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Design and Development of a Closed Two Loop Thermal Management Configuration for PEM Fuel Cell

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Abstract. Thermal Management is vital for the sustained performance of a Polymer Electrolyte Membrane (PEM) fuel cell at its optimal operating conditions. One of the impediments in developing such thermal management system for a PEM fuel cell in vehicular applications is weight, volume and parasitic power constraints of the thermal management system. An issue with closed loop system is the heat addition from fuel cell into the cooling loop. This heat can be subdued by the use of heat transfer modules like plate heat exchanger (PHE) and radiators in the loop. In the present study a thermal management system is designed which can remove heat from the fuel cell to ambient effectively and allow the stack to operate at a peak power of 1.5kW$_{elec}$ conditions for more than 60 minutes of duration. Coolant flow rate optimization and thermal management configuration design are conducted to increase the heat transfer from fuel cell. The average thermal power removed by the coolant from cell for all the thermal management configurations is calculated. A relation between the average thermal power, flow rate and thermal management circuit has been established.

Keywords: PEM fuel cell, thermal management, cooling loop, coolant, Plate Heat Exchanger, Radiator

1. Introduction

Thermal management of a PEMFC system has been a pivotal factor to ensure high performance and efficiency of the cell. Apart from electricity & water, heat is another byproduct produced by the cell which is emanated during the electrochemical reaction between hydrogen and oxygen [1]. Several issues are associated with the thermal management of PEMFC for which temperature play a major role as discussed by Kandlikar et al. [2].The temperature rise and its distribution are completely dependent on the amount of heat retained by the stack. Several effective techniques have been investigated for the heat removal such as free air breathing and air cooling techniques [3-5] which have some limitations with respect to the capacity, size etc.,. However a liquid coolant system is preferred over air because of coolants larger specific heat capacity .The various heat generating sources in a fuel Cell and the mode of heat transfer from cell to several sources like coolants, reacting gases and ambient air with governing equations are discussed briefly by Shan et al. [6]. Zong et al. [7] discussed the heat transfer from the stack to the coolant flowing through the cell and the dependence of coolant temperature on the overall stack temperature. The coolant absorbed heat from the stack by convection and its temperature is assumed to be constant across the cell. However the flow rate of the coolant through the cell is also an important parameter in maintaining the temperature of the stack which is discussed in present study. The coolants used in removing heat from a fuel cell stack are required to be cooled to ensure that the coolant enters the stack at a desired temperature. Several designs where various cooling apparatus for cooling the coolant flowing thorough a fuel cell have been discussed [8-10]. Effective use of various heat transfer modules like radiators and heat exchangers is required to ensure that the fuel cell is maintained at its optimal conditions for a long duration of time. Dohoy Jung et al. [11] described the need for maintaining of the temperature of the fuel cell at its optimal operating conditions and refers to the use of

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radiator fan assembly to cool the coolant. The amount of heat generated inside a fuel cell depends on the heat removed by the coolant flowing through it. Pandiyan et al. [12] discussed the heat transfer through the fuel cell, quantification of the heat removed from the cell and the sources of heat generation.

The present study addresses the two major variants viz., flow rate and temperature of the coolant in developing a two loop cooling system for a 1.5 kW fuel cell stack. Further an effective thermal circuit which optimizes the stack performance for longer durations with less volume of coolant use is identified.

2. Experimental

A closed single loop and two loop thermal management systems were developed for cooling of the fuel cell stack of 1.5 kW_{elec} peak power. In the closed loop configuration, coolant water was flowing through the fuel cell stack from a reserve tank which holds a fixed volume of 10 liters of coolant water. Thermocouples were inserted at the primary coolant inlet, outlet of coolant from the stack and one inserted on the stack for measuring temperatures. In the two loop thermal management systems there exists a secondary cooling circuit consisting of a reserve tank to hold another fixed volume of 10 liters of coolant water, and a plate heat exchanger (PHE) to exchange heat between the primary and secondary loops. A radiator/ fan assembly was used in all the three different thermal management configurations R, R_p and R_s to remove the excess heat in the cooling circuit by convection into the ambient. Temperature of the primary coolant inlet and outlet were measured and the average thermal power removed by coolant from the fuel cell stack was evaluated. The fuel cell stack temperature was monitored for the sustained performance at the optimal operating conditions and peak power.

