Chapter 11
Design and Development of a Water-Cooled Proton Exchange Membrane Fuel Cell Stack for Domestic Applications

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11.1 Introduction

Energy production, storage and conversion are the buzz words today in the global energy scenario and will be the focus in the coming years also. The ever-decreasing fossil fuel reserves is the main triggering factor in the development of renewable energy technologies. Energy technologies, that are replenishable on use are generally termed as renewable energy source. These energy sources like wind, solar are highly reliable if they are distributed over a large geographical location. Moreover, these technologies are highly helpful in stabilizing energy prices at the global level. Many of the renewable technologies with few or no moving parts makes operation cost at lower levels. Clamor for reducing the carbon footprint globally is also a motivating factor for the countries to switch to new and renewable energy sources and technologies.

In the recent past, due to advances in the hydrogen storage and handling, fuel cell technology is very popular and widely used. It can be used in both stationary and portable power applications as well as transportation sector. Fuel cells work similar to batteries without consuming the electrode and these cells are capable of producing electricity as long as the fuel (hydrogen or a source of hydrogen) and oxidizer (air or oxygen) is available. Efficient, quiet and no harmful emissions (only heat and water), in comparison with internal combustion engines are the reasons for the wide acceptance of fuel cells globally. Often times, a single fuel is incapable of producing the required power output and this necessitates the use of fuel cell stacks.

Many researchers worked extensively on fuel cell stacks and in this chapter, focus is given on Proton Exchange Membrane Fuel Cell (PEMFC) stacks. Luo et al. (2019) experimentally studied on PEM fuel cell stack employed air cooling. They found that distribution of temperature in the cells is greatly affected by the cooling air flow

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and uneven water distribution. Syampurwadi et al. (2017) studied the influence of number of cells and stack on the fuel cell performance. In this study, experiment was conducted in two steps. In the first step, the gas flow rate is varied and the number of cells was kept constant at one. Subsequently, number of cells was varied. When the number of cells is on increase, current density also increased, thereby causing an increase in fuel cell temperature. Due to the increase in temperature, the performance of the cell was increased but the risk of failure was also on increase. Chen et al. (2016) developed a 2 kW, 4 cell high power air cooled PEMFC stack. Youssef et al. (2018) developed and analyzed performance of PEMFC stack based on different bipolar plate designs. The maximum power output is 70 W from 11 cell stack. Karthikeyan et al. (2014) conducted experiments on PEMFC based on various flow channel design for an active area of 25 cm^2 and 70 cm^2, for single and two cell stacks. The flow channel with Landing:Channel (L:C) ratio of 1:1 gives maximum output for all cases compared to all other flow channels. Wan et al. (2014) measured the temperature on each cell of a 5 k W PEMFC stack by using situ temperature measurement technique using 36 T-type thermocouples. Due to temperature difference across each cell of the stack, it is found that the overall performance was decreased. Neto et al. (2013) developed and described the thermal and experimental characterization of 1 k W PEMFC stack which contains 24 cells.

Zhang et al. (2010) developed a 100 W PEM fuel cell and tested at elevated temperature under various humidity. It was found that adequate anode humidification is indispensable for elevated temperature of PEMFC. Wen et al. (2009) studied and compared the effects of clamping on the performance of a single cell and a ten-cell PEMFC stack. From the experiment, they found that power density is proportional to the bolt number, when the clamping torque is same. The mix of 6-bolt with 16 Nm clamping torque gave maximum power output. Kim and Hong (2008) discussed the effect of humidity and temperature on 10 stack PEM fuel cell. Compared to change in temperature, change in humidity is seriously affected by the performance of fuel cell. Chen and Zhou (2008) explained the steady and dynamic behavior of commercial 10 stack PEM fuel cell. The pressure drop signal is used to predict the power. Yim et al. (2008) operated 40 W PEM fuel cell under low humidifying condition. Husar et al (2007) explained failure of 7 stack PEM fuel cell due to gasket degradation. Leakage of reactants causes the degradation and other issues in the gaskets and as a result a dip in performance of fuel cells is found. Yan el al. (2007) studied on unsteady characteristics of PEM FC during dynamic loading. In dynamic loading, air stoichiometry, humidity, loading rates are significantly influencing the temperature inside the fuel cell.

Santarelli et al. (2007) studied the variations in the electrical performance of a PEMFC stack under the influence of different cathode flow rates. Water flooding is the major issue in PEM fuel cell when air stoichiometry value decreases. The current density increases with increase in air stoichiometry value due to the higher rate of electrochemical reaction. Higher rate of electrochemical reaction will increase the cell temperature and this in turn will reduce the flooding effect. Park and Li (2006) analyzed the performance of PEMFC stack under different flow rates and operating temperatures. From their results it is very clear that the effect of temperature is more

significant than the flow rate. Rodatz et al. (2004) developed 6 kW, 100 cell PEM stack and studied the operational aspects of stack under practical conditions. The major issues in large fuel cell are uneven flow distributions of the reactant gases and non-uniform temperature distribution due to the leakage of membrane. The membrane leaks due to hot spots, as well as large pressure difference. Scholta et al (2004) developed and tested 10 kW PEMFC stack. In order to achieve cost reduction, a stack concept using graphite composite bipolar plates was developed. Johnson et al (2001) assembled a 3-kW cell and tested under different loading conditions as well as carried out a thermodynamic analysis. Murphy et al. (1998) analyzed a light weight PEM fuel cell stack. For manufacturing of fuel cell parts, they used a metal conductive element together with nonconductive elements fabricated from thermoplastics through an inexpensive mass production technique. The maximum power output from the cell was 520 W.

