Design and Optimization of a Closed Two Loop Thermal Management Configuration for PEM Fuel Cell Using Heat Transfer Modules

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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 the fuel cell for all the thermal management configurations has been calculated. A relation between the average thermal power, flow rate and thermal management circuit has been established.**

***Index Terms*—PEM fuel cell, thermal management, cooling loop, coolant, Plate Heat Exchanger, Radiator**

I. Introduction

Thermal management of a PEMFC system has been a pivotal factor to ensure high performance and efficiency of the cell. Apart from water, heat is another byproduct produced by the cell which is emanated during the electrochemical reaction between hydrogen and oxygen as given in Frano Barbir [1]. Several problems 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 [3-6]. Thermal management system involves supply of a coolant to the fuel cell which absorbs the heat produced inside the cell. The heat absorbed by the coolant is to be removed into the ambient effectively. Also, uniform temperature distribution is desired to run the cell effectively. Air breathing techniques are used for cooling the Fuel Cell stacks of low capacity. The air breathing cooling system as discussed in Schmitz et al. [3] in which emphasis was given on cathode opening size and study of wetting properties of the diffusion layer thorough air breathing of the PEM Fuel Cell. Ambient cooling via free breathing of the Cell was also discussed. Kolar et al. [4] discussed the variation of local cell temperature and power densities in a PEM Fuel Cell along the height of the Cell which was operated through air breathing technique. But this technique of open Air breathing [3-4] cannot be replicated for larger stacks which are an assembly of several single cells connected to each other and also doesn't allow an open cathode cooling. Air cooled thermal management in which air is blown over the cooling plates as inserted in a Fuel Cell is a widely adopted technique in cooling stacks which generate less than 1kW thermal power. The Fuel Cell thermal management system as described by Agbossou et al. [5] for a 34 W thermal power generation using air cooled convection method. Forced convection was implemented to remove the thermal power generated by the cell. Park et al. [6] studied the thermal management of a Fuel Cell with compressed air as coolant. The current withdrawn from the stack was 10A, 15A and 20 A respectively and the peak power generated was 150 W. Both Agbossou et al. and Park et al. did not support the concept of Fuel Cells generating thermal power of more than 2.0 kW. Cooling of stacks using conventional air convection, forced convection and compressed air blowers are inefficient for fuel cell stacks generating huge amount of heat. Also, the specific heat capacity of air is relatively small and requires large amounts of air to be pumped into the Fuel Cell. . This requires the coolant channels to be designed for increased residence time which adds to the complexity of the cooling process. Further to achieve uniform temperature distribution across the cell for stacks with larger thermal power, a liquid coolant system is preferred which has larger specific heat capacity when compared to air. In view of the available liquid coolants, water is considered to be the best suitable coolant due to its higher heat capacity, with very low ionic conductivity of 5.5×10^{-6} S/m and easy to handle nature. Thus, efficient heat removal by coolant water from the cell ensures to maintain the stack performance high.

The various heat generating sources in a fuel cell and the mode of heat transfer from cell to several sources like coolants and reacting gases with governing equations are discussed briefly in Shan et al. [7]. The coolant flow through the flow field channels and the heat transfer mechanism from the coolant to the environment by using a radiator is discussed. In addition Shan et al [7] describes a procedure to dissipate heat to the ambient via convective heat transfer mechanism. Zhou et al. [8] discussed the heat transfer from the stack to the fluid flowing through the cell and the dependence of coolant temperature on the overall stack temperature. The coolant absorbed heat from the stack by

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convection and its temperature is assumed to be constant across the cell. The variations in stack temperature and coolant temperature and the corresponding energy balances have been discussed. However, apart from temperature, 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 the present study.

