CAPILLARY SYSTEMS AS ALTERNATIVES TO COOLING FOR FUEL CELLS

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Abstract.
A two-phase heat transfer system is proposed as an alternative for cooling and thermal control of PEM fuel cells (PEMFC - Proton Exchange Membrane Fuel Cell). The proposed system consists of a couple of heat pipes connected to a CPL (Capillary Pumped Loop), coupled to a module which simulates the fuel cell. The operation temperature control has an important influence over the fuel cells performance. According to experimental results, within the operation limits recommended by the manufacturer, as the operation temperature increases the fuel cell performance also increases. High temperatures dry the membrane decreasing the required proton conduction and the chemical reaction. CPL's and heat pipes are high heat transfer devices commonly used for aerospace applications. Small size and no extra energy cost for pumping the working fluid are inherent characteristics of both systems. In this work ceramic wick and stainless mesh wicks have been used as capillary structure of the CPL and heat pipes, respectively. Acetone has been used as the working fluid for the CPL and deionized water for the heat pipes Two differents heat pipe designs have been tested in LabCET/UFSC and the results are presented in this paper.

Keywords: *Cooling capillary system, PEM fuel cells, Thermal control.*

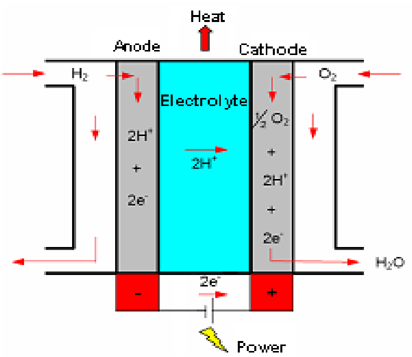
1. INTRODUCTION

Nowadays the search for alternative energy sources is much requested. The motivation of this work is to contribute to become viable the system which use alternative energy sources. One of these systems is the fuel cell that is an electrochemical device which converts chemical energy into electrical energy.

The fuel cells are compacts, noiseless and pollute less than the conventional energy generation systems. They also guarantee high quality current and high efficiency.

A fuel cell is composed by an electrolyte which transports ions between two electrodes. The fuel (hydrogen) enters in the anode while the oxidant (oxygen or air) enters inside cathode. In the proton exchange membrane fuel cell (PEMFC) the electrolyte is a proton conducting membrane that transports de H^+ ions from the anode to cathode. In the cathode, there is an exothermic reaction between $2H^+$ and ½ O_2 which produces water (Fig.1.b). The electrons flow trough an external circuit generating a continuous current. An operation scheme of fuel cell is presents in Fig.1.a.

a)



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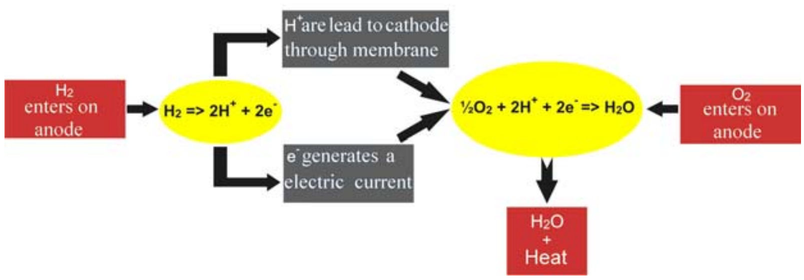


Figure 1.a) Operation scheme of PEMFC. b) Flowchart of reactants and products in a PEMFC.

Due to its low operation temperature, compact size, low weigh, start quickly, long useful life and the capacity to work in a discontinuous regime, the PEMFC are proposed as alternative for portable energy generation systems and in vehicles (Ghenciu, 2002). However, one of the technological limits of the PEMFC use is the efficient thermal management.

The temperature control has a fundamental importance for PEMFC performance. High temperatures dry the membrane and interrupt the proton conduction and energy generation. In the other hand high temperatures are beneficial for the chemical reaction. There is a short optimal temperature range that takes into account the contradictory temperature effects in the PEMFC performance. High temperature gradient inside the fuel cell is also contributes to decrease their performance. In order to make the PEMFC technology available and affordable it is required to develop an efficient cooling system wherein PEMFC temperatures control is made with low energy consumption.