Siddiqui and Dincer (2019) developed a direct ammonia fuel cell stack. Authors improved energy and exergy efficiencies of fuel cells at higher humidifier temperatures. Zhang and Kandlikar (2012) presented a review on various cooling techniques in PEMFC stacks. They reviewed the pros and cons of heat spreaders, liquid and air cooling. Details of phase change cooling were also presented. In comparison with air cooling, water cooling is very much effective to counter the variation in temperature across different cells in the stack.

From the proceeding review, it is clear that many investigators were studied in detail, about fuel cell stacks employing air and water cooling. As water cooling is very efficient in comparison with the air-cooling strategies, the present chapter, details of the design, fabrication and testing of a water-cooled PEMFC stack employing 10 cells each having an active area of 50 cm^2. Usually, detailed description of the design and fabrication is missing in most of the literature, but in this chapter the relevant details of the components used, including the design and fabrication of the water plate, details of mono polar and bipolar plates, gaskets, current collector, flow channels, arrangement of major components used and so on are described for the benefit of researchers in this area.

11.2 Design and Fabrication Details of PEMFC Stack

The details regarding the design of various components in the fuel cell stack and the fabrication details are given in this section. Table 11.1 gives the details of the major components used in the development of the PEMFC stack in the present study. Schematic arrangement of the major components used in the PEMFC stack is shown in Fig. 11.1.

Details of the design and fabrication of some of the major components are explained in the following section.

	Sl. No	Name of the component	Represented in Fig. 11.1	Quantity (nos.)
Table 11.1 Details of the major components used in the PEMFC stack	1	Membrane electrode assembly	MEA	10
	2	End plate	Endplate	2
	3	Current collector	CC	2
	4	Cathode with water plate	CA-WP	5
	5	Bipolar plates	CA-AN	5
	6	Water plate with anode	WP-AN	1
	7	Monopolar (anode)	AN	4
	8	Support graphite plate	Support graphite plate	2
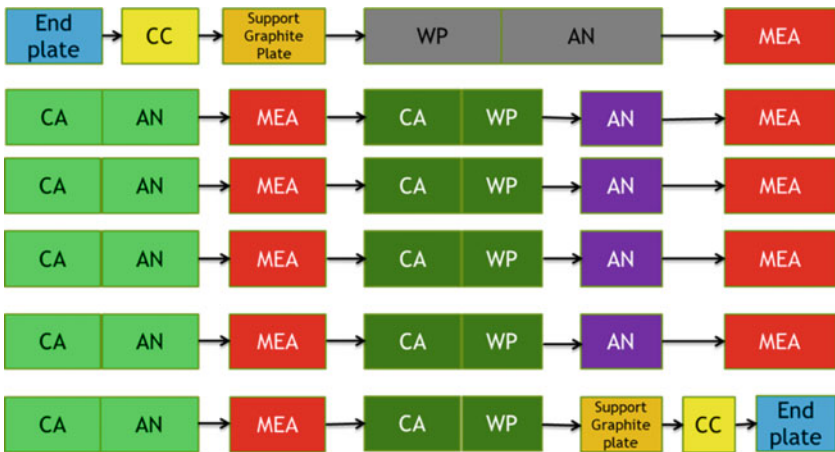
Fig. 11.1 Schematic arrangement of major components used in the development of the PEMFC stack

