell, it was about 14.04 °C. The lowest temperature difference of 4.06 °C was observed on the 20th cell. The heat pipes heating technique produced lower temperature difference, the average temperature difference on working area was about 1.19 °C.

The temperature gradient is a rate of temperature change with respect to distance of heat flow. In this study, the temperature gradient across stack was calculated by the difference of average temperature on the working area of the first cell and the 20th cell compared to the heat transfer distance. The temperature gradients across fuel cells stack of ordinary heating technique and heat pipes heating technique were 0.606 °C per cell and 0.214 °C per cell, respectively. The former method incurred a larger temperature gradient due to longer heat transferred distance. In contrast, the latter technique provides a smaller temperature gradient since the generated heat was directly transferred to the fuel cells stack by heat pipes which located at every four cells. The relationship between the temperature gradient and the heat transfer distance can be explained by thermal conduction, q, and thermal resistance, R, principle [27]:

$$q_{\text{conduction}} = kA\frac{\Delta T}{L} \tag{8}$$

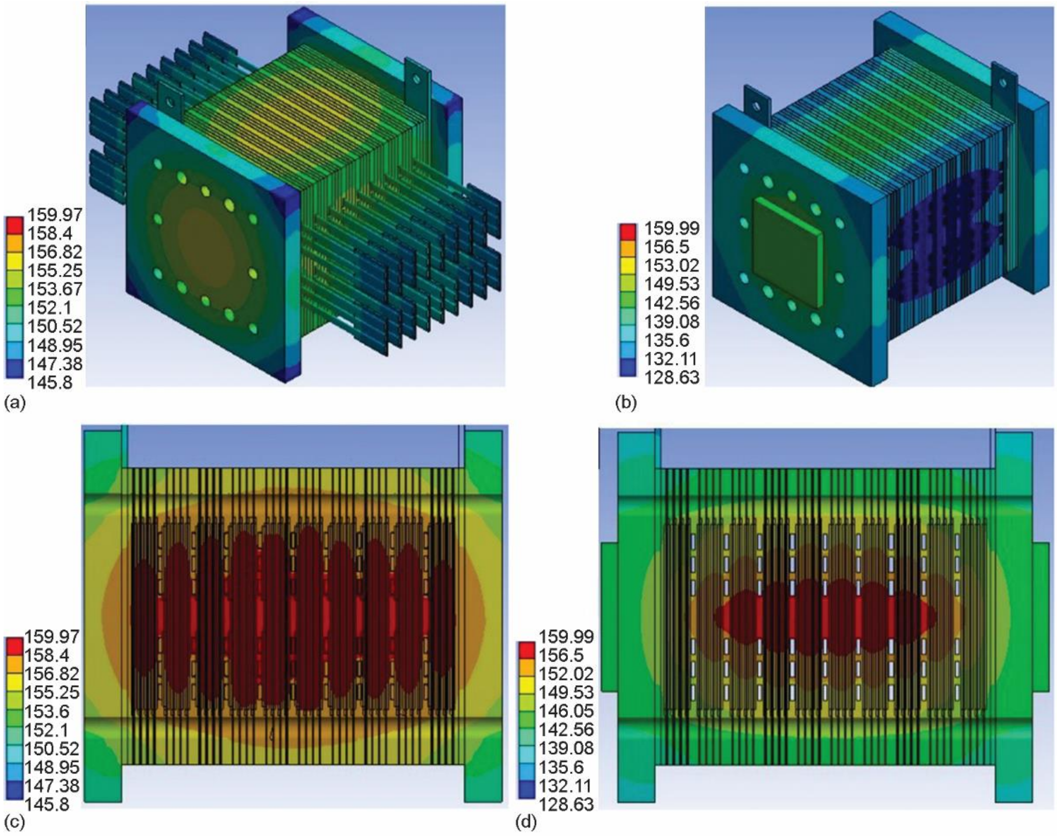
$$R_{\text{conduction}} = \frac{L}{kA} \tag{9}$$

where k [Wm^{-1}K^{-1}] is the material conductivity, A [m^2] – the cross-sectional surface area, ΔT [K] – the temperature difference between two points, L [m] – the heat transfer distance, and $R_{\text{conduction}}$ – the thermal resistance of conduction. The heat transfer distance of the ordinary heating technique is the length between the 20th cell and heat source. The longer distance causes higher thermal resistance. Consequently, a higher temperature gradient will present. In contrast, the heat pipes heating technique transfers heat from source to the core of the special bipolar plate in every four cells. The shorter heat transfer distance performs more uniform heat distribution and low temperature gradient across the fuel cells stack.

