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PORTABLE PEM FUEL CELL SYSTEM: WATER AND HEAT MANAGEMENT

SITI NAJIBAH ABD RAHMAN[1], MOHD SHAHBUDIN MASDAR[1,2,3,*],
MASLI IRWAN ROSLI[1,2,3], EDY HERIANTO MAJLAN[1], TEUKU HUSAINI[1],
WAN RAMLI WAN DAUD[1,2,3], SYAHRIL ANUAR MD REJAB[4],
CHEW CHIEN LYE[4]

[1]Fuel Cell Institute, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia
[2]Research Center for Sustainable Process Technology (CESPRO), Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia
[3]Department of Chemical and Process Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia
[4]Sime Darby Research Sdn. Bhd., Jalan Pulau Carey, 42960 Pulau Carey, Selangor, Malaysia
*Corresponding Author: shahbud@ukm.edu.my

Abstract

Portable polymer electrolyte membrane (PEM) fuel cell power generator is a PEM fuel cell application that is used as an external charger to supply the demand for high energy. Different environments at various ambient temperatures and humidity levels affect the performance of PEM fuel cell power generators. Thermal and water management in portable PEM fuel cells are a critical technical barrier for the commercialization of this technology. The size and weight of the portable PEM fuel cells used for thermal and water management systems that determine the performance of portable PEM fuel cells also need to be considered. The main objective of this paper review was to determine the importance of water and thermal management systems in portable PEM fuel cells. Additionally, this review investigated heat transfer and water transport in PEM fuel cells. Given that portable PEM fuel cells with different powers require different thermal and water management systems, this review also discussed and compared management systems for low-, medium-, and high-power portable PEM fuel cells.

Keywords: PEM fuel cell, Portable power generator, Water management, Thermal Management.

1. Introduction

Fuel cell is an electrochemical device that generates electricity and heat by converting fuel, such as hydrogen and oxidant, to energy. This device is a relevant and renewable power source for the future. Fuel cells are environmentally friendly because their sole by product is water, and it do not emits harmful and greenhouse gases. Besides that, fuel cells have no moving parts, they are silent devices. Among the different types of recognized fuel cells is the polymer electrolyte membrane (PEM) fuel cell, which exploits the simplicity of the fuel cell as it utilizes solid polymer as electrolyte [1].

Portable PEM fuel cells units are built to be charged and moved as auxiliary power units in military and other applications. The power range of a portable PEM fuel cell is between 5 W and 10 kW, depending on the application. PEM fuel cell is suitable for portable application because of its rapid start-up capability, low operating temperature, and compactness due to the thin membrane electrode assembly (MEA) that can be developed [2]. Portable PEM fuel cell systems require a simple design, ease of use, high efficiency, optimum performance, compact size, and operability at a temperature range of −40 °C to 60 °C [3, 4].

The development and commercialization of portable fuel cell as a mobile power source remains a challenge. One of the challenge is the need to consider the size and weight of the portable fuel cell to meet the packaging requirement for certain commercial systems [5]. The stand-alone fuel cell cannot generate power, it required of some subsystems in supplying fuel and oxidant and achieving balance of plant (BOP) to provide necessary control for the fuel cell to efficiently generate electricity at the desired operating condition. Therefore, the portable PEM fuel cell system is more complex than batteries, which has only one system. Power generated by portable fuel cells determines stack and BOP sizes, whereas time operation depends on storage size [2]. An increase in power generation and duration period increases the size and weight of the portable fuel cell.

Thermal and water management are the main concerns in PEM fuel cells because stack temperature affects electrochemical kinetics of the electrodes, as well as the transport ability of reactant gases through porous media [6]. Whereas, the water content influences the proton conductivity of electrolytes, and sufficient water content is essential for the prevention of membrane dehydration [2]. Portable PEM fuel cells must be designed to operate under various environments as its performance depends on ambient temperature and humidity. Thus, proper water and thermal management are crucial in a fuel cell’s ability to adapt to a certain environment [7].

Some of the BOP in PEM fuel cells is used for thermal and water management systems, including humidifier, air condenser, pump, and valve, contributing to fuel cell cost and size [8]. Thus, removing or simplifying the BOP and water and thermal management of PEM fuel cell can improve its size and portability [3]. The design of BOP for water and thermal management must be lightweight and compact with good performance. In addition, heat and water transport mechanisms of PEM fuel cell must first be well understood before selecting the management system designs for portability development.