Park and Caton, (2008) studied the temperature and humidification influence of PEMFC. The experimental results showed that for densities power less than 0.2W/cm^2 was unnecessary the additional cooling systems, however to densities power higher, the lack of adequate cooling resulted in a relevant power decrease, e.g. for 0.3W/cm^2 with cooling based forced convection and compressed air over the channels, the system supplied 140W; without compressed air, the power dropped to 90W, in both cases the gas inlet was 100% moist.

The most popular cooling systems nowadays are heat transfer monophasic systems, generally with water or air. Two-phase heat transfer systems present the advantage to transport a greater heat amount for a small temperature differences. An additional advantage of the capillaries two-phase systems like heat pipes, CPL's and LHP's (loop heat pipe) is the little or none extra energy cost.

A common project of three research French centers (CETHIL, LET and LAPLACE) developed a two-phase heat spreader (TPHS) as a cooling system, simulating the application in PEMFC. However, they did not propose a coupled way between fuel cell and the cooling system. TPHS are like mini flat heat pipes with a unique vapor channel. The fluid goes from heat sink to the heat source by capillary action. Each research center developed their own TPHS and the results were compared and presented in the 14th IHPC (Rullière et al., 2007). Different capillary structures and pairs of material and work fluid have been tested. The results depicted high efficiency. The best result is obtained in thermosyphon orientation for methanol as work fluid and with the TPHS made of longitudinal grooves, the maximum temperature not exceed 75°C and the difference between the evaporator and the condenser was 3.5K.

Faghri et al. (2005a and 2005b) showed two patents about different two-phase systems for fuel cells cooling. Nevertheless, they did not present results aiming to validate the proposed mechanisms. The presented cooling systems were heat pipes in two different configurations for PEMFC. The first propose is micro heat pipes integrated into a fuel cell bipolar plate and the another one is the flat heat pipes integrated into a bipolar plate.

Vasiliev and Vasiliev Jr, (2008) proposed different designs of heat pipes for thermal fuel cell: micro/mini heat pipes, loop heat pipe (LHP), loop thermosyphon, LHP with noninverted meniscus of the evaporation, pulsating heat pipe panels and sorption heat pipe (SHP). They proposed that as a suggestion for application in fuel cell. They did not do tests for validation.

A brief review of the current status about thermal management issues in a PEMFC stack is discussed by Kandlikar, (2009). The author does not suggest cooling systems, however, he offers basis to better understand the necessary thermal effects to develop an efficient cooling system and consequently the PEMFC optimization.

The aim of this work is to study different configurations of the two-phase heat transfer systems that utilize capillarity as a circulation work fluid way. Among the proposed capillaries systems are in series heat pipe integrated into bipolar plates associated to a CPL for PEMFC effective thermal control. Two heat pipe designs were tested separated without association to CPL.

2. SYSTEM DESIGNS

2.1. Heat Pipes

Heat pipes are two-phase systems used mainly in heat transfer of electronic devices. They consist of a heat sink and a heat source, and can present an adiabatic zone. The work fluid is pumped to the evaporator by capillary action. In the evaporator, when fluid is heated it change phase from liquid to vapour. The vapour goes to the condenser exchange heat returning to the liquid phase. The system works in a closed cycle and electrical energy is not required for circulating the working fluid. A heat pipe scheme is presented in Fig. 2.

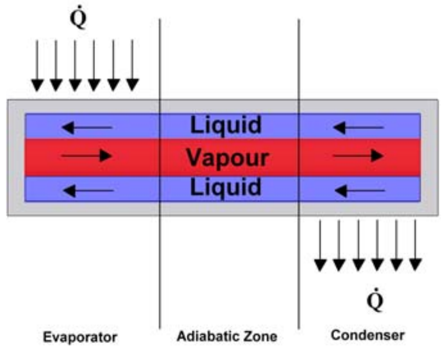


Figure 2. A heat pipe scheme showing the evaporator, adiabatic zone and condenser area.