Cooling process

The main objective of the cooling system is to maintain a uniform temperature distribution across working area of cell and low temperature gradient between each cell of stack, which is important for reaching a proper working condition of HT-PEMFC. The heat generated from the electrochemical reaction will increase the stack temperature, which has to be kept at the same level during operation because the consequential effects on the cell performance and durability. The air cooling method is the simplest cooling technique since only the installation of a fan or blower is required. However, the result of high temperature gradient across the stack is a big issue. To simplify the simulation, MEA was replaced by a constant heat source in the stack, the amount of generated heat was calculated according to eqs. (1)-(7).

Figure 4 presents temperature distribution profiles across the stack with two different techniques. The maximum temperature, about 160 °C, occurs at the middle of stack for both methods. The lowest temperatures were found at the corner of end plates, fig. 4(a), and the cooling channels, fig. 4(b). Figures 4(c) and 4(d) present the temperature distribution profiles in the longitudinal cross-section view at the centre line of stack. The highest temperature areas both located at the centre of stack in two different cooling techniques. However, the heat pipes cooling technique produced larger coverage. Similar temperature profiles which the temperatures on both sides are lower than the middle of stack were observed, because the intensity and position of heat sources were the same. Nevertheless, the temperature distribution between the centre and corner of working area were different. As it can be seen in fig. 4(e), compared with the temperature differences of 7.1 °C and 16.75 °C at the first cell and 20th cell with air cooling, the heat pipe cooling technique showed a better temperature distribution with an average value at about 2.94 °C.



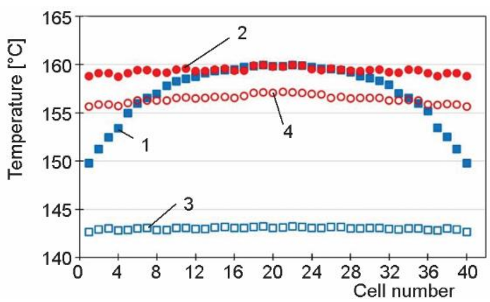


Figure 4. The temperature distribution of the HT-PEMFC stack; (a) isometric view of heat pipes cooling stack, (b) isometric view of air-cooling stack, (c) longitudinal cross-section view of heat pipes cooling stack, (d) longitudinal cross-section view of air cooling stack, and (e) temperature at the corner and centre of the working area; *1 – T_{cen} ordinary technique, 2 – T_{cen} HP technique, 3 – T_{cor} ordinary technique, and 4 – T_{cor} HP technique*

Temperature gradient across stack was calculated by the difference between the lowest and highest of the average temperature on working area compared to the heat transfer distance. The highest of average temperature on working area occurred at the 20th cell and the lowest average temperature located at the first cell. The results showed that the temperature gradient of heat pipes cooling technique and air cooling technique were 0.054 °C per cell and

0.267 °C per cell, respectively. The minimal temperature gradient was gained by using heat pipes as the heat transfer device. The heat pipes were inserted into the cooling channels of the special bipolar plates. The function of heat pipes here is not only releasing the heat out to the ambient, but also distributing the heat energy inside the plates by replacing the free space in cooling channels with high conductive heat pipes result in the temperature uniformly acrossed the stack. On the contrary, the air cooling technique maintained stack temperature by controlling the amount of forced convection air, which can only discharge the generated heat. Moreover, the thermal conductivity of air was lower than heat pipe, which resulted in a higher-temperature gradient across the working area [13, 28]. The maximum temperature gradient in the working area is the temperature between the core of stack and corner of the outermost cell. The maximum temperature gradient 0.85 °C per cell was found in the air cooling stack, which can be verified by a similar stack model proposed by Reddy and Jayanti [12], they concluded a high-stoichiometric air cooling technique caused the maximum temperature gradient of 0.8 °C per cell. Therefore, a lower temperature gradient across stack to achieve uniform temperature distribution on working area can be done better by heat pipes cooling technique.