11.2.1 Design and Fabrication of Cathode Flow Channel

Figure 11.2 shows a photograph of the cathode 3 pass serpentine flow channel. The channel to landing ratio for this flow channel is 1:1. The channels are made on the graphite plate by Computer Numerical Control (CNC) machining. Generally, the graphite material is used for the manufacturing of flow channels due to the high
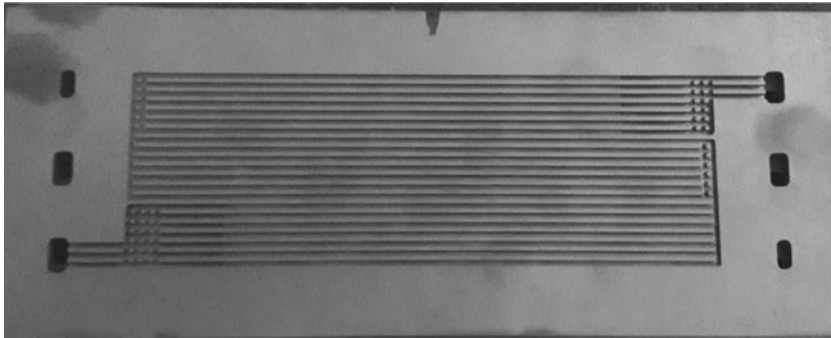
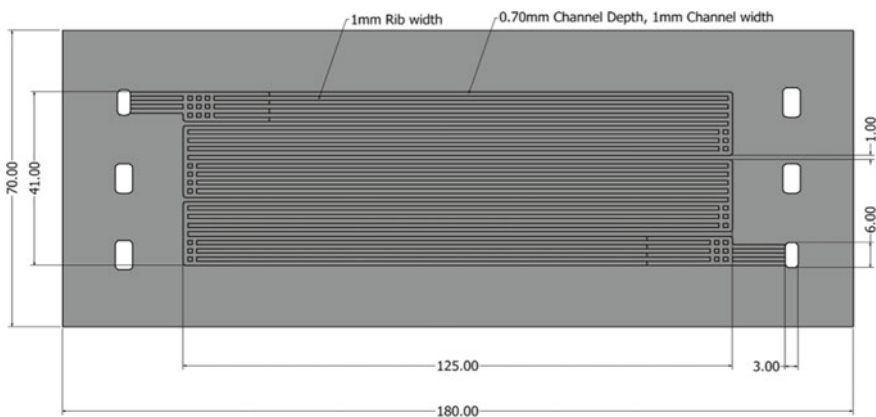**Fig. 11.2** A photograph of cathode 3 pass serpentine flow channel

Fig. 11.3 Design of anode 5 pass flow channel

machinability and less corrosiveness. On the other side of the cathode plate contain water channel.

Figure 11.3 shows details of anode 5 pass flow channel. The plate is having an overall dimensions of 180 mm × 70 mm. The flow field is with dimensions of 125 mm x 41 mm. The channel to landing ratio is kept at 1:1. The channel depth is 0.70 mm. These are also made of graphite plate by CNC machining process.

11.2.2 Design and Fabrication of Water Plate

Figure 11.4a shows the detailed design of the water plated used in fuel cell. Water plates will be useful for the effective flow of cooling water. Due to the reactions occurring in the fuel cell, temperature build up is present and it can deteriorate the performance of the fuel cell. Also, for the working of the fuel cell initially, hot water
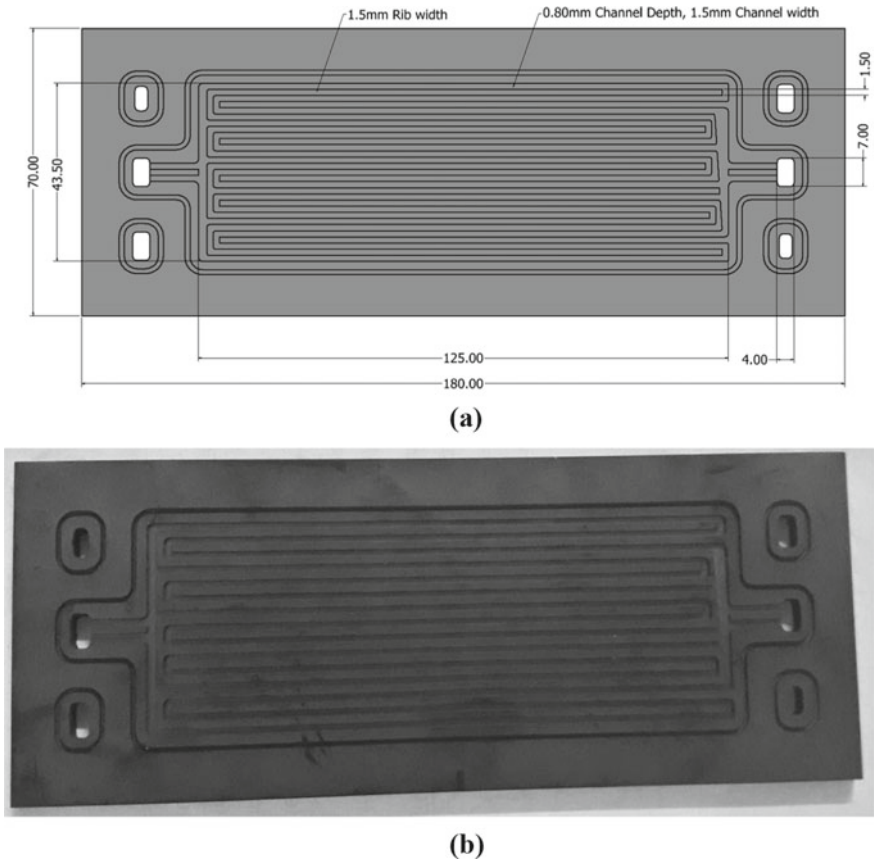
Fig. 11.4 **a** Design of water plate used in the present study. **b** A photograph of water plate used in the present study

is supplied through the water channel. The channel to landing (rib width) ratio used for this flow channel is 1:1. The channel width is 1.5 mm and the rib width is 1.5 mm. The channel depth is 0.80 mm. A photograph of the water plate used in the present study is shown in Fig. 11.4b.