Therefore, this paper discusses management issues and outlines heat transfer and water transport mechanisms in PEM fuel cells. Additionally, different practical prototype thermal and water management systems from previous experimental studies were reviewed according to the power capacity (low, medium, high) of portable PEM fuel cells. Different applications require different thermal and water management system designs.

2. Heat Generation and Transfer

Approximately 60% of chemical energy content in hydrogen gas is converted into electricity, whereas the remaining 40% is generated as heat and waste in MEA of PEM fuel cell [9]. PEM fuel cell produces irreversible heat and entropic heat generated by electrochemical reactions, latent heat release or absorption during the phase change of water, and ohmic or Joule heating that arises from proton/electron reactions [10]. The reversible path of entropy change of the electrochemical reaction or reversible heat generates entropic heat. Meanwhile, waste heat is generated by irreversible electrochemical reaction when the charges overcome the over potential, especially at high current density [9]. The temperature of PEM fuel cell elevates when average current density and over potentials increase simultaneously, leading to high waste heat generation rate, especially at gas inlet region [11]. Other waste heat, ohmic heat, or Joule heat is generated by electron or proton current flow in the component when PEM fuel cells encounter ohmic resistance that corresponds to voltage loss.

Waste heat needs to be properly removed from fuel cells to avoid the formation of hot spots. Hot spots strongly affect fuel cell performance through conduction-convection modes based on the cooling system used. PEM fuel cell stacks are cooled by air, water, heat spreaders, or other coolants. Air-cooled and water-cooled systems are more convenient and simple to operate and use, are commonly employed in portable PEM fuel cells. Two types of heat transfers are involved in air-cooled systems: (i) conductive heat transfer of the entire stack in the opposite direction of air flow as heat flow is determined by temperature gradient and (ii) forced convection heat transfer that flows in the direction of the air (Fig. 1). A 3D numerical model was developed in a previous study by Shahsavari et al. [12], in which the bipolar plate in-plane thermal conductivity and air velocity are important parameters to be considered in the thermal management of air-cooled fuel cells because convection heat transfer is greater than conductive heat transfer in the fuel cell. Moreover, an experimental study demonstrated by Akbari et al. [13] show that the maximum surface temperature significantly drops by increasing the air inlet flow rate.

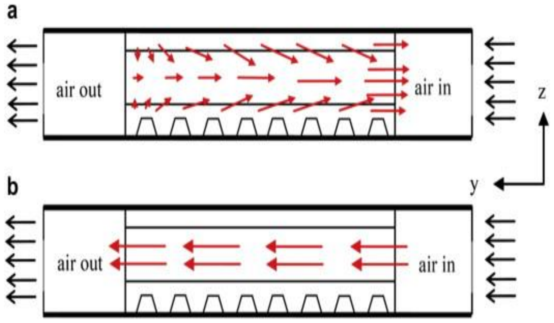

Fig. 1. Flow of heat transfer in air-cooled PEM fuel cell: (a) conductive heat transfer and (b) convection heat transfer [12].

A water-cooled cooling system is used for large active cell areas because the system can obtain non-uniform temperature distribution inside the PEM fuel cell. In addition, liquid has a higher heat transfer coefficient than air flow at the same pumping power [14]. Water coolant flows in the cooling channels, which are incorporated in the bipolar plate. Researchers have developed a model for the thermal analysis of water-cooled PEM fuel cell to characterize heat distribution across the stack [15]. The cooling circuit in their PEM fuel cell stack model was parallel to the anode of one cell and the cathode of the next. The red dashed arrow in Fig. 2 shows the possible heat flow. The cooling circuit in their PEM fuel cell stack model was parallel to the anode of one cell and the cathode of the next. Conduction drives heat transfer from the wall of the cooling channel in their stack to fluid. The cooling system design applied in the experimental study of portable PEM fuel cell is discussed and reviewed in the next section.