The first heat pipe design consists of Swagelok stainless steel (316L) seamless tubing with outside diameter of 4.76mm (3/16in). Single stainless steel mesh layer is use as capillary structure. The Mesh number of the wick used in all devices in this work is 100. The working fluid of all heat pipe designs is deionized water. The Fig. 3.a shows the first heat pipe design and Fig.3.b shows the vapour and liquid channel in a cross section view.

A particularity of a heat pipe used in a fuel cell is to have a bigger evaporator length compared to condenser length. The first heat pipe design has the following lengths: evaporator 135mm, adiabatic zone 20mm and condenser 30mm. The total length is 185mm. All the zones are insulated with an expanded polymer commercially available as Polipex™.

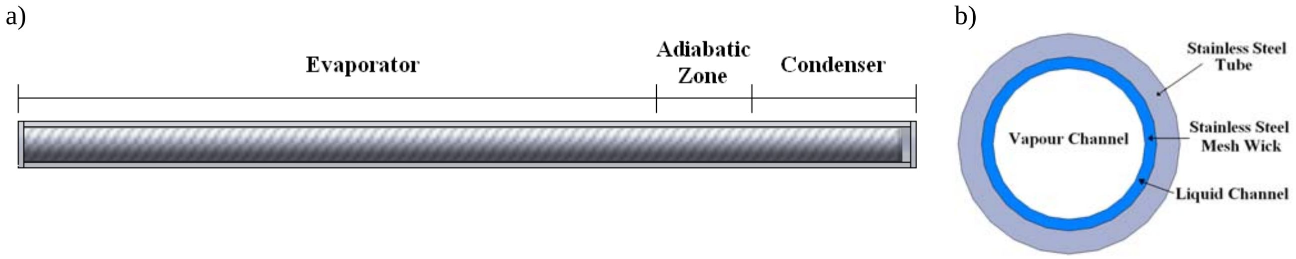


Figure 3. a) Conventional heat pipe in lateral view. b) Heat pipe section view.

The second design is a heat pipe assisted by thermosyphon (Fig. 4). This "L" shaped design was proposed to simplify the future connection between the heat pipe and the CPL. This configuration also increases the heat transfer area. This heat pipe design consists of total horizontal length of 175mm completely used as evaporator. The vertical zone has 55mm and it works as a condenser. There is not an adiabatic zone. The working fluid is pumped by the porous structure placed inside the tube in the horizontal zone and uses the gravity force for circulating in the vertical zone. The tube characteristics used in this device is Swagelok stainless steel (316L) seamless with outside diameter of 6.35mm (1/4in). Two stainless steel mesh layers are used as the capillary structure.

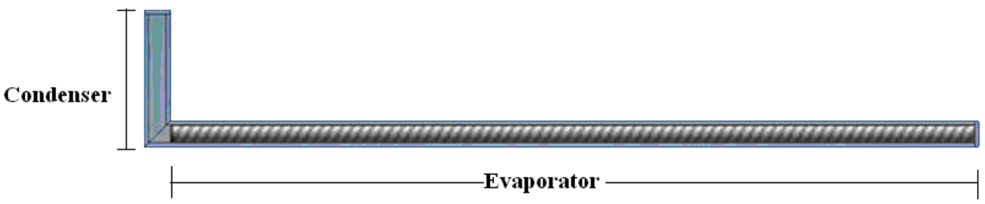


Figure 4. Heat pipe assisted by thermosyphon.

2.2. CPL

Capillary Pumped Loop (CPL) and heat pipe has similar operation. The difference between them is their geometry configuration. CPL has evaporator and condenser separated by liquid and vapour lines. And it has a reservoir for controlling the phase change temperature in the evaporator. A scheme of CPL is presented in Fig.5.

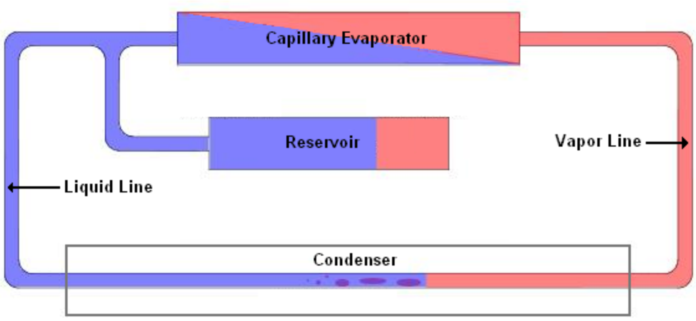


Figure 5. Capillary Pumped Loop (CPL).

