A COMBINED CAPILLARY COOLING SYSTEM FOR COOLING FUEL CELLS

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Abstract. *The operation temperature control has an important influence over the PEMFC (Proton Exchange Membrane Fuel Cell) performance. A two-phase heat transfer system is proposed as an alternative for cooling and thermal control of PEMFC. The proposed system consists of a CPL (Capillary Pumped Loop) connected to a set of constant conductance heat pipes. 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 CPL and deionized water for the heat pipes. Experimental results of three ¼ inch stainless steel outlet diameter heats pipes and one CPL have been carried out and presented in this paper. Further experiments are planned coupling the proposed cooling system to a module which simulates the fuel cell.*

Keywords*: Cooling capillary system, PEM fuel cell, CPL, Heat pipe.*

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.

A fuel cell is composed by an electrolyte which transports ions between two electrodes. Hydrogen enters in the anode while the oxygen or air enters inside cathode. In PEMFC the electrolyte is a proton conducting membrane that transports de H^+ from the anode to cathode. In the cathode, there is an exothermic reaction between $2H^+$ and ½ O_2 which produces water. The electrons flow through an external circuit generating continuous current, "Fig. 1.a". The flowchart of reactants and products in a PEMFC is presented in "Fig. 1.b".

a) b)

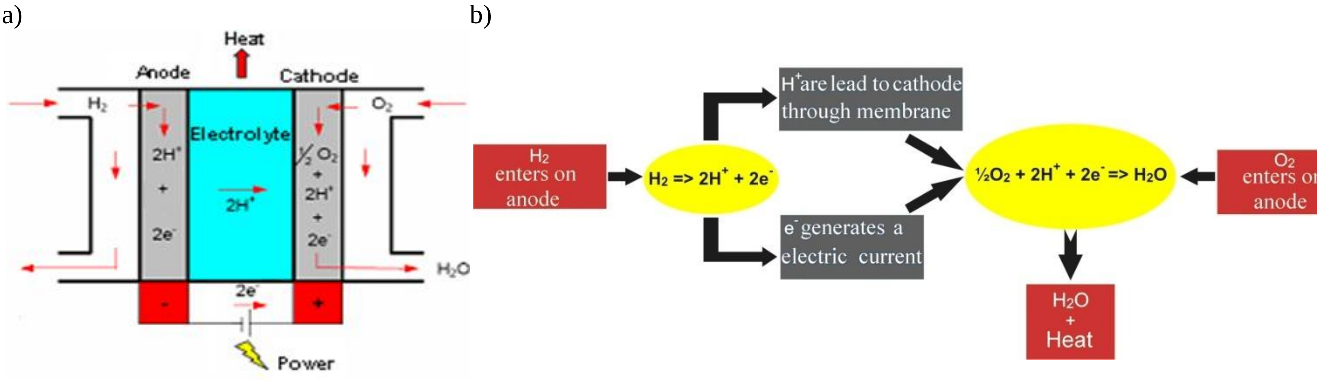

Figure 1. a).Operation scheme of PEMFC and b) Flowchart of reactants and products in a PEMFC.

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. In order to make the PEMFC technology available and affordable it is required to develop an efficient cooling system with low energy consumption.

The most popular cooling systems nowadays are heat transfer monophasic systems, generally with water or air.

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 (Rullière., 2007). 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. 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. (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 another one is the flat heat pipes integrated into a bipolar plate.

Vasiliev (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 present tests for validation.

Joung (2007) presented a LHP that shows potential for the thermal control of a PEMFC. They designed and adopted a planar bifacial wick structure for the LHP with thermo contact surfaces with an active area of 25 cm^2. The work fluid is methyl alcohol and the capillary structure is made of sintered stainless steel with pore size of 2 mm and porosity of 34%. For the range of power applied 10 – 30 W the operating temperature of LHP is lower than 85°C for the horizontal position. In theory this is acceptable results for a PEMFC thermal cooling. However, they did not propose a coupled way between fuel cell and the cooling system.