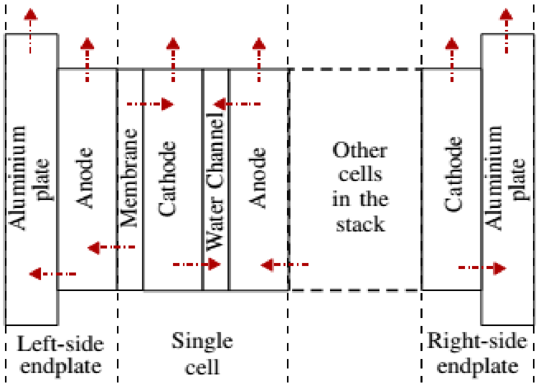

Fig. 2. Location of cooling circuit in PEM fuel cell stack [15].

3. Water Transport Mechanism

The water content distribution in PEM fuel cell is from the following: (i) water production in the cathode catalyst layer (CCL) by electrochemical reactions, (ii) water transportation that provides back diffusion from the cathode to the anode, (iii) water transfer by electro-osmotic drag from the anode to the cathode, and (iv) supply by external humidification system from air and hydrogen streams [16]. Water movements in PEM fuel cells may occur simultaneously, resulting in a complex water balance (Fig. 3). Electro-osmotic drag is when water molecules are dragged by the proton (H+) flow from the anode to the cathode [16].

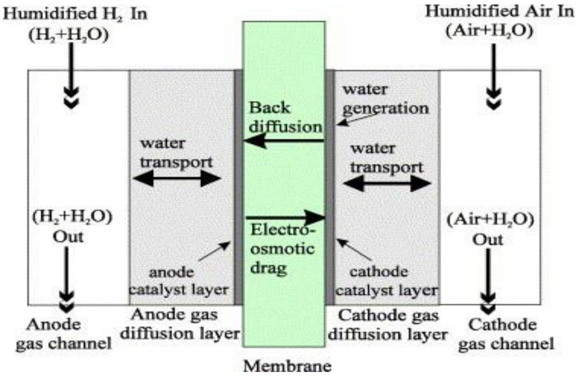

Fig. 3. Schematic of water transport in PEM fuel cell [17].

Water is produced by the oxygen reduction reaction in CCL, resulting in a higher water concentration at the cathode side than at the anode side. Therefore, water diffuses into the membrane from the cathode to the anode because of the high water concentration gradient between the cathode (high water concentration) and anode (low water concentration) until an equilibrium concentration is achieved between the two sections. This water transport mechanism is known as back diffusion [17]. Electro-osmotic drag and back diffusion affect the PEM fuel cell's water balance, which determines membrane hydration, as explained in the next section.

4. Thermal Management

Thermal management is extremely important for the fuel cell to have good performance and high efficiency without any degradation in the construction materials. Improper thermal management systems can result in membrane dehydration and cathodes flooding, which can increase proton resistance, induce proton conductivity, and reduce fuel cell performance. Membrane dehydration caused by a lack of water content results from temperature increase within the stack as the reaction occurs at a high air flow rate [16]. Moreover, the electrocatalyst surface area is reduced because the platinum particle size increases as the temperature increases, resulting in a degradation effect [18]. Moreover, perfluorosulfonic acid polymers (Nafions), a common PEM fuel cell membrane electrolyte, suffers from degradation under low humidity at 80 °C [19]. The temperature and relative humidity (RH)of the PEM fuel cell stack must be maintained between 60 °C to 80 °Cand RH greater than 80% respectively [20].

Generally, high-proton conductivity is achieved at high temperature. Operating the PEM fuel cell slightly below the maximum operating temperature can be advantageous. Thus, a proper thermal management system is important in maintaining the desired temperature and hydration under high external loads. Thermal management, such as a cooling system, is also an essential system that must be applied in portable PEM fuel cells. Some studies categorize cooling systems for portable PEM fuel cells into low, medium, and high power capacity.

4.1. Low power portable PEM fuel cell

Low-power portable fuel cell devices (5-100 W) usually use ambient air as cooling medium at either the same or separate stream with oxidant. Air-cooled fuel cell systems are relatively inexpensive because they do not require auxiliary units, such as air compressor, humidifier, and water cooling loop, which can be found in convectional fuel cell designs [12]. A system design known as open cathode design demonstrated in a previous study by Inman et al. [21] that uses an air-breathing stack and external fan for air supply and cooling. In their study, a fan controller is used to regulate fan speed by varying the voltage across it, which is based on the fuel cell stack output voltage. Fan speed increases at a low fuel cell voltage to maintain the desired oxygen concentration and cooling, and vice versa for higher cell voltage. A maximum power of 17 W is not upheld for long periods because an undersized fan cannot supply sufficient oxidant to the fuel cell stack, causing system inefficiency. Development of a suitable design for cathode flow channel can reduce size and energy consumed by the cooling system, providing better overall efficiency [22].