The CPL designed is being manufactured. It has a unique capillary evaporator, one reservoir, one condenser and liquid and vapour lines. The CPL working fluid is acetone (99.5%). The capillary structure is porous ceramic medium with 50% porosity and pores size less than 10μm. This ceramic porous medium is manufactured in LabCET/UFSC by slip casting and sintering with process parameters proposed by Berti et al, 2006. The dimensions of capillary structure are: diameter 20mm and length 114mm. The vapour channels were machined in the outside surface of porous ceramic medium (Fig. 6.a). Inside the porous medium a liquid channel will be drilled (Fig. 6.b). The ceramic porous medium will be inserted inside a stainless steel envelope of 20mm inner diameter. Liquid and vapour lines will consist of Swagelok stainless steel (316L) seamless tubing with outside diameter of 4.76mm for the vapour line and 2.10mm for the liquid line. Condenser will be manufactured with fins and fan to force air flow (Fig. 7).

a) b)

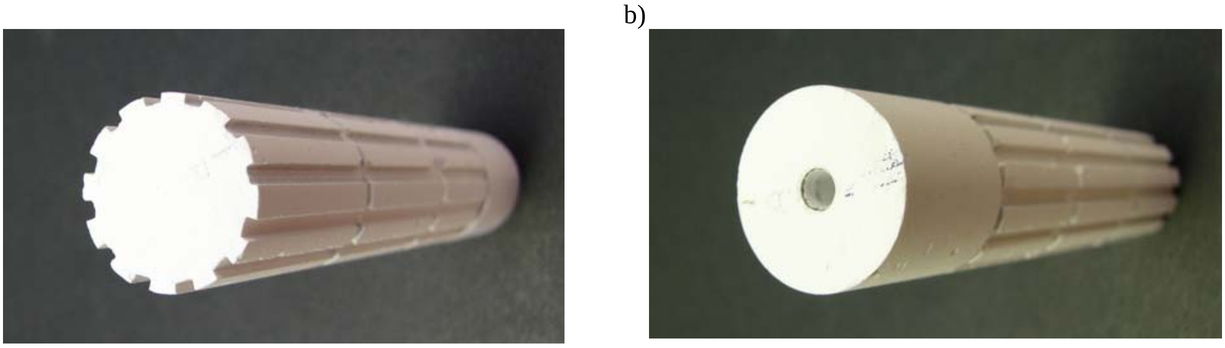


Figure 6. Porous ceramic structure of CPL a) vapour channels and b) liquid channel.

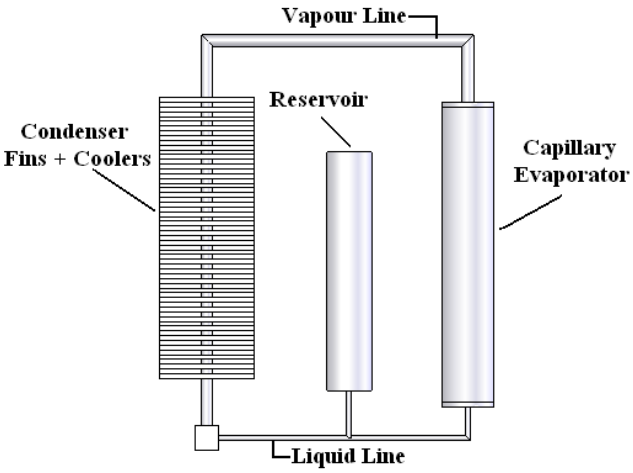


Figure 7. Scheme of CPL (in construction).

2.3. Fuel Cell Module

An experimental apparatus will be build to simulate a PEMFC allowing the integration of cooling and thermal control systems. The fuel cell module is based on Electrocell^{TM} fuel cell existing at LabCET/UFSC. This fuel cell is a stack composed for 10 unit cells. The total nominal stack power is 200W.