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 capillaries systems proposed heat pipes operating in series coupled into bipolar plates are associated to a CPL (Capillary Pumped Loop) for PEMFC effective thermal control. The three heat pipes and the CPL were tested separated without association because the module that simulates the fuel cell is in construction.

Heat pipes are two-phase heat transfer systems used mainly in 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 changes phase from liquid to vapor. The vapor goes to the condenser, heat exchanging and returns 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”.

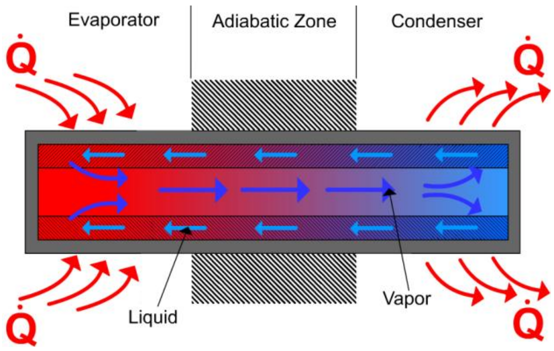

Figure 2. A heat pipe scheme indicating the evaporator, adiabatic zone and condenser area.

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 vapor lines. And it has a reservoir for controlling the phase change temperature in the evaporator. A scheme of CPL is presented in “Fig.3”.

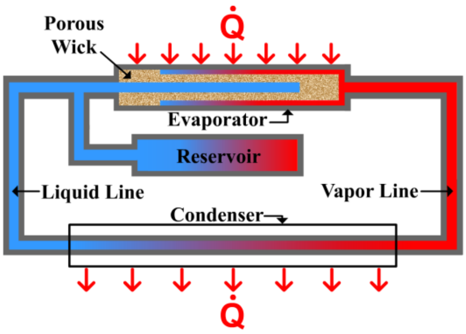

Figure 3. Capillary Pumped Loop (CPL).

2. EXPERIMENTAL SETUP

An experimental apparatus simulates a PEMFC allowing the integration of cooling and thermal control systems. The fuel cell module is based on an existing 200 W Electrocell® fuel cell in operation at LabCET/UFSC. This fuel cell is a stack composed for 10 unit cells. In this work the proposed module simulates a single cell. The module is composed by one 20 W skin heater between a graphite plate and one thermal insulator plate as shown in “Fig. 4”. 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. For application in this work, three heat pipes for dissipating a total 20 W are required.

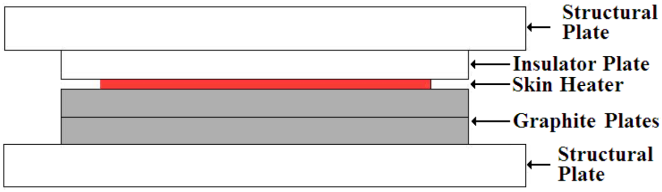

Figure 4. Fuel cell module.

In “Fig. 5” is presented the proposed integrated cooling system. It shows heat pipes inserted in two graphite plates for transporting heat from fuel cell to CPL. The condensation zones of the heat pipes corresponds to the evaporator zone of CPL. The reasons for using CPL as condenser is the low energy consumption and mainly because it allows control of PEMFC temperature.

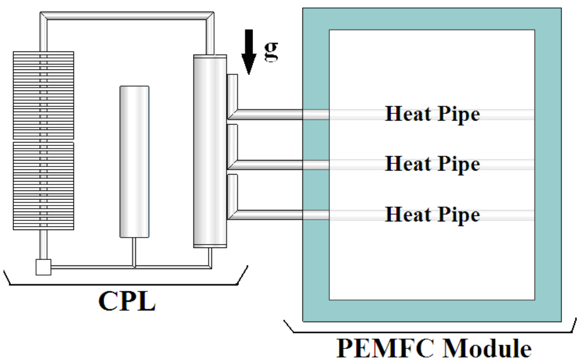

Figure 5. Integrated cooling system.