Another study from Urbani et al. [23] developed a portable PEM fuel cell with similar cooling system design as Inman et al. [21]. The energy loss of 10 cell stacks is higher than predicted, which can be overcome by air recirculation via fan in the portable system. Air circulation can provide greater air convection at the cathode side of the air-breathing PEM fuel cell stack. The portable PEM fuel cell system in their study supplied continuous output power of 12 W at 9.5 V to power a portable DVD player for 3 h [23].

Increasing air supply at the cathode side for cooling can dry out the membrane. A study from Oszcipok et al.[24] involved a 30 W portable PEM fuel cell system that could start up between −20 °C and 40 °C. The researchers used ambient air as cooling medium, which was supplied by a cooling fan that was turned on when the stack temperature increased to 65 °C. The ambient air supply at the cathode side via cathode pumps in their portable PEM fuel cell was separated with the cooling system. Cool air flowed in cooling ribs, which were integrated in the end-plates of the PEM stack. Aside from maintaining the stack temperature, thermal management also avoids the PEM fuel cell stack from being too cold for start-up. No proton conductivity occurs below 0 °C because the water as proton carrier is frozen in pure Nafion® PEM fuel cell [6]. Thus, the PEM fuel cell stacks shown by Oszcipok et al. [24] are attached to an electrical foil for cold start-up at −20 °C. Membrane dehydration is prevented using a separate oxidant input and cooling system; the portable PEM fuel cell was operated for 3 days at −20 °C and 40 °C [24].Thus, their portable PEM fuel cell system was capable for long-term operation.

4.2. Medium power portable PEM fuel cell

A cooling system similar to low-power portable PEM fuel cell (air-cooled via open cathode design with cooling channel) was implemented for medium-power portable PEM fuel cell with power of 100 W to 2 kW [22]. Devrim et al. [25] used an air-cooled cooling system for a 650 W PEM fuel cell stack for 500 W portable fuel cell applications. This cooling system can maintain the temperature of the fuel cell stack at 65 °C using the forced air stream from ambient air supplied by a fan over the cooling channel. Generated excess heat is then removed by convection. The cooling system is on-off type, which is turned off for 8 min and turned on for 20 min. High power at 647 W of PEM fuel cell stack was obtained at a constant temperature of 65 °C controlled by an air-cooled cooling system.

Another study fabricated a 500 W air-cooled portable PEM fuel cell stack with separate air streams [7]. The stack temperature was controlled by several axial cooling fans. Based on their study, the researchers found that axial cooling fans consume less than 2% of the total power output with optimized operation [7].

4.3. High power portable PEM fuel cell

To our knowledge, there is no study available in the literature regarding the development high-power portable PEM fuel cells generating 2-5 kW of energy.

However, a study has focused on the cooling system of a PEM fuel cell generator of large power capacity (>5 kW), which may be applied for large-power portable PEM fuel cell [6]. This type of portable fuel cell has a complex PEM fuel cell stack design, resulting in more heat transfer and more challenges for the thermal management system [9]. High-power PEM fuel cells require more complex thermal management, as coolants are used instead of ambient air, which is utilized in low and medium power portable PEM fuel cells.

The study from Hwang proposed a thermal control unit for thermal management in 5.8 kW PEM fuel cell generator, as shown in Fig. 4 [6]. The cooling system consisted of heating and cooling circuits that recirculated the coolant medium, which was a mixture of propylene and deionized water at a 1:1 ratio. The function of the cooling circuit was to cool down the stack by pumping coolant to the parallel cooling channels in the stack, as well as to remove heat dissipated by the stack. As the stack temperature increased, the thermostat was assigned to deliver more coolant over the radiator to cool down the stack. The radiator and convectional fan were operating in the cooling circuit to reject heat and increase the cooling capacity of the coolant. Meanwhile, the heating circuit assisted in warming up the stack for cold start-up by flowing stack coolant in the circuit and restricting coolant flow from the stack to the cooling circuit. Based on the study, the optimum stack coolant inlet temperature was between 58 °C and 63 °C to maintain a working temperature of approximately 80 °C and achieve high efficiency of the PEM fuel cell generator system [6].