The coolants used in removing heat from a fuel cell stack are further required to be cooled to ensure that the coolant is maintained at desired operating temperature. Several designs as observed in [9-11], where various cooling apparatus for cooling the coolant flowing thorough a fuel cell are discussed. A radiator fan assembly is used in order to remove the heat from the fluid loop into the ambient through convective heat transfer mechanism. Ishikawa [10] describes a two loop cooling apparatus where in the primary coolant fluid exchanges heat with another secondary fluid in an intermediate cooling system. The intermediate cooling system consists of a liquid medium. The secondary fluid is cooled using radiator via convective heat transfer mechanism into the ambient. In this system, the intermediate cooling system too absorbs heat and the heat transfer between the two fluids will decrease over a period of time. Thus in place of liquid medium heat exchangers can be better and efficient mediumin exchanging heat between two liquids. Ouyang et al. [11] discussed the use of reservoir water tanks as heat exchangers to the coolant fluids and also radiators which dissipate the heat from the coolant fluids in to the ambient via convective heat transfer. Though the role of radiator is to remove heat from the coolant through convection, the average temperature difference between the coolant inlet and outlet temperatures is just around 5 ℃, which implies that the temperature drop across the radiator is not very large.

The effective use of various heat transfer modules is required to ensure that the fuel cell is maintained at its optimal conditions for a long duration of time. Dohoy Jung et al. [12] describes the need for maintaining of the temperature of the fuel cell at its optimal operating conditions and a maximum temperature of 80 ℃, which produce an effect on the performance of the cell and durability. This study also refers to the use of radiator with a fan assembly to cool the coolant and gives an insight into the behavior of the stack temperature with respect to the coolant inlet temperature to the cell. The amount of heat generated inside a fuel cell depends on the heat removed by the flowing coolant through it. Rajalakshmi et al. [13] discussed the heat transfer through the fuel cell, quantification of the heat removed from the cell and the sources of heat generation such as the various resistances and their contribution was reported.

Thus from the above review of literature, there is a need for the effective removal of excess heat stored in the coolant fluid in addition to the heat transfer components. Various designs and methods have been implemented but only a system with a radiator in the loop allows effective heat dissipation from the fuel cell system to the ambient. It is also understood that there are two major factors responsible for the effective heat removal from the stacks viz. flow rate of the coolant in both the primary and secondary loop and design of efficient thermal circuit. The present paper addresses these two major variants for a 1.5 kW fuel cell stack with two loop cooling system. Further an effective thermal circuit, which plays a critical role in the stack performance for longer durations with less volume of coolant, suitable for vehicular applications is identified.

II. 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 capacity. The Hydrogen from compressed cylinders and air from a blower were used as fuel and oxidant to the stack respectively. The stack was operated below 50 ℃ owing to the design of the stack and operating protocols were established for such a stack. In the closed primary single 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. These temperatures are measured using precise thermocouples, which are accurate to + 0.1 ℃. In the two loop thermal management systems there exists a secondary cooling circuit in addition to the primary single loop and also 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. Further a radiator/fan assembly was used for the above thermal management systems and three different thermal management configurations have been designed. They are R, R_p and R_s respectively 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. Also the heat removal across the PHE and radiator/fan assembly has been evaluated to study the thermal distribution in the configurations used. The fuel cell stack temperature was monitored for the sustained performance at the optimal operating conditions and peak power.