Notations:

R: Thermal Management system with single loop and radiator/fan assembly

Rp: Thermal Management system with two loop, plate heat exchanger and radiator/fan assembly in primary loop

Rs: Thermal Management system with two loop, plate heat exchanger and radiator/fan assembly in secondary loop (see Fig 1 for R_s configuration schematic example)

3. Results and Discussion

Firstly the fuel cell performance is evaluated from its operating temperature. In the present study it is desired that the thermal management system removes surplus heat out of the fuel cell, at its peak power conditions and maintain the stack temperature around 50°C.

Initially with a single loop thermal management system R, radiator employed, with primary coolant flow rate maintained at 2.5 lpm, it can be seen that the fuel cell stack reached the threshold temperature of 50°C in less than 25 minutes [Fig. 2]. This lower duration in using R is due to the greater heat accumulation in the primary loop tank. In order to reduce the heat augmentation in the primary loop, heat transfer modules were introduced, viz., PHE between primary and secondary loops for transferring some amount of heat content from primary to secondary loop. The flow rate in the primary loop is varied between 2.5 lpm and 3.5 lpm keeping the secondary coolant flow rate at a constant 4.5 lpm. The corresponding fuel cell temperature profiles are shown in Fig. 2 , where it is evident that the R_p configuration with 3.5 lpm flow rate allowed the stack to operate at the peak power conditions for more than 60 minutes and maintaining its temperature around 50°C. It was not possible to maintain the stack temperature around 50°C for longer duration with other configurations. However it is required that this conclusion is justified further by studying the heat profiles and their distributions for all the thermal management configurations.

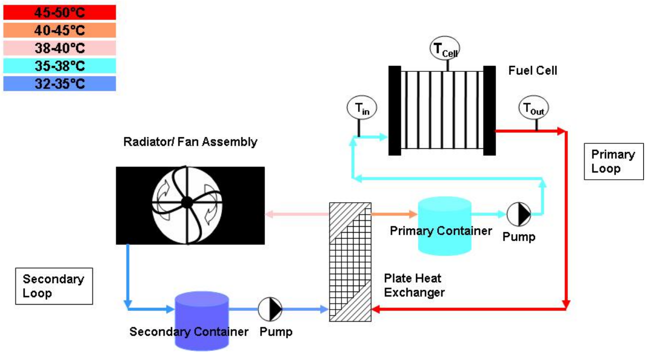

Fig.1: Rs configuration Schematic

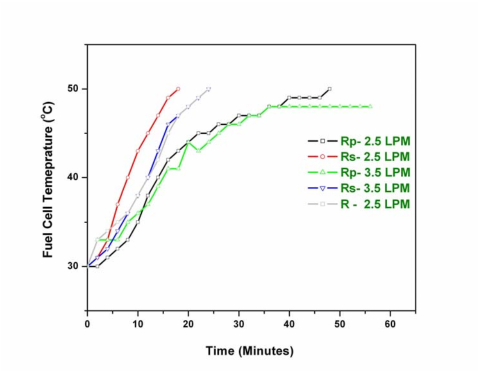

Fig.2: Stack Temperature profile

3.1. Heat removal from the fuel cell

The amount of heat generated by a fuel cell during its operation is around 1.2 to 1.5 times of the electrical power generated depending on the voltage at which the cells are operated. Surplus heat inside the fuel cell needs to be removed in order to maintain the stack temperature under optimum range. The coolant water flowing through the fuel cell removes this surplus heat. The amount of heat thus removed by the primary coolant is given in Eqn.1.

$$\dot{Q} = \dot{m} c_p \Delta T \tag{1}$$

Where, $\dot{Q}$, $\dot{m}$, c_p and ΔT corresponds to the quantity of heat removed from the stack, mass flow rate of the primary coolant, specific heat of water and the temperature difference of the primary coolant across the fuel cell. The heat removed by the coolant for all the three configurations is given in Fig.3. It can be observed from Fig.3 that the maximum heat removed from the fuel cell is observed with R_p configuration with 3.5 lpm of primary coolant flow rate. Also the heat removal distribution extended to more than 60 minutes of the fuel cell operation. Greater flow rate of primary coolant resulted in greater heat removal. However the heat distribution over an extent is defined by the primary coolant inlet temperature as shown in Fig.4. As can be seen from Fig.4 that as long as the primary coolant temperature could be maintained below of 40°C at a given flow rate, the stack can also be maintained around 50°C as shown in Fig.2.