A fuel cell module will simulate a unique cell and will be manufactured as indicated in Fig.8. The module is composed by one graphite plate, one thermal insulator plate and one skin heater between the plates able to dissipate 20W. For structural function there will be two steel plates. The graphite plate role is to simulate the PEMFC bipolar plates wherein it will be inserted the heat pipes.

In this project the dimensions of graphite plate are: length 135mm, height 175mm and variable thickness depending on the heat pipe design. Dimensions of skin heater: length 120mm, height 120mm and thickness smaller than1mm.

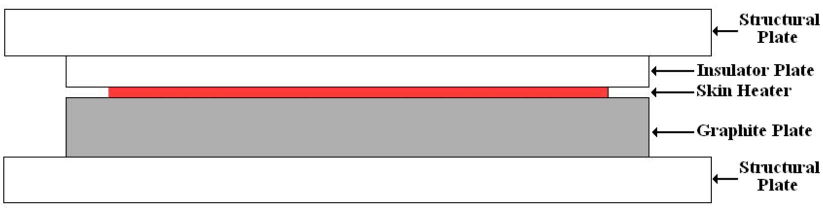


Figure 8. Fuel cell module.

2.3. Integrated Cooling System

Figure 9 presents the integrated cooling system proposed. This figure shows heat pipes inserted in the graphite plate for transporting heat from fuel cell to CPL. Between PEMFC and CPL there will be an adiabatic zone. Inside the evaporator of CPL will be inserted the condensation zone of heat pipes. The reasons for using CPL as condenser is the low energy consumption and mainly because it allows control of PEMFC temperature.

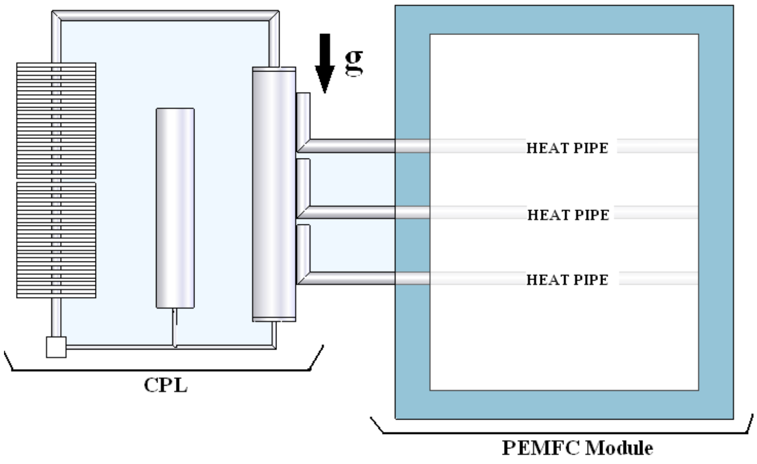


Figure 9. Integrated cooling system with heat pipe assisted by thermosyphon.

3. EXPERIMENTAL SETUP

This paper presents the results just for two heat pipes designs. All experiments were performed at LabCET/UFSC. All material undergoes a standard ultrasonic cleaning process, in this case, the Odontobras 2840D Ultrasonic Cleaner model. The initial plane-geometric configuration of the mesh wick was modified to a cylindrical configuration in order to cover the tube internal surface. Then, the subsystem was pumped down using an E2M2 - BOC Edwards vacuum pump.

Afterward this preliminary process, the heat pipe is loaded with the working fluid. The fill process is really critical and demand special attention, because the small quantity to be charged (less than 1 ml). Furthermore incondensable gas is prejudicial for the performance.

Thermocouples type T (cooper/constantan) from Omega^{TM} were placed along the heat pipes as showed in Fig. 10 and Fig.11 in order to make possible the thermal analysis.