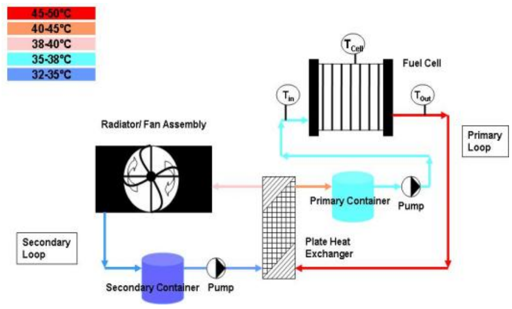

Fig. 1. Two loop cooling system schematic-Rs Configuration

III. 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)

IV. Results & Discussions

A. Fuel Cell Polarization Curve and Performance Studies

The fuel cell performance can be evaluated from its corresponding polarization curve during its operation. The polarization curve is a tool to study the fuel cell voltage and current distribution for its overall operation duration. The corresponding polarization curve for the present study is given in Fig 2. The curve shown in Fig 2 shows the increase in current density and corresponding power density with decreasing voltage (load applied). It can be observed that for the experiments with the primary coolant flow rates of 2.5 and 3.5 lpm the operational voltage at the initial stage of no current was almost similar. However with increase in the load or decrease in the voltage, it can be observed that the maximum current density that can be achieved from the fuel cell using 2.5 lpm and 3.5 lpm primary coolant flow rate is around 0.14 A/cm^2 and 0.15 A/cm^2. Also from Fig 2 the total power density drawn from the fuel cell for a primary coolant flow rate of 2.5 lpm is around 0.08 W/cm^2. However the power density for the primary coolant flow rate of 3.5 lpm is around 0.09 W/cm^2 at the given voltage. This enhancement in current and power densities of the fuel cell with increase in coolant flow rate can be attributed to the efficient heat removal from the fuel cell where the primary coolant flow rate is 3.5 lpm. Greater heat removal from the fuel cell resulted in a sustained and enhanced performance of the fuel cell. Initially, the fuel cell performance is evaluated from its operating temperature.

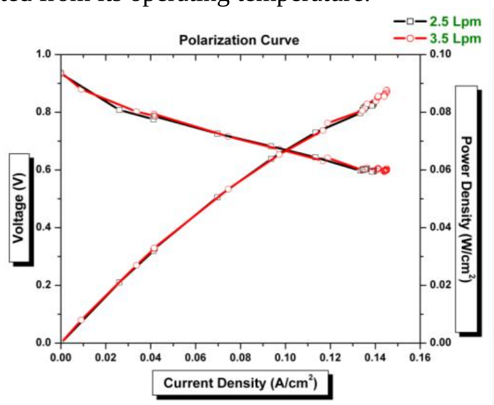

Fig. 2. Polarization curve for the fuel cell operation

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 ℃.

Initially with a single loop thermal management system R, radiator employed, with primary coolant flow rate maintained at 2.5 lpm, it can be observed that the fuel cell stack reached the threshold temperature of 50 ℃ in less than 25 minutes [Fig. 3]. This lower duration results in using R in the primary loop tank and due to the greater heat accumulation. . 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 further 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. 3 , 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 ℃, compared to 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. The following sections will discuss the heat distribution across the fuel cell, plate heat exchanger and radiator/fan assembly.

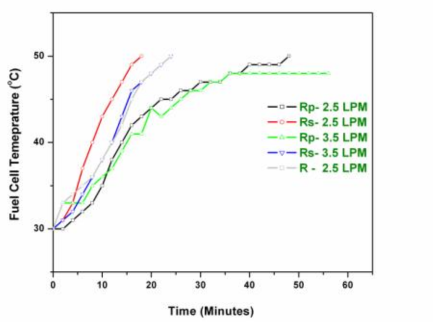

Fig. 3. Fuel cell temperature distribution with operational duration at variable configurations and coolant flow rates

B. 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

$$\dot{Q} = \dot{m} c_p \Delta T \quad (1)$$

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 coolant for the entire three configurations is given in Fig.4. It can be observed from Fig.4 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.

Flow rate of the coolant is one factor that plays a major role in the heat removal process from the Fuel Cell stack. Greater the flow rate, more the coolant flowing through the Fuel Cell stack per unit time and thus more the quantity of the heat removed. Also with increase in the flow rate of coolant, the overall heat transfer coefficient for the heat exchange between the coolant and the fuel cell increases. However there is also a limitation to the flow rate that can be used in the primary circuit which is determined by the flow channel dimensions in the cooling plates of the fuel cell stack besides leakage issues. Thus for the present fuel cell stack in use the maximum flow rate of coolant is set at 3.5 lpm.The heat removal from the Fuel Cell stack for the present study is reported in Fig 4. It can be observed that the average thermal power removal is greater for the configuration Rp at 3.5 Lpm flow rate which is around 2.2 kW and the least is observed for the Rs configuration at 2.5 lpm flow rate which is around 1.5 kW. The configurations R at 3.5 Lpm flow rate and Rs at 2.5 lpm flow rate removed a thermal power of around 1.9 kW and 1.5kW respectively from the fuel cell. Finally configuration Rp at a flow rate of 2.5 lpm could remove an average thermal power of around 2.1 kW from the fuel cell. It can be observed that larger the thermal power removed from the fuel cell stack, the better is the duration performance of the fuel cell stack at the optimal operating conditions. Apart from the flow rate of coolant to the fuel cell, it is also the coolant inlet temperature that determines the distribution and extent to which the fuel cell can be operated at the peak load operating conditions.