11.2.3 Nafion Membrane Preparation

Commercially available Nafion 115 membrane is treated before the use in PEMFC. The pre-treatment is done using a standard procedure:

(1) The membrane is boiled in 5 wt% H_2O_2 solution at 80 °C for 1 h
(2) Rinsed with de-ionized (DI) water at 80 °C for 1 h

(3) Boiling membrane in 0.5 M H_2SO_4 at 80 °C for 1 h

(4) Rinsing with DI water at 80 °C for 1 h.

11.2.4 Catalyst Layer Fabrication

Catalyst fabrication is done using colloidal procedure based on the modification of the Photoetch methods. The procedure of modified Photoetch method is as described below:

(1) Sulfite complexes of Pt are decomposed by hydrogen peroxide at 80–90 °C to form aqueous colloidal solution of Pt.

(2) The colloidal Pt particles are absorbed on carbon black to form the catalyst.

(3) Any amorphous oxide formed is reduced in Hydrogen steam.

11.2.5 Membrane Electrode Assembly (MEA)

Commercially available MEA are five layered which consists of: Anode gas diffusion layer, anode catalyst layer, Nafion 115, cathode catalyst layer and cathode gas diffusion layer. For manufacturing MEA the gas diffusion layer (GDL), catalyst layer and the polymer electrolyte membrane is done at 135 °C and 4 MPa under a hydraulic hot press for 2 min.

11.2.6 Gaskets

Gaskets are the important part in fuel cell. It acts as an insulator and leakage protector. In the development of the present fuel cell stack, two different gaskets with different thickness, 0.2 mm and 0.1 mm are made with the same material. Normally gaskets are used in 3 places, between the anode flow channel and MEA, cathode flow channel and MEA and between current collector and flow channels. Here, 0.2 mm thickness gasket is used between the anode flow channel and MEA as shown in Fig. 11.5 and between the current collector and flow channel as shown in Fig. 11.6. The gasket has thickness of 0.1 mm is used in between the cathode flow channel and MEA as shown in Fig. 11.7.

11.2.7 Current Collector

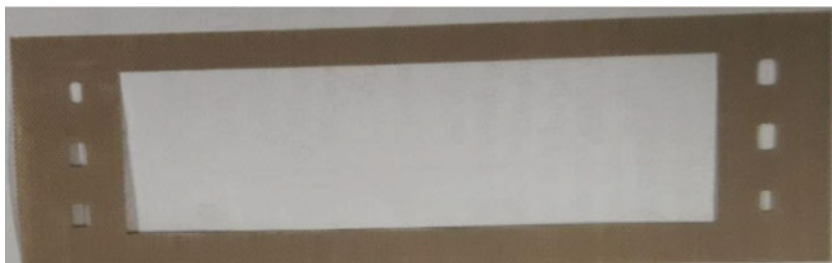Current collector plate is used to collect the electrons that are produced in the fuel cell.

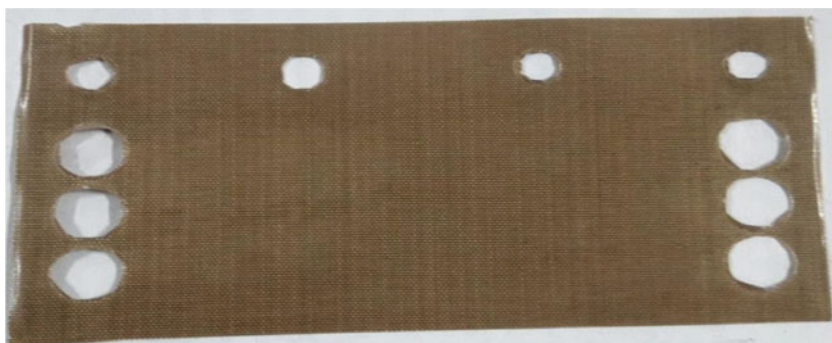**Fig. 11.5** Gasket used between anode flow channel and MEA

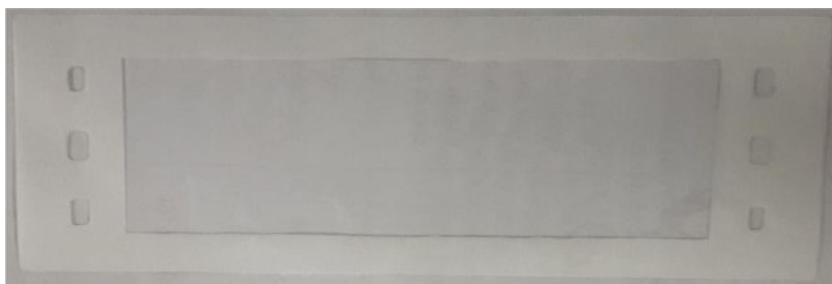**Fig. 11.6** Gasket used between current collector and flow channel

Fig. 11.7 Gasket with thickness 0.1 mm

Normally, it is made up of copper material. The electrons move to the external circuit from current collector. Here one side of the current collector is coated with carbon for increasing the number of electrons. Figure 11.8 is a photograph of the current collector without carbon coating and Fig. 11.9 is the current collector with carbon coating.