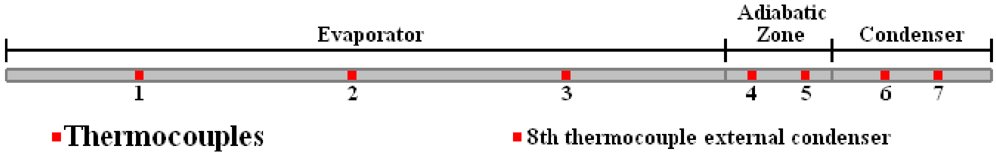


Figure 10. Thermocouples position along the first heat pipe design.

An Agilent acquisition system, model 34970A with 20 channels and a computer were used for the data acquisition process of temperature. For all tests in this work, the system power supply used was an Agilent N6700B and the resistor is a skin heater. A Lauda cryostat model E200 was use as condenser.

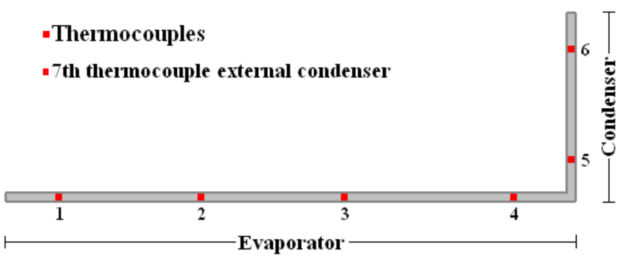


Figure 11. Thermocouples position along the second heat pipe design

Two kinds of procedures for the experiments of heat pipe tests were adopted in this work. The first one, applying a constant power during a period of 1 hour. In this case, two different values of power were tested 5W and 7.5W for the conventional heat pipe and 10W and 15W for the heat pipe assisted by thermosyphon.

The second kind of tests differs on the way of power application. In this case, the test starts with the small value of power (5W), during a time of 1 hour, elapsed this first time, the power is increased to the second value, 7.5 W, during a similar time interval. Finished the second time interval, the power was set to 10 W, also during 1 hour. The second kind of test is performed just for the conventional heat pipe.

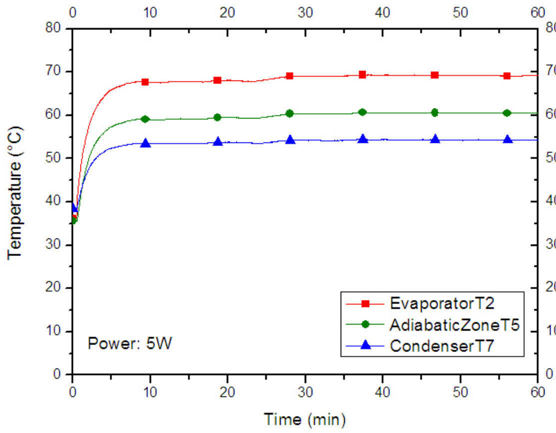
The maximum error in temperature measurement is ± 1.6 K. For the power applied the maximum error is ± 0.2 W.

4. RESULTS AND DISCUSSIONS

The Fig.12 presents graphs temperatures versus time for different power applied in a conventional heat pipe with single mesh wick. In Fig. 12.a., 12.b. and 13 the temperature were measured by the thermocouples 2, 5 and 7 for the evaporator, adiabatic zone and condenser, respectively. Fig 10 indicates the position of each thermocouple in this experiment. At all the situations a cryostat bath was used to keep a constant temperature at 40ºC in the place that worked as condenser to simulate the CPL conditions. However it failed in maintain constant the temperatures in the condensation zone of heat tube. All the tests for this heat pipe design showed temperatures above 40ºC at the condenser.

For application in PEMFC whose optimum operating temperature is 70-80° C, it is necessary to have four heat pipes in series for dissipating a total 20W heat generated. The maximum heat dissipated in this case is 5W for each heat pipe.

a)



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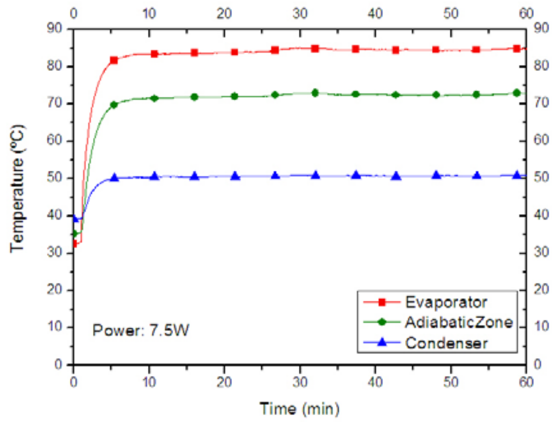

Figure 12. Temperature versus time in second heat pipe design: a) power applied 5W and b) 7.5W.