In this case, the heat pipe is assisted by thermosyphon. This “L” shaped design was proposed to increase the heat transfer area and also allow a better connection between the heat pipes and the CPL.

The heat pipes consist of stainless steel (316L) seamless, with 6.35 mm outside diameter and 0.89 mm wall thickness. The total horizontal length is 170 mm. The evaporator has 120 mm length and adiabatic region 44 mm length. The vertical zone has 39 mm and it works as a condenser. 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. Two stainless steel mesh layers are used as the capillary structure. The Mesh number of the wick is 100. The working fluid is deionized water. The “Fig. 6.a” shows the heat pipe design and “Fig.6.b” shows the vapor and liquid channel in a cross section view in the evaporator area. A particularity of a heat pipe used in a fuel cell is to have a bigger evaporator length compared to condenser length. All the zones are insulated with an expanded polymer commercially available as Polipex™.

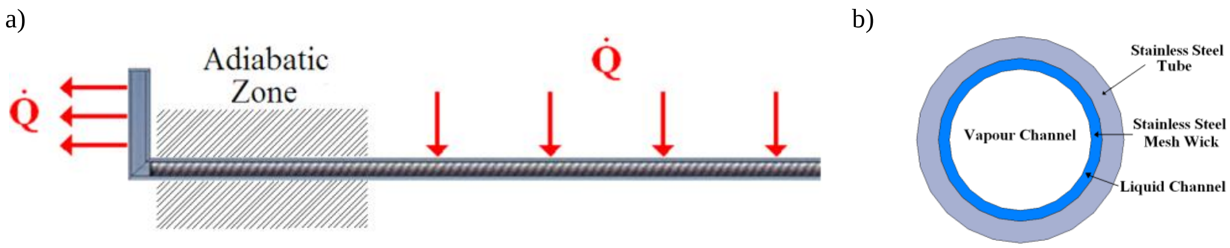

Figure 6. Heat pipe assisted by thermosyphon: a) lateral view; b) evaporator section view.

The CPL has a unique capillary evaporator, one reservoir, one condenser and liquid and vapor lines. The CPL working fluid is acetone (99.5%). A porous ceramic wick with 50% porosity and pores size less than 10 µm is used as capillary structure. The dimensions of capillary structure are: diameter 20 mm and length 114 mm. The vapor channels were machined on the outside surface of porous wick, “Fig. 7.a”. Inside the porous wick a liquid channel was drilled, “Fig. 7.b”. The ceramic porous wick is inserted inside a stainless steel envelope of 20 mm inner diameter.

The ceramic porous wick has been manufactured in LabCET/UFSC by slip casting and sintering using a technique as proposed by Berti (2006).

a) b)

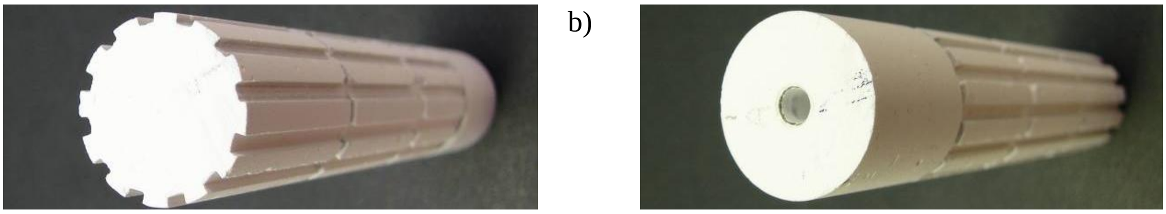

Figure 7. Porous ceramic structure of CPL a) vapor channels and b) liquid channel.

The liquid and vapor lines consist of stainless steel (316L) seamless tubing with outside diameter of 4.76 mm for the vapor line and 2.10 mm for the liquid line. The condenser was assembled with fins and two fans to force air flow, “Fig. 8”. The reservoir is designed to contain at least 120% of the working fluid enough to fill the entire system. It is made of stainless steel with outside diameter of 19.05 mm. The evaporator and the reservoir are insulated with Polipex™.