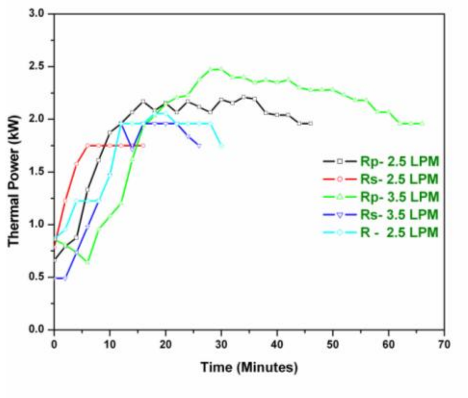

Fig. 4. Thermal power removal by primary coolant from fuel cell by varying thermal configurations and coolant flow rates

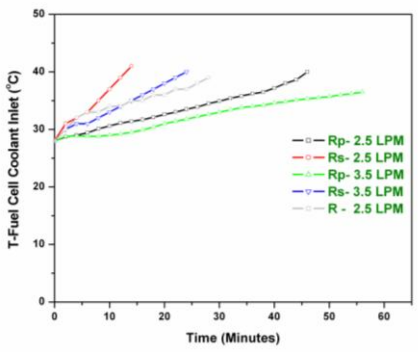

Fig. 5. Primary coolant inlet temperature distribution to the fuel cell at variable configurations and coolant flow rates

The temperature distribution of the coolant inlet can be seen from Fig.5. As long as the primary coolant temperature could be maintained below of 40 ℃ at a given flow rate, the stack can also be maintained around 50 ℃ as shown in Fig.3. The temperature distribution of the fuel cell with operating performance as seen from Fig 3 and Fig 5 concludes that an increase in flow rate of coolant results in greater extent of the fuel cell performance at its corresponding peak load conditions.

C. 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].

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

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].

$$U = \frac{1}{(1/h_c + 1/h_o)} \quad (3)$$

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

$$\overline{Nu}_L = 0.664 \mathrm{Re}_L^{1/2} \mathrm{Pr}^{1/3} \quad (4)$$

$$\mathrm{Re}_L = \frac{u_\infty L}{\nu} \quad (5)$$

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

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 3, 4&5 that greater the flow rate of the primary coolant, more is the heat removal from stack and greater the fuel cell operational duration.

D. 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.

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

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.

E. 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

1) 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.

$$\dot{Q}_P = \dot{Q}_{rad} = kA\frac{\Delta T_{lm}}{dt} \tag{8}$$

2) 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.

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

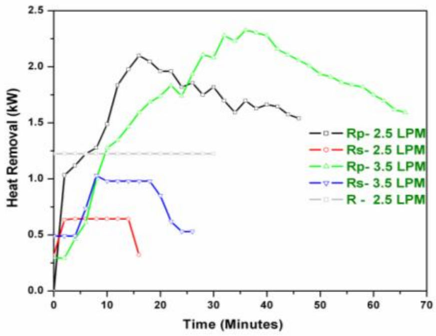

Fig. 6. Net heat removal from the fuel cell to ambient

3) 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.

$$\dot{Q}_P = \dot{Q}_{hx} = UA_{hx}\Delta T_{lm} \tag{10}$$

TABLE I: PERCENTAGE HEAR REMOVAL FROM THE FUEL CELL

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	1.6kW	0.76kW	47.5	26
	2.5	1.5kW	0.57kW	38	16
R	3.5	1.9kW	1.25kW	65	30

Thus the overall heat removed from the various cooling loops and its distribution over the duration of the stack is given in Fig. 6. The percentage of heat removal from all these configurations is given in Table.1.

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.

V. 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 also 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.

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