Figure 13 shows the test with different power applied in levels for the conventional heat pipe. The test presents good results for the heat pipe under non-static power application. The heat flux dissipated by this heat pipe design is about 0.37 W/cm^2.

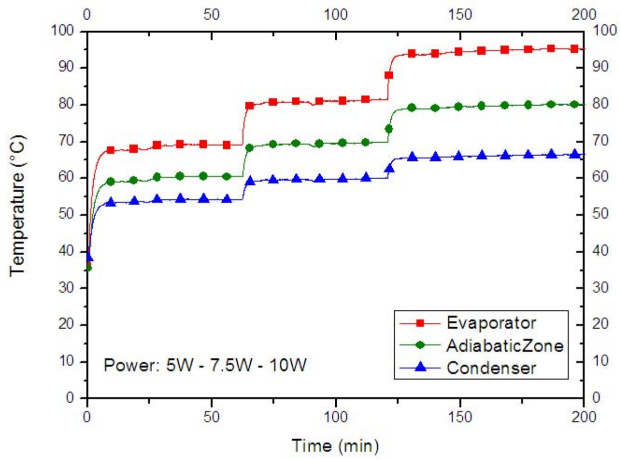

Figure 13. Power in different and successive applications in conventional heat pipe.

Figure 14 presents the results for the heat pipe assisted by thermosyphon. In this case, the condenser temperature is maintained constant after start-up. It is necessary for a PEMFC cooling to have two heat pipes in series for dissipating a total 20W heat generated i.e., for power dissipated less than 10W for each heat pipe. In Fig. 14.a. and 14.b. the temperature were measured by the thermocouples 2, 5 and 6 for the evaporator, condenser bottom and condenser top, respectively. Fig 11 indicates the position of each thermocouple in this experiment. The heat flux dissipated by the heat pipe assisted by thermosyphon is about 0.21 W/cm^2.

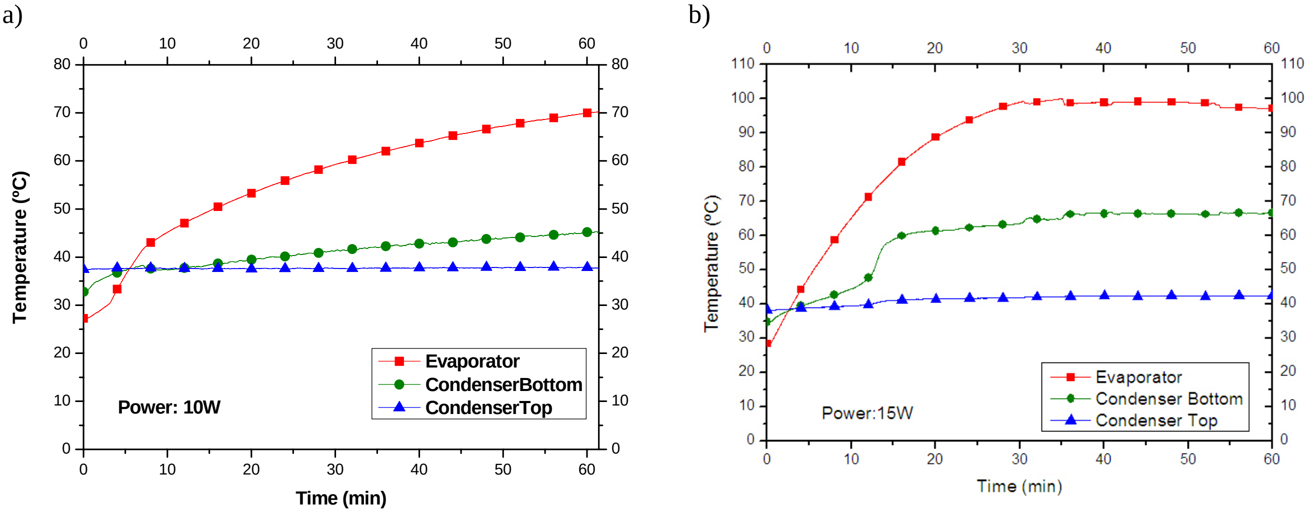

Figure 14. Temperature versus time in heat pipe assisted by thermosyphon: a) power applied 10W and b) 15W.