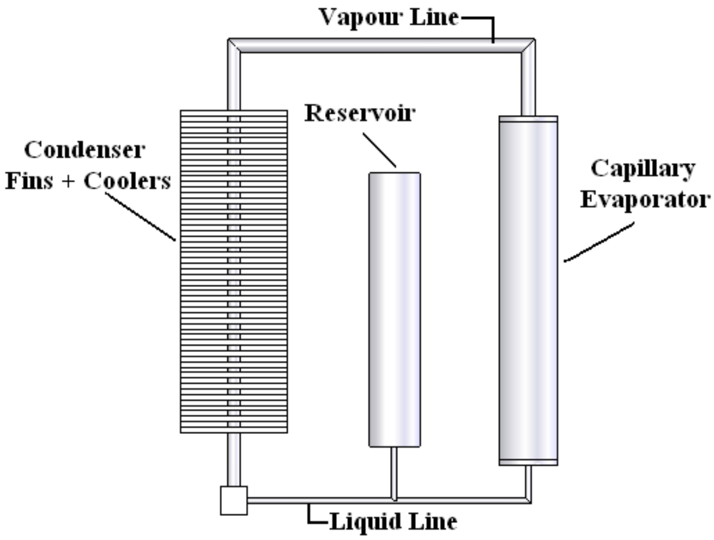

Figure 8. Scheme of the CPL.

Before the heat pipes manufacturing, all material undergoes to a standard ultrasonic cleaning process, in this case, the Odontobras 2840D Ultrasonic Cleaner model. The wick mesh was modified for a cylindrical configuration in order to cover the inner surface of the tube. Finally the heat pipes were pumped down using an E2M2 - BOC Edwards vacuum pump and loaded with water as the working fluid. The fill process has been really critical, because the small quantity to be charged (less than 1 ml). Furthermore non-condensable gas is prejudicial for the performance. Thermocouples type T from Omega™ were placed along the heat pipes as shown in “Fig.9”. An Agilent acquisition system, model 34970A with 20 channels and a computer were used for temperature acquisition. The system power supply used was an Agilent N6700B and the resistor is a skin heater. A Lauda cryostat model E200 has been used to remove the heat of the condenser.

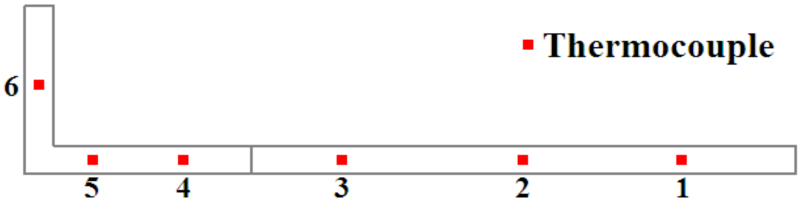

Figure 9. Thermocouples position in heat pipe.

Two scenarios ware considered for testing: (a) A constant power input of 7.5 W; (b) Power inputs of 5, 7.5 and 10 W, during a time of 15 minutes each.

For the CPL manufacturing, only the metal pieces undergo to the standard ultrasonic cleaning process. Here a special care has been given to the ceramic evaporator manufacturing due to its fragile mechanical properties. The CPL was pumped down and loaded with acetone as the working fluid. The CPL was filled with somewhat about 68 % of its total volume. Thermocouples type T from Omega™ were placed along the CPL, as showed in "Fig.10". The maximum error in temperature measurement is 1.6 K and in power applied is 0.2 W. The condenser was assembled by two standard 12V DC coolers for CPU microprocessor by Microbon™.