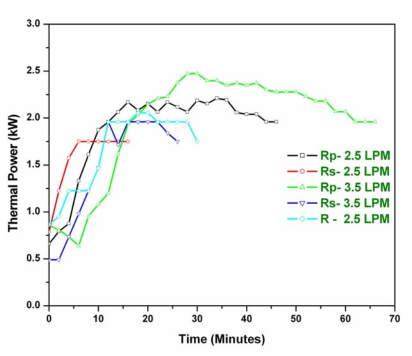

Fig.3: Heat removal from fuel cell profile

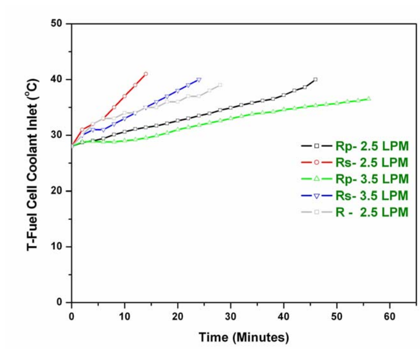

Fig.4: Primary coolant inlet temperature profile

3.2. Heat transfer across the Plate Heat Exchanger

The heated primary coolant exiting the Fuel Cell is passed through a plate heat exchanger for heat exchange with the secondary coolant. The net heat transfer $\dot{Q}_{hx}$ across the heat exchanger can be calculated from three different approaches namely (i) heat lost by the primary coolant across the heat exchanger (ii) heat gained by the secondary coolant across the heat exchanger (iii) heat transfer across the heat exchanger using the mean temperature difference as given in Eqn.2 [13].

$$\dot{Q}_{hx} = \dot{m}_p c_p \Delta T_p = \dot{m}_s c_p \Delta T_s = UA\Delta T_{lm} \tag{2}$$

Here $\dot{m}_p$, $\dot{m}_s$, ΔT_p , ΔT_s , U , A , ΔT_{lm} corresponds to the primary coolant flow rate, secondary coolant flow rate, temperature drop across the primary coolant, temperature gain across the secondary coolant, overall heat transfer coefficient, total heat transfer area and the log mean temperature difference of the coolants across the heat exchanger. The overall heat transfer $\dot{Q}_{hx}$ across the plate heat exchanger as calculated from Eqn.2 depends primarily on the temperature difference ΔT_{lm} and the overall heat transfer coefficient U of the heat exchanger. The method for the calculation of the overall is defined in the Eqns. (3-6) [13].

$$U = \frac{1}{\left(1/h_c + 1/h_o\right)} \tag{3}$$

Where h_c and h_o are the individual heat transfer coefficients of the cold side and hot side of the heat exchanger. A general equation representing the individual heat transfer coefficient is given in Eqn.6

$$\overline{Nu}_L = 0.664\,\mathrm{Re}_L^{1/2}\,\mathrm{Pr}^{1/3} \tag{4}$$

$$\mathrm{Re}_L = \frac{u_\infty L}{\nu} \tag{5}$$

$$h = \overline{Nu}_L\left(\frac{k}{L}\right) \tag{6}$$

Observing the Eqns. (2-6) it can be concluded that net heat transfer coefficient U increases with increase in mean velocity u_∞ (flow rate for the present study) of the flowing fluid. This supports the observations from Fig 2, 3&4 that greater the flow rate of the primary coolant, more is the heat removal from stack and greater the fuel cell operational duration.

3.3. Heat transfer across the radiator/fan assembly

There is a need for radiator/fan assembly as another heat transfer source to remove the augmenting and accumulating heat in the cooling loops to the ambient (heat sink). The net heat removal from the cooling loop by the radiator/fan assembly is described in a similar method as that of plate heat exchanger. The following Eqn.7 describes the various governing methods for calculating the overall heat transfer from the coolant to the ambient across the radiator.

$$\dot{Q}_{rad} = \dot{m}_c c_p \Delta T_c = \dot{m}_a c_a \Delta T_a = kA\Delta T_{lm} \tag{7}$$

Where $\dot{m}_c$, c_p , ΔT_c , m_a , c_a , ΔT_a , k , A , ΔT_{lm} represent the flow rate of the coolant through radiator, specific heat capacity of water, temperature drop of the coolant across radiator, flow rate of the air across the radiator, specific heat capacity of air, temperature gain in the air flowing across the radiator, heat transfer coefficient of the heat transfer, heat transfer area and the log mean temperature difference across the radiator.