Effect of the temperature distribution on the electricity generation

Current density, [Acm^{-2}] is the term used for presenting the electricity generation ability of fuel cells at a certain voltage output, which can be affected by the stack temperature. The relationship between the temperature and current density had been published by research groups [29, 30]. At constant voltage of 0.5 V, the current density can be calculated according to the temperature as eq. (10):

$$i = 4.75\cdot 10^{-7}T^3 - 6.153\cdot 10^{-4}T^2 + 0.2738T - 41.22 \tag{10}$$

where T [K] is the temperature and i is the current density. Since the temperature distribution is not uniform, the temperature profile on the working area was divided into 25 equal parts with each size of 2×2 cm^2, and a local average temperature was calculated. By applying local average temperature to eq. (10), the local current density can be obtained as shown in fig. 5. To reveal the current density distribution on fuel cells stack, the local average temperatures of the first cell and the 20$^{\text{th}}$ cell were compared. The relationships between local current density and temperature distribution on the first cell of the HT-PEMFC stack were shown in figs. 5(a) and 5(b). The maximum and minimum local current densities located at the centre and corner of working area, respectively.

The current density difference for the first cell was 25.2 mA/cm^2 by heat pipes cooling and 47.9 mA/cm^2 by air cooling. The relationships between local current density and temperature distribution on the 20$^{\text{th}}$ cell of stack are presented in figs. 5(c) and 5(d). The heat pipes cooling technique possessed the maximum local temperature of 159.91 °C at the centre of cell which resulted in the maximum current density of 535.7 mA/cm^2. It was 24.5 mA/cm^2 higher than the minimum local current density which occurred at the corner area. For air cooling technique, the maximum temperature located at the centre of working area was 159.9 °C and the induced current density was 535.6 mA/cm^2. The current density difference between the centre and corner of working area was 123.8 mA/cm^2.

The current density gradient is a rate of current density change respect to distance. It was decided by the maximum and minimum of average current density across the stack, which located at the 20$^{\text{th}}$ cell and the first cell. The current density gradients were

0.44 mA/cm^2 per cell and 2.19 mA/cm^2 per cell with heat pipes cooling and air cooling, respectively. At the highest temperature of the working area was about 160 °C, cooling by heat pipes can keep the average stack temperature at 157.88 °C and obtain an average stack current density of 519.3 mA/cm^2. However, with the ordinary air cooling technique, the average temperature can only be retained at 150.05 °C, and the induced average stack current density was 455.4 mA/cm^2. Since the heat pipe is a high thermal conductivity device which can effectively transfer heat, the generated heat from the core of stack can be discharged to the ambient and also evenly distributed across the plate by fufill the cooling channel. Therefore, the heat pipes cooling technique can provide more uniform temperature distribution across the HT-PEMFC stack, which will lead to a uniform current density performance.