Although the liquid-type coolant showed high performance by demonstrating good cooling capability than air-cooled system, but the additional auxiliary units, such as large size radiator, may contribute to coolant degradation, high cost and large portable size [26]. These technical challenges must be considered for the development of high-power portable PEM fuel cells.Besides that, liquid-type cooling system has a very complex system and it need a reliable control to control all the cooling BOP. Thus, low- and medium-power of portable PEM fuel cells that utilize air-cooled system is more preferable for commercialize than liquid-type coolant of high-power portable PEM fuel cells.

Degradation related to thermal management is also correlated with improper water management. Other water management issues in PEM fuel cells and water management strategies in portable PEM fuel cells are reviewed in the next section.

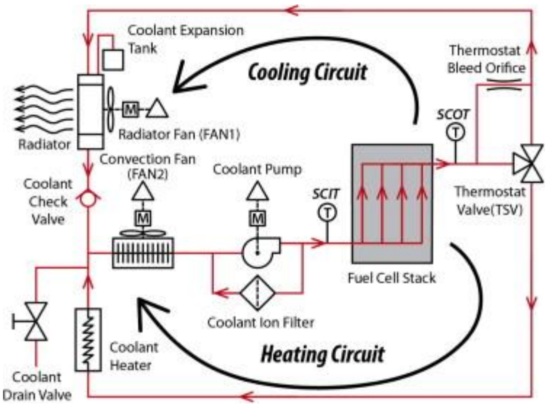

Fig. 4. Schematic of thermal control unit for 5.8 kW PEM fuel cell generator [6].

5. Water Management

The proton conductivity of electrolyte increases with the increase in water content. However, very high water content can lead to flooding, whereas very low water content causes membrane dehydration, which reduces proton conductivity [2]. Dehydration at the anode side commonly occurs at high-current density even if the cathode is sufficiently hydrated [27]. This behaviour is caused by the electro-osmotic drag mechanism overcoming back diffusion, drying out the membrane and reducing proton conductivity [28].

The opposite of dehydration is the flooding phenomenon. The flooding phenomenon occurs when liquid water is present and accumulates in the flow-field channels and/or electrode gas porosities, preventing gas diffusion [11]. Liquid water accumulation in PEM fuel cells may occur because of improper liquid water removal from the cathode side [29], low gas flow rate, and low operating temperature [30].

Nafion membrane, the most common PEM fuel cell material manufactured by DuPont, needs to be fully hydrated to be a good proton conductor [31]. Sufficient water content is essential in polymer electrolyte for good proton conductivity and to prevent membrane dehydration and flooding phenomena by balancing the water production and water transport in PEM fuel cells. A proper water management system is also required in portable PEM fuel cells to maintain possible water content equilibrium in stack so that the system can achieve high performance.

Inlet anode hydrogen gas and/or cathode air streams usually need to be humidified before entering PEM fuel cells [1]. Humidified hydrogen gas is required to hydrate the membrane at high-power densities if water back diffusion from the cathode to the anode is insufficient. Traditional PEM fuel cells need a humidifier unit to control the humidity of the air in stack [8]. However, this traditional PEM fuel cell system is large and costly, and it is incompatible with portable fuel cell applications. Therefore, self-humidified or “internal humidification mode” of PEM fuel cell stack was developed and used to replace separate humidifier units, providing smaller, lighter, and more cost-effective fuel cells. Low-power portable PEM fuel cells utilize the open cathode design for oxidant and air-cooling supply, which indirectly affects the humidity of the fuel cell stack. PEM fuel cell design also affects the humidity of the stack by the size of the open cathode area. Larger open cathode area leads to evaporation of more generated water, which causes a decrease in hydration and proton conductivity of the membrane [32]. In addition, several parameters, such as reactant flow rate, temperature, and current density, must be selected precisely for cell hydration and self-humidifying PEM fuel cell [33].