3.4. Net heat removal from the Primary cooling loop

It can be observed that in the present thermal management system, the plate heat exchanger and radiator/fan assembly are the two heat transfer modules to remove the heat circulating in the cooling loops. The aim in introducing the heat transfer modules it to remove the maximum amount of this circulating heat from the primary loop to ambient. However, depending on the configuration in application, the quantity of net heat removed from the primary loop will be a contribution from the two heat transfer modules.

Heat removal from R configuration

In the R configuration, the net heat removal from the primary loop is contributed from the radiator/fan assembly alone. Thus the net heat removed is given by Eqn.8.

$$\dot{Q}_R = \dot{Q}_{rad} = kA\frac{\Delta T_{lm}}{dt} \quad (8)$$

Heat removal from R_p configuration

In the R_p configuration, the net heat removal from the primary loop is contributed both by the plate heat exchanger and radiator/fan assembly only. Thus the net heat removed is given by Eqn.9.

$$\dot{Q}_P = \dot{Q}_{rad} + \dot{Q}_{hx} = kA_{rad}\frac{\Delta T_{lm}}{dt} + UA_{hx}\Delta T_{lm} \quad (9)$$

Heat removal from R_s configuration

In the R_s configuration, the net heat removal from the primary loop is contributed from the plate heat exchanger alone. The radiator/fan assembly is placed in the secondary loop and receives heat carried by the secondary loop. Thus the net heat removed is given in Eqn.10.

$$\dot{Q}_P = \dot{Q}_{hx} = UA_{hx}\Delta T_{lm} \quad (10)$$

Thus the overall heat removed from the various cooling loops and its distribution over the duration of the stack is given in Fig. 5. The % of heat removal from all these configurations is given in Table.1.

Table 1

Thermal Configuration	Lpm	$\dot{Q}$ Average	$\dot{Q}_P$ Average	% Heat removal	Fuel cell duration (minutes)
R_p	3.5	2.2kW	1.8kW	82%	66
	2.5	2.1kW	1.6kW	76%	46
R_s	3.5	0.76kW	1.6kW	47.5%	30
	2.5	0.57kW	1.5kW	38	26
R	3.5	1.9kW	1.25kW	65%	16

From Table.1, it is clear that using R_p configuration with 3.5 lpm flow rate, 82% of augmented heat in the primary loop is released through the heat transfer modules and specifically the radiator in the primary line, making the fuel cell to operate for longer duration. Further work is in progress to evaluate the efficient thermal configuration loop for high capacity fuel cell stacks. Further research can also be extended in understanding the behavior of various other coolants by introducing them into the secondary loop and studying their applicability in replacing water as the primary coolant.

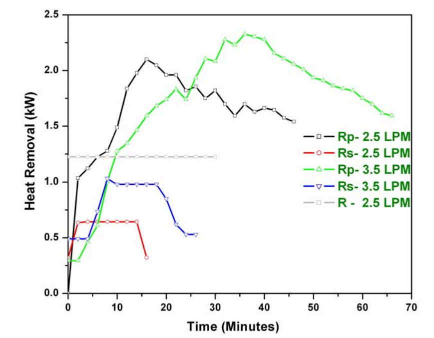

Fig.5 Heat removal from primary loop profile

4. Conclusions

It can be concluded that efficient thermal management plays a pivotal role in the fuel cell dynamics and its performance. The thermal management configurations using plate heat exchanger and radiator fan assembly have been developed, which are helpful for effective heat management in the fuel cell. The cumulative heat transfer from all the configurations, parameters like flow rate of coolant and coolant inlet temperature play a major role in the optimum design of the system. It has been observed from these studies that the configuration R_p with radiator/fan assembly positioned in the primary loop resulted in the maximum heat removal from the fuel cell for any given flow rate of coolant. It is concluded that the objective of maintaining the fuel cell functioning at its peak power of 1.5 kW_{elec} for more than 60 minutes is achieved using the R_p configuration with 3.5 lpm primary coolant flow rate. These experimental data coincides well with theoretical formulations.

5. Acknowledgements

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