5. CONCLUSION

The conventional heat pipe has a quick start-up, constant and homogeneous evaporator temperature and a small outside diameter.

Comparing with the conventional heat pipe, the heat pipe assisted by thermosyphon has a longer start-up and has a bigger outside diameter. In spite of the heat pipe assisted by thermosyphon presents lower heat flux dissipation, it is necessary less number of these heat pipes for dissipating the 20W generated by a single fuel cell. In addition, it presents a better coupling with the CPL. For these reasons the integrated cooling system will be make with the "L" shape heat pipe design.

The results presented in this paper are preliminary. Nevertheless, with the preliminary results, heat pipes present as promising alternatives in application for an efficient cooling system for PEMFC.

For future research will be developed an integration between heat pipes and CPL for the tests in PEMFC thermal control.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Berti, L.F., Rambo, C.R., Reimbrecht, E.G., Bazzo, E., Hotza, D., 2006. "Manufacturing and Characterization of Ceramic Wick Structures for Capillary Pumped Loop", 17th CBECIMat (Congresso Brasileiro de Engenharia e Ciência dos Materiais), Paraná, Brazil, pp. 102-104 (in Portuguese).

Faghri, A., 2005a. "Integrated Bipolar Plate Heat Pipe for Fuel Cell Stacks", U.S. Patent Pub. No. 2005/0037253.

Faghri, A., 2005b. "Micro Heat Pipe Embedded Bipolar Plate for Fuel Cell Stacks", U.S. Patent Pub. No. 2005/0026015

Ghenciu, A. F., 2002. "Review of Fuel Processing Catalysts for Hydrogen Production in PEM Fuel Cell Systems", Current Opinion in Solid State and Material Science, Vol. 6, pp. 389-399.

Kandlikar, S.G., Lu, Z., 2009. "Thermal Management Issues in a PEMFC Stack – A Brief Review of Current Status", Applied Thermal Engineering, Vol.29, No. 7, pp. 1276-1280.

Miyake, R.G., Bazzo, E., 2006. “Experimental Analysis of a PEM Fuel Cell 15W”, ENCIT 2006 - 11th Brazilian Congress of Thermal Sciences and Engineering, Vol.1, Paraná, Brazil, pp. 41-44 (in Portuguese).

Park,Y.H., Caton, J.A.,2008. “Development of a PEM Stack and Performance Analysis Including the Effects of Water Content in the Membrane and Cooling Method”, Journal of Power Sources, Vol. 50, pp. 1255-1262.

Rullière, R., Lefèvre, F., Lallemand, M., 2007. “Prediction of the Maximum Heat Transfer Capability of Two-Phase Heat Spreaders – Experimental Validation”, International Journal of Heat and Mass Transfer, Vol. 179, pp. 584-591.

Rullière, R., Lefèvre, F., Lallemand, M., Ayel, V., Burban, G. Romestant, C., Alexandre, A., Fourcade, H., Dutour, S., Joly, J., 2007. “Experimental Study of Two-Phase Heat Spreaders for PEMFC Cooling Applications”, 14th International Heat Pipe Conference, Session 06, Santa Catarina, Brazil.

Steidel, P.S., 2005. “Theoretical and Experimental Analysis of a PEM Fuel Cell and Perspectives of Application in Distributed Generation Systems”, Thesis Master in Mechanical Engineering – Master degree in Mechanical Engineering, Santa Catarina, Brazil(in Portuguese).

Vasiliev,L., Vasiliev Jr.,L., 2008. “Mini-Micro Fuel Cells”, Springer Netherlands Publisher, pp. 117-124.

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