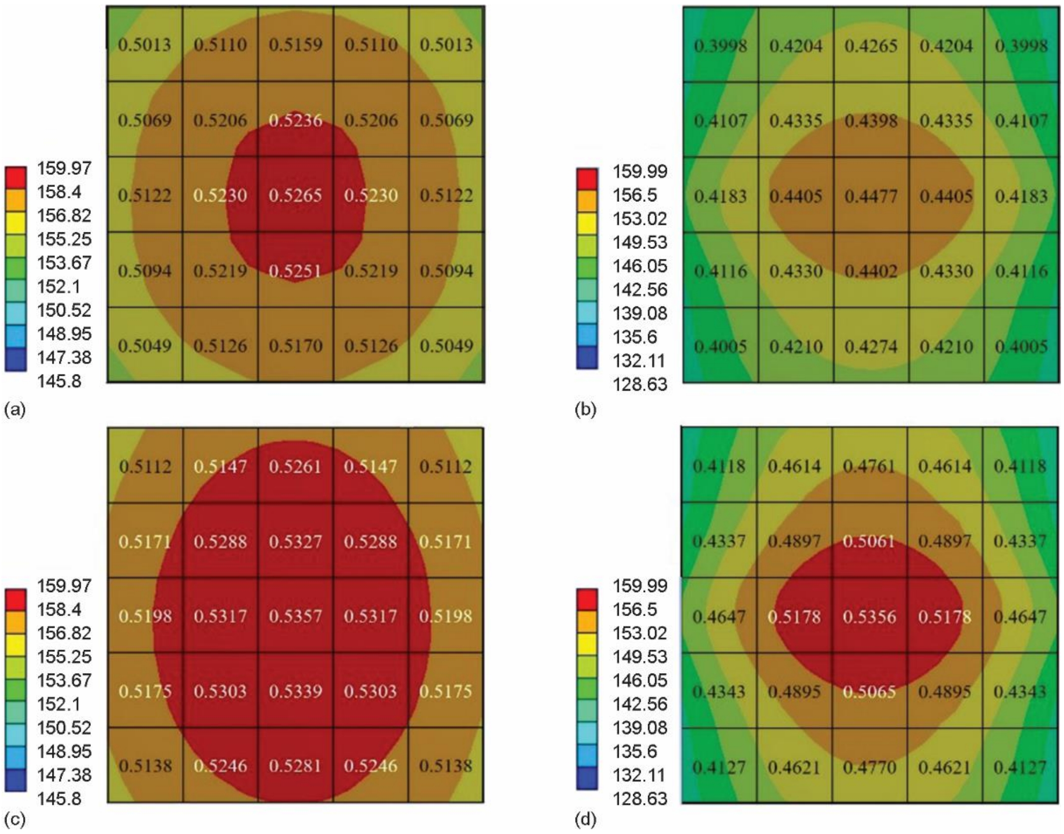


Figure 5. Relationship between temperature distribution and current density [Acm^{-2}]; (a) the first cell of heat pipes cooling technique, (b) the first cell of air cooling technique, (c) the 20th cell of heat pipes cooling technique, and (d) the 20th cell of air cooling technique

Conclusion

Physical models of HT-PEMFC were built to investigate the effects of using heat pipe on heating and cooling approaches, the temperature distribution on the working area and the temperature gradient across fuel cells stack were observed. The ordinary heating method of using the heating pads and ordinary cooling method by using forced air convection were compared to the heat pipes heating and cooling technique. In the heating process, the heat pipes heating technique kept the average temperature difference on working area about 1.19 °C, in contrary, 14.04 °C and 4.06 °C were found on the first cell and the 20th cell with the air cooing technique. Since the air cooling technique provided long distance heat transfer from the heat source to middle cell of stack, a high temperature gradient across the stack will be formed. On the other hand, with the heat pipe installed in every four cells, the heat pipes heating technique can achieve a uniform temperature distribution. During the cooling process, the operating temperature was controlled about 160 °C. The heat pipe cooling technique provided more uniform heat distribution across stack due to heat pipes not only draws out heat from the centre of cell to ambient but also distribute heat inside bipolar plates. In contrast, air cooling technique provides high temperature drop during the cooling channel of the plates. The stack temperature gradient of the heat pipes technique and air cooling technique were 0.054 °C per cell and 0.267 °C per cell, respectively. The temperature of working area also affects the current density. The 455.4 mA/cm^2 of average current density performed by the air cooling technique compared to 519.3 mA/cm^2 from the heat pipes cooling technique. It could be concluded that the heat pipes heating and cooling technique show more uniform temperature distribution on working area and low temperature gradient across fuel cells stack than the ordinary heating and cooling technique. It also provides more uniform current density since the heat pipes provides high thermal conductivity lead to the heat is efficiently and evenly transferred across the cell.

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