Fig. 11.8 A photograph of the current collector without carbon coating

Fig. 11.9 A photograph of the current collector with carbon coating

11.2.8   Fuel Cell Assembly: Ten Stack Fuel Cell

One cell consists of a membrane electrolyte assembly sandwiched between two graphite plates machined with 1:1 serpentine flow field. Here, similar ten cells are used to make the stack. The assembly was clamped by two aluminium fixtures using M5 screws, with a torque of 4 Nm by using torque wrench. A photograph of the fuel cell stack used in the present study is shown in Fig. 11.10.

11.2.9   Monopolar Plates

In the monopole cell pack, the monopolar plate has only one flow channel on each side to supply of fuel or oxidant.

A computer aided design (CAD) model of the monopolar stack configuration is shown in Fig. 11.11. Monopole design is mainly applied to low power and high voltage devices.

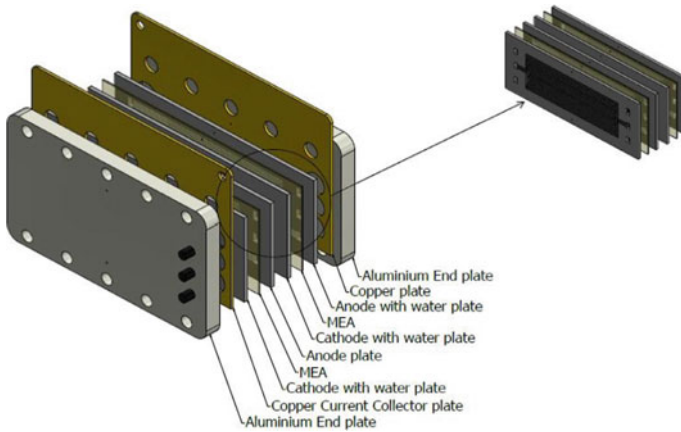**Fig. 11.10** A photograph of the PEMFC stack used in the present study

Aluminium End plate
Copper plate
Anode with water plate
MEA
Cathode with water plate
Anode plate
MEA
Cathode with water plate
Copper Current Collector plate
Aluminium End plate

Fig. 11.11 CAD model of the monopolar plates stack configuration

11.2.10 Bipolar Plates

A CAD model of the stack configuration using bipolar plates is shown Fig. 11.12. In order to supply the fuel and the oxidant, flow channels are made on both sides of the graphite plate, so the plate becomes a bipolar plate. Though many shapes are used to make the flow channel, a serpentine design is used in the present case. For
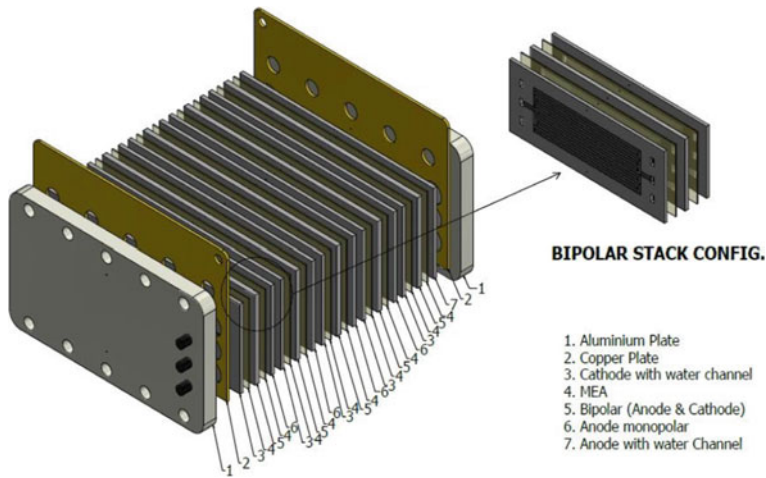
BIPOLAR STACK CONFIG.

1. Aluminium Plate
2. Copper Plate
3. Cathode with water channel
4. MEA
5. Bipolar (Anode & Cathode)
6. Anode monopolar
7. Anode with water Channel

Fig. 11.12 CAD model of the bipolar plates stack configuration

the present experimental investigations, both monopolar and bipolar plates are used to develop the 10 stack PEMFC.

11.2.11   Test Rig

The test station consists of electronic load box and control system. Electronic load box is used to measure voltage produced corresponding to the given input. Electronic load box is connected with the monitoring system for the performance analysis of the fuel cell. Anode side of the cell is connected to the negative side of the load box and cathode side with positive side. In inside the loading box change in resistance gives the corresponding loads. In the present work, BK PRECISION loading box, model no: 8518, made in India is used for the loading purpose. Figure 11.13 shows the loading box.