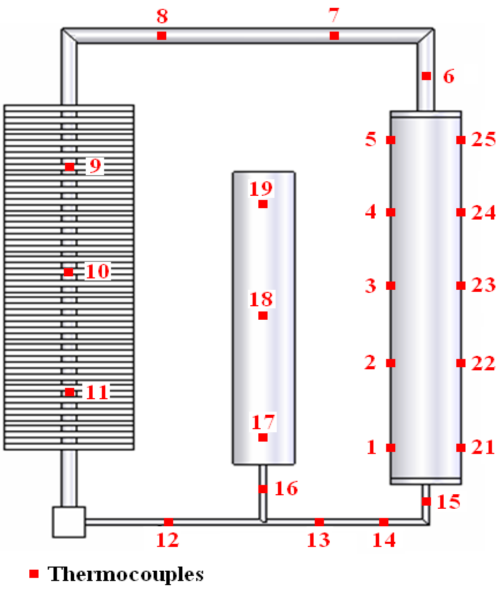

Figure 10. Thermocouples location along the CPL

Two scenarios ware considered for testing: (a) A constant power input of 20 W; (b) Power inputs of 10, 15, 20, 25 and 30 W during a time of 30 minutes each. The reservoir temperature was set at 40°C for the first test and 45°C for the second one.

3. RESULTS AND DISCUSSIONS

In this paper only the results concerning three heat pipes and one CPL are presented. The fuel cell module is still under construction. In order to simulate the expected behavior of the CPL evaporator, the cryostat bath was set at a constant temperature of 50ºC in the condenser of the three heat pipes. According to the results, the condenser area of the heat pipes was not sufficient to reject the power input in the evaporator, increasing the temperature above 50°C.

The temperature behavior concerning the first, second and third heat pipes are shown in "Fig. 11", "Fig. 12" and "Fig. 13", respectively.

a) b)

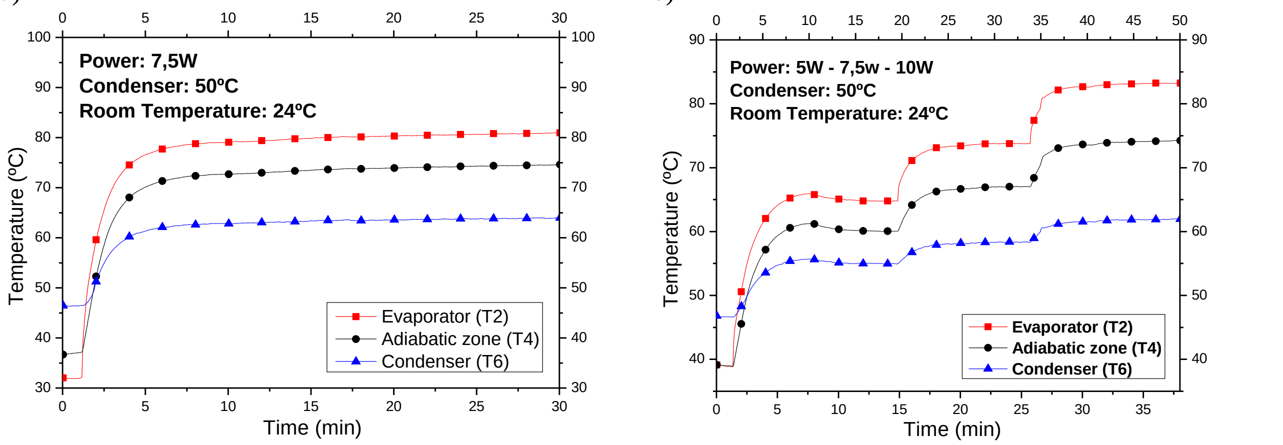

Figure 11. Temperature behavior in the first heat pipe: a) 7.5 W; b) 5, 7.5 and 10 W.

a) b)