5.1. Low power portable PEM fuel cell

A low-power, 12.5 W portable PEM fuel cell from Inman et al. [21], used self-humidified membrane as it greatly simplifies the system by excluding the usage of external humidifier. Water was purged through port located at anode side to prevent flooding. A 30-W portable PEM fuel cell developed by Oszcipok et al. [24] did not use self-humidified membrane because the fuel cell was designed for operate under various ambient temperature, such as cold (−20 °C) and hot (40 °C) environments. The stack was integrated with internal membrane humidity exchanger for water management system during the operation at ambient temperature of 40 °C. Based on Fig. 5, the water separator with purging valve was used remove water residues that were blown out by the reaction gas from the flow field and porous structures of the catalyst and gas diffusion layers during shut down operation. The present of freezing residual water in fuel cell stack can fillthe porous structures in the gas diffusion layer and prevent gas distribution, which is a significant problem during cold-start up.

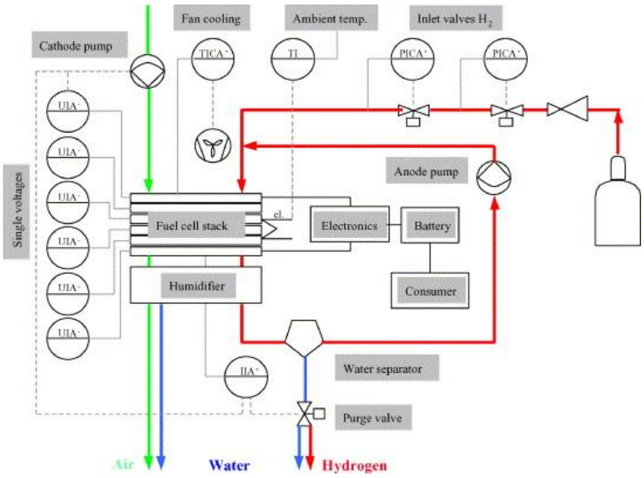

Fig. 5. Schematic of the 30-W outdoor portable PEM fuel cell [24].

5.2. Medium power portable PEM fuel cell

Medium-power portable PEM fuel cell does not use self-humidified membrane because the high air flow rate supplies sufficient oxygen to generate required power to dry out the membrane. Thus, medium-power portable PEM fuel cells need additional units, such as a humidifier to humidify hydrogen and/or air before entering the stack to prevent membrane dehydration.

The water management strategies used by Devrim et al. [25] for their 500 W portable PEM fuel cell achieved good performance by controlling the operating conditions, such as air flow rate, stack temperature, and air inlet humidity. Gas flow rate strongly affects the water content in PEM fuel cell stack and drains away water from plate channels and gas diffusion layers [13]. Based on Devrim et al. [25] study, the best PEM fuel cell performance was obtained by humidifying the air before letting it enter the stack using a membrane gas-gas exchange humidifier. Stack temperature was maintained at 65 °C, and stoichiometry of hydrogen and air was 1.2 and 3, respectively.

Another study of medium-power portable PEM fuel cell from Sohn et al. [7] used humidified reactant air from heated water reservoir, which was controlled at set temperatures of 30 °C, 40 °C, and 50 °C for system water management. The study also tested three relative humidity conditions at 37%, 48%, and 66%, which were controlled by stack temperature and inlet reactant air, to find relative humidity that provides uniform cell voltage [7]. The researchers found that 66% relative humidity improved stack power compared with 37% and 48% relative humidity.

5.3. High power portable PEM fuel cell

The water management system in high-power portable PEM fuel cell is more complex than that in low- and medium-power portable PEM fuel cell. Given that more heat is generated in high-power portable PEM fuel cell, stack temperature and air flow rate elevate, requiring additional units such as air filter, air blower, and larger pump.

The water management system in the PEM fuel cell generator by Hwang was involved in air and hydrogen delivery systems [6]. Ambient air was filtered first using activated carbon media to remove gas contaminants before it was pumped by cathode air blower to membrane humidifier, as shown by the green arrow line in Fig. 6. Moreover, a condensate drain port removed liquid water from the bottom of the humidifier. An exhaust gas recirculation blower circulated water vapor from anode exit to the anode inlet. This action was important to avoid the development of liquid water in stack, and for fresh hydrogen to be distributed equally to the stack cells.