The controlling system consists of temperature control, humidity control, reactant flow rate control, cooling water flow control and temperature controls. Cooling water is supplied to the cell by using peristaltic pump as shown in Fig. 11.14. The peristaltic pump is by M/s Ravel Hitechs Pvt. Ltd with model no: RH120S, made in India.

For the best performance and avoiding the damage to the membrane electrode assembly, the humidity control is essential. In the present study, 80% relative humidity is given for both hydrogen and oxygen. For hydrogen and oxygen, two separate humidity controller systems are used. A photograph of the humidity controller arrangement is shown in Fig. 11.15.

Fig. 11.13 Electronic load box

Fig. 11.14 Peristaltic pump used in the present study

11.3 Experimental Investigations

Results of the experimental investigations carried out on single cell, two cell stack and the 10-cell stack are detailed in the following section. Experiments are carried out to assess the performance of the PEMFC under various conditions by changing different parameters such as operating temperatures and oxygen flow rates. All the experiments are done at atmospheric pressure. These experiments helped to study the behavior of the fuel cell and understand how the performance of the fuel cell varies with changes in different operating conditions. It is observed that the results obtained through the experiments are in good agreement with the behavior of fuel cells in the literature.
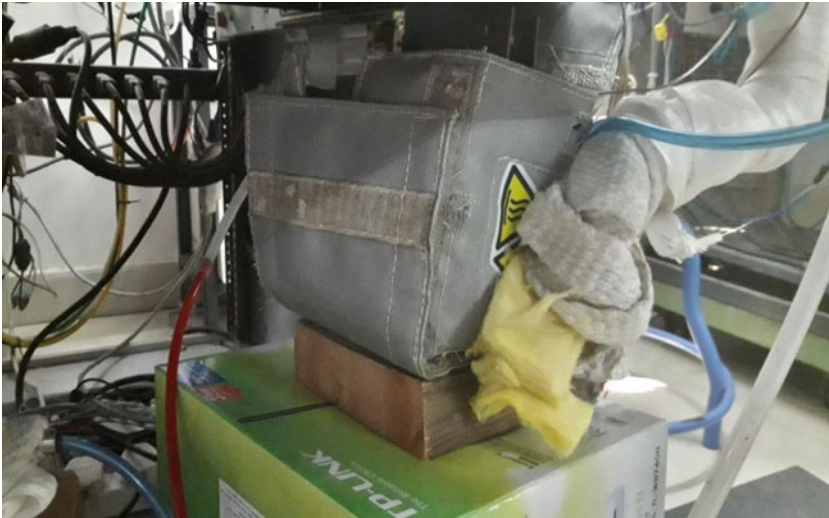
Fig. 11.15 Humidity controller

11.3.1 Single Cell Fuel Cell

Experiments are conducted on single cell. Power density of single cell at various temperatures are measured. A photograph of the single cell on test station is shown in the Fig. 11.16. The maximum open circuit voltage produced on the cell is 0.9 V. The maximum power output from the cell is 30.5 W (50 A, 0.61 V) at a hydrogen flow rate at 720 ccm and Oxygen flow rate at 500 ccm.

11.3.1.1 Effect of Operating Temperature

The performance of PEMFC at various temperatures 40 °C, 50 °C and 60 °C is shown in Fig. 11.17. PEMFC showed an increasing performance (increase in power

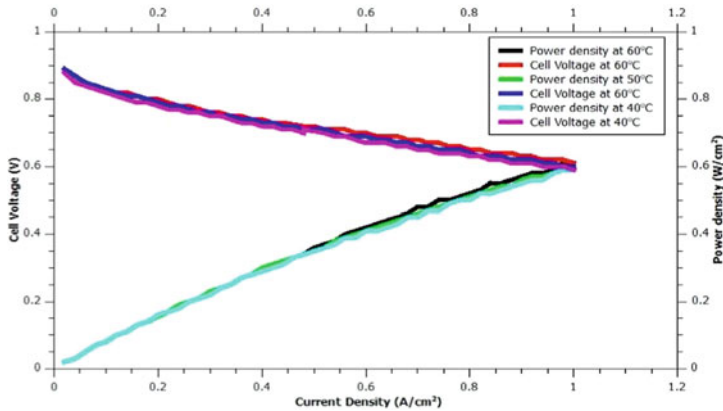**Fig. 11.16** Single cell fuel cell on test station

Fig. 11.17 Effect of operating temperature on the performance of a single fuel cell

density) as the operating temperature is increased. This is because of the fact that the increase in the temperature contributed to the improvement of chemical kinetics of reactions. Hence the performance was increased due to the increase in electron productivity. When the temperature is increased beyond 60 °C, it is found that the membrane is getting damaged, so the temperature is controlled such that it should not rise more than 60 °C.