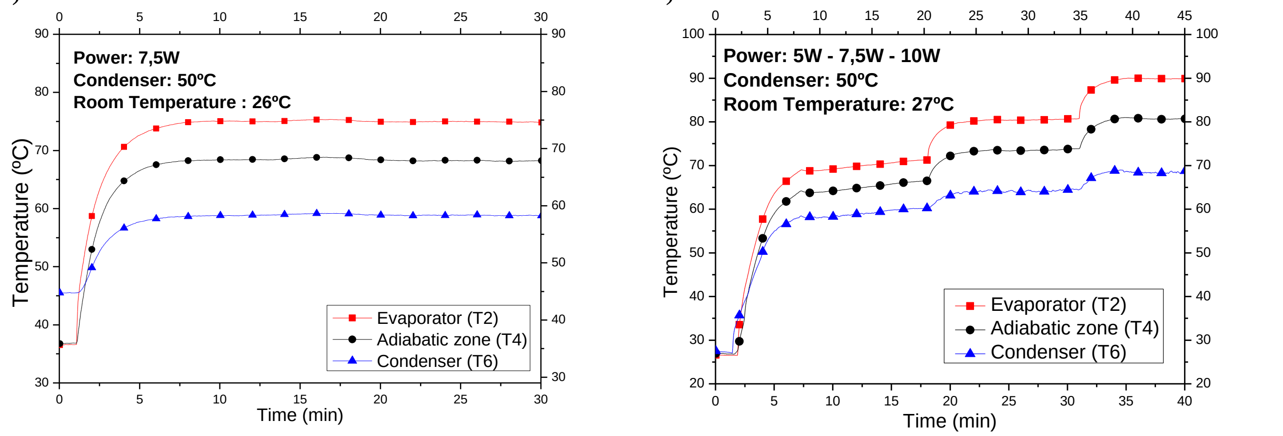

Figure 12. Temperature behavior in the second heat pipe: a) 7.5 W; b) 5, 7.5 and 10 W.

In all tests the startup takes more time than conventional heat pipes. The temperatures were measured using the thermocouples 2, 4 and 6 for the evaporator, adiabatic zone and condenser, respectively, as shown in “Fig. 9”.

The condenser temperatures were measured above the desired 50ºC, in the range of 55 - 65ºC. On the other side, the evaporator temperature were measured and kept around the desired optimum range of 70 – 90ºC. The room temperatures were measured in the range of 24 – 27ºC. The corresponding thermal resistances were calculated equal to 2.2, 2.2 and 2.5 °C/W, for the first, second and the third heat pipe, respectively.

a) b)

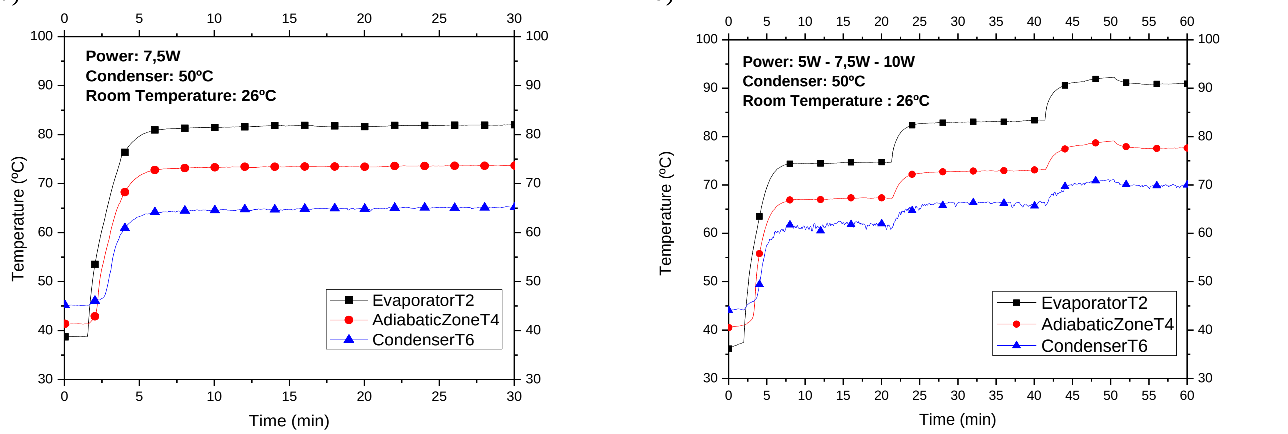

Figure 13. Temperature behavior in third heat pipe, a) 7.5 W; b) 5, 7.5, 10 and 12.5W.