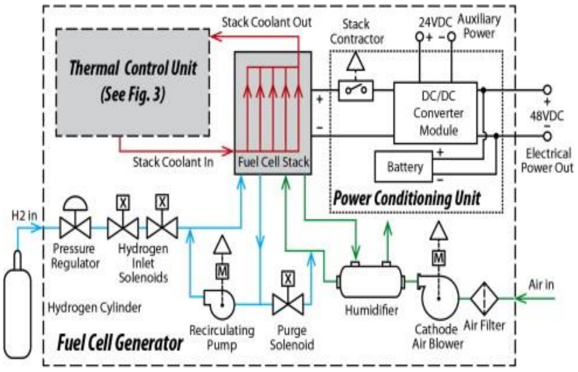

Fig. 6. Schematic of the 5.8 kW PEM fuel cell generator [6].

6. Pre-commercial Portable PEM

Portable PEM fuel cells are not commercialized yet, but some companies have developed pre-commercial portable PEM fuel cell. An example of a 500 W medium-power portable PEM fuel cell from Palcan Energy Corporation Palcan-P750 uses air-cooled coolant medium in their cooling system. The dimensions of Palcan-P750 are 425 mm × 365 mm × 420 mm, and it weighs approximately 26 kg, including the hydrogen storage of metal hydride [34].

Figure 7(a) shows an example of a 5 kW pre-commercial high-power portable PEM fuel cell. This fuel cell uses air-cooled coolant medium in its cooling system. The dimensions of TB-5000 are 425 mm × 365 mm × 420 mm, and they are approximately 55 kg in weight. The portable PEM fuel cell uses water-cooled cooling system in FCGen 1300 Ballard PEM fuel cell stack as shown in Fig. 7(b).

Table 1.Summary of thermal and water management system of low-, medium-, and high-power portable PEM fuel cells.

Type of Portable PEM fuel cell	Refs	Thermal Management System	Water Management System	Performance
Low Power	[21]	Open cathode design uses fan to supply air as reactant and cooling.	Self-humidified membrane and anode purging system.	Unstable maximum power of 17W due to undersized fan.
	[23]	Air-breathing stack for supplying oxidant (ambient air) and fan for the cooling system.	Not available	Continuous output power at 12 W to power a portable DVD player for 3 h.
	[24]	Cooling system is separate from oxidant stream and air-cooled from fan flow at cooling ribs and end-plates.	Internal membrane humidifier exchanger integrated with the stack and water separator to remove water residues during shut down.	Stable power of 30W generated for outdoor application at −20°C and40 °C about 3 days and no freezing problem occurred at −20 °C.
Medium Power	[25]	Cooling system is separate from oxidant stream and air-cooled from fan flows through the cooling channel.	Air was humidified by membrane gas-gas exchange humidifier before entering the stack.	Optimum performance at a power of 647 W and 50 A at 65 °C.
	[7]	Cooling system is separate from oxidant stream and air-cooled from several axial cooling fans flows through the cooling channel.	Air was humidified by heated water reservoir before entering the stack.	The axial cooling fans successfully consumed less than 2% of the total power output with optimized operation.
High Power	[6]	Cooling circuit was cooled down the stack using pump coolant to flow to the parallel cooling channels in the stack and remove heat dissipated by the stack. Heating circuit assisted in warming up the stack for cold start-up.	Humidified air is used as reactant. Water vapor was circulating from the anode exit to the anode inlet by exhaust gas recirculation blower.	PEM fuel cell capable to delivered more power than power demand of the external load (3.5kW) with stack current and voltage range of 105-120 A and 34-36 V respectively.

(a) Tropica's TB-5000 [35] **(b) FCGen 1300 Ballard PEM fuel cell [36]**

Fig. 7. Pre-commercial high-power portable PEM fuel cell.

7. Conclusions

The thermal and water management system of portable PEM fuel cells depend on power and output performance, as shown in Table 1. At room temperature, the low-power portable PEM fuel cell stack was designed as an open cathode for cooling and self-humidifying membrane, which showed a simple and compact design as a portable application. By contrast, portable PEM fuel cell requires additional heating during cold-start up in different environment. In medium-power portable PEM fuel cell, air-cooled medium, which flows through the cooling channel, is used for cooling; the air inlet must also be humidified before entering the stack to prevent membrane dehydration in the open cathode stack. High-power portable PEM fuel cell uses liquid-type coolant and humidified, and filtered for thermal and water management. We can conclude that a higher generated power leads to more complex thermal and water management systems, which require additional units that will result in larger size and higher cost.

Acknowledgement

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