11.3.2 Two Stack PEM Fuel Cell

Power density of the fuel cell with two stacks is also reported. The open cell voltage is 1.89. Two stack PEMFC on test station is shown in the Fig. 11.18. The maximum power output from the cell is 66.5 W at a temperature of 60 °C (50 A, 1.33 V) when the hydrogen flow rate at 1700 ccm and oxygen flow rate at 1400 ccm. A comparison of the power density at 40, 50 and 60 °C is shown in Fig. 11.19. Power density is found to be better at 60 °C in comparison with the other operating temperatures.

11.3.3 Ten Stack Proton Exchange Membrane Fuel Cell

Power density of ten stacks fuel cell at various temperature and flow rate is measured. Ten stack PEMFC on test station is shown in the Fig. 11.20. The open circuit voltage is 9.6 V. The maximum power output from the cell is 303 W (50 A, 6.06 V) when the hydrogen flow rate at 5000 ccm and Oxygen flow rate at 2700 ccm.

The performance of PEMFC at various temperatures 40 °C, 50 °C and 60 °C for the 10 stack fuel cell is given in Table 11.2. The cell showed an increasing performance
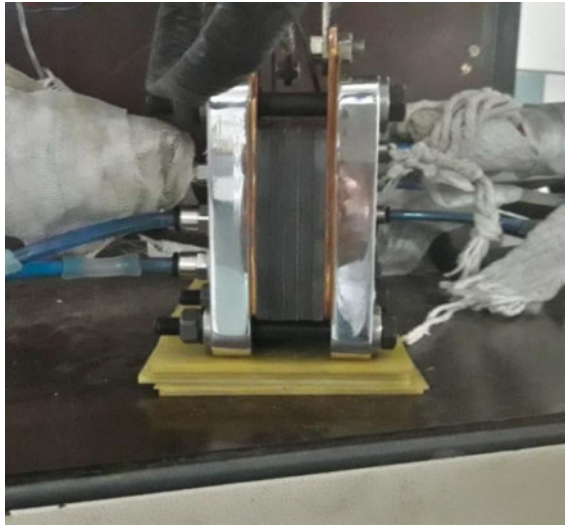
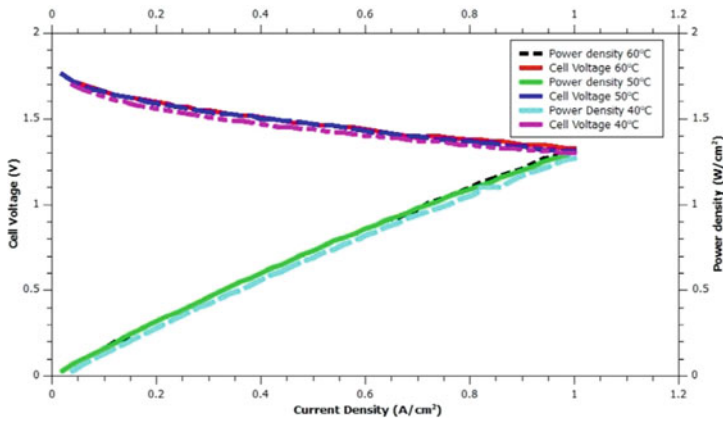**Fig. 11.18** Two stack PEM fuel cell

Fig. 11.19 Performance of two stack PEMFC

trend as the operating temperature is increased. The ten stack PEMFC showed a maximum power of 303 W at an operating temperature of 60 °C.

11.3.3.1 Influence of Flow Rate

Figure 11.21 shows the variation of cell voltage and power density with different flow rate of oxygen and hydrogen (2500/1400 cc/m, 4200/2400 cc/m and 5000/2700 cc/m) at 60 °C. The flow rate is increased as the current density is increased.

Fig. 11.20 Ten stack PEMFC on test station

Table 11.2 Performance of ten stack PEMFC at various temperatures

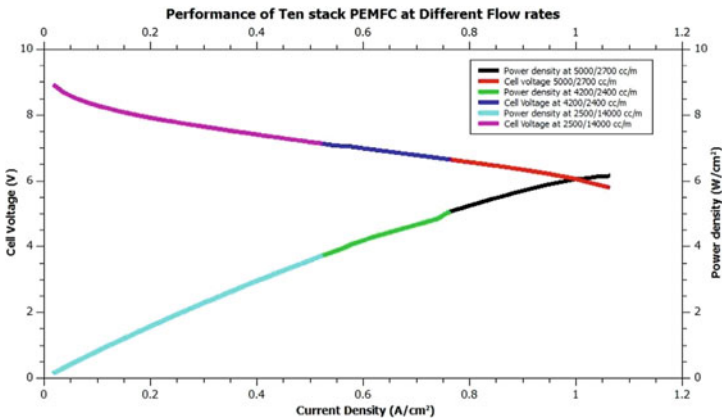| Sl. No	Temperature (°C)	Current density (A/cm^2)	Voltage (V)	Power (W)
1	40	0.96	5.88	282.5
2	50	1	5.94	297
3	60	1	6.06	303