The thermal behavior concerning the CPL is presented in “Fig. 14”, where the first graph shows a constant power input of 20 W and 40ºC at the reservoir and the second graph shows power inputs of 10, 15, 20, 25 and 30 W for reservoir temperature set at 45ºC. The temperatures were measured using the thermocouples 1, 3 and 5 for the evaporator, 6 for the outlet evaporator, 10 for the condenser 2, 15 for the inlet evaporator and 18 for the reservoir 2 (see “Fig. 10”). All the tests were successful. The startup took less than 10 minutes. Although well successful it was observed some instability during the tests, probably related to the steam flow and consequently the fluid circulation along the loop. It is noticeable that while there are instabilities, the temperature of the thermocouple 5 is lower than in other thermocouples of the evaporator. It could happen due to initial restrictions to steam circulation. Further experiments are planned in order to better understand this behavior. In general CPL seems to be reliable, but the temperatures are possible too high for fuel cell application. In the heat pipes tests, the condenser bath was set at 50°C, but not even the heat pipe condenser as well as the CPL evaporator operates in at the desired temperature.

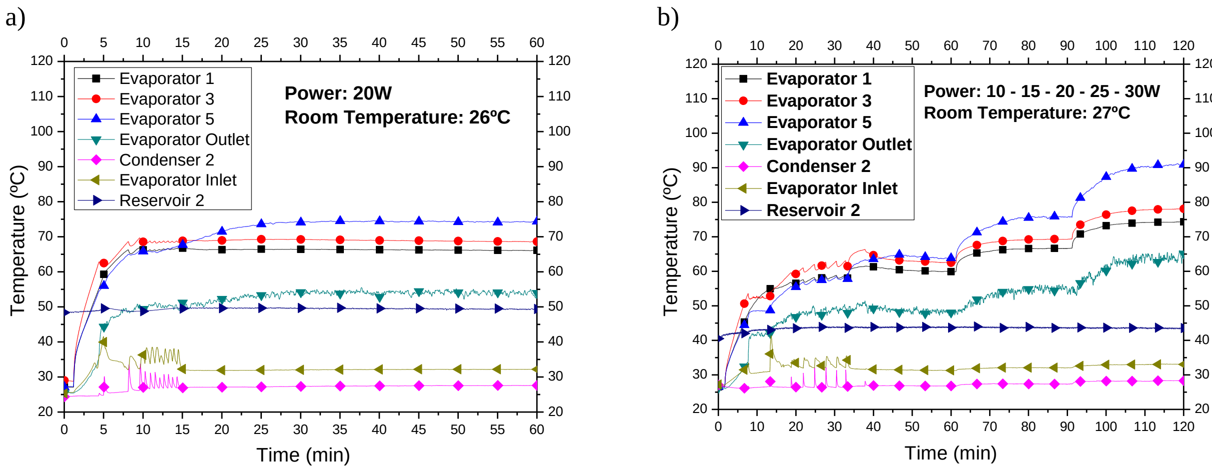

Figure 14. Thermal behavior of the CPL: a) Power input 20 W; b) Power inputs: 10, 15, 20, 25 and 30W

4. CONCLUSION

A two-phase heat transfer system consisting of three heat pipes assisted by thermosyphon and one CPL has been proposed as an alternative for cooling and thermal control of PEMFC. Heat pipes present a promising alternative for an efficient cooling system for PEMFC application. Preliminary tests were performed considering the heat pipes and the CPL for deionized water and acetone as the working fluids, respectively.

All the tests were considered successful, attending the required heat dissipation and the optimum temperature operation for the fuel cells. However, further improvements are required in order to reach the desired temperature at the heat pipes condenser and the CPL evaporator.

Further experiments are planned coupling the proposed cooling system to a module which simulates the fuel cell. Also further studies are planned considering the application of variable conductance heat pipes. For future research will be developed integration between heat pipes and CPL for the tests in PEMFC thermal control.

5. ACKNOWLEDGEMENTS

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