Fig. 11.21 Performance of PEMFC at various flow rates

11.4 Conclusions

A ten-stack water-cooled PEMFC stack is designed, fabricated and tested. Each cell is having an active area of 50 cm^2. Salient features of this work can be summarized as follows:

- The stack performed better at 60 °C, in order to deliver maximum power output. When the temperature is increased from 40 to 60 °C, the output power increased by 20.5 W.
- The maximum power output from the single cell is 30.5 W (50 A and 0.61 V) at a hydrogen flow rate at 720 ccm and Oxygen flow rate at 500 ccm.
- The maximum power output from the two-cell stack is 66.5 W at a temperature of 60 °C (50A and 1.33 V) when the hydrogen flow rate at 1700 ccm and Oxygen flow rate at 1400 ccm.
- The maximum power output from the 10 stack PEM fuel cell is 303 W (50 A and 6.06 V) when the hydrogen flow rate at 5000 ccm and Oxygen flow rate at 2700 ccm.

References

Chen C-Y, Huang K-P, Yan W-M, Lai M-P (2016) Development and performance diagnosis of a high power air-cooled PEMFC stack. Int J Hydrogen Energy 11784–11793

Chen J, Zhou B (2008) Diagnosis of PEM fuel cell stack dynamic behaviors. J Power Sources 177:83–95

Husar A, Serra M, Kunusch C (2007) Description of gasket failure in a 7 cell PEMFC stack. J Power Sources 169:85–91

Johnson R, Morgan C, Witmer D, Johnson T (2001) Performance of a proton exchange membrane fuel cell stack. Int J Hydrogen Energy 26:879–887

Karthikeyan P, Velmurugan P, George AJ, Kumar RR, Vasanth RJ (2014) Experimental investigation on scaling and stacking up of proton exchange membrane fuel cells. Int J Hydrogen Energy 39:11186–11195

Kim S, Hong I (2008) Effect of humidity and temperature on a proton exchange membrane fuel cell (PEMFC) stack. J Ind Eng Chem 14:357–364

Luo L, Jian Q, Huang B, Huang Z, Zhao J, Cao S (2019) Experimental study on temperature characteristics of an air-cooled proton exchange membrane fuel cell stack. Renew Energy 143:1067–1078

Murphy OJ, Cisar A, Clarke E (1998) Low-cost light weight high power density PEM fuel cell stack. Electrochim Acta 43(24):3829–3840

Neto RC, Teixeria JC, Azevedo JLT (2013) Thermal and electrical experimental characterization of a 1 KW PEM fuel cell stack. Int J Hydrogen Energy 38:5348–5356

Park J, Li X (2006) Effect of flow and temperature distribution on the performance of a PEM fuel cell stack. J Power Sources 162:444–459

Rodatz P, Buchi F, Onder C, Guzzella L (2004) Operational aspects of a large PEMFC stack under practical conditions. J Power Sources 128:208–217

Santarelli MG, Torchio MF, Cali M, Giaretto V (2007) Experimental analysis of cathode flow stochiometry on the electrical performance of a PEMFC stack. Int J Hydrogen Energy 32:710–716

Scholta J, Berg N, Wilde P, Jorissen L, Garche J (2004) Development and performance of a 10 kW PEMFC stack. J Power Sources 127:206–212

Siddiqui O, Dincer I (2019) Development and performance evaluation of a direct ammonia fuel cell stack. Chem Eng Sci 200:285–293

Syampurwadi A, Onggo H, Indriyati, Yudianti R (2017) Performance of PEM fuel cell stack as affected by number of cell and gas flow-rate. In: IOP conference series: earth and environmental science 60. ISSN 1755–1315 (Online)

Wan Z, Shen J, Zhang H, Tu Z, Liu W (2014) In situ temperature measurement in a 5 kW-class proton exchange membrane fuel cell stack with pure oxygen as the oxidant. Int J Heat Mass Transf 75:231–234

Wen C-Y, Lin Y-S, Lu C-H (2009) Experimental study of clamping effects on the performances of a single proton exchange membrane fuel cell and a 10-Cell stack. J Power Sources 192:475–485

Yan X, Hou M, Sun L, Cheng H, Hong Y, Liang D, Shen Q, Ming P, Yi B (2007) The study on transient characteristic of proton exchange membrane fuel cell stack during dynamic loading. J Power Sources 163:966–970

Yim S-D, Sohn Y-J, Yoon Y-G, Um S, Kim C-S, Lee W-Y (2008) Operating characteristics of 40 W-class PEMFC stack using reformed gas under low humidifying conditions. J Power Sources 178:711–715

Youssef MES, Amin RS, EI-Khatib KM (2018) Development and performance analysis of PEMFC stack based on bipolar plates fabricated employing different designs. Arab J Chem 609–614

Zhang G, Kandlikar SG (2012) A critical review of cooling techniques in proton exchange membrane fuel cell stacks. Int J Hydrogen Energy 37:2412–2429

Zhang H, Yang D, Tao K, Zheng X, Ma J (2010) Investigation of PEMFC stack operating at elevated temperature. World Electr Veh J 4:481–486