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Research paper

# Flat heat pipes for potential application in fuel cell cooling

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## HIGHLIGHTS

- Flat heat pipes as reliable alternatives for PEM fuel cells cooling.
- The use of microgrooves for capillary pumping of the working fluid.
- A useful tool for the design of PEMFC cooling systems.
- Theoretical and experimental results of a 12 W flat heat pipe.
- Heat pipes arrangement to ensure a suitable PEMFC operation.

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## ABSTRACT

A thin flat heat pipe is proposed as a reliable alternative for Proton Exchange Membrane Fuel Cell (PEMFC) cooling. The flat heat pipe includes a sealed casing with two microgrooves to provide the required capillary pumping of the working fluid. Deionized water was used as the working fluid. In this work, a numerical and experimental analysis is presented. A heat transfer model is proposed to evaluate the capillary limit, the operating temperature and the required working fluid inventory. The main goal is to cool the PEM fuel cells to ensure a suitable operation in the required temperature range between 70 and 90 °C with small thermal gradient. The proposed control system consists of a set of stainless steel flat heat pipes, with 100 mm length, assembled in parallel. The tests showed that proposed heat pipe was able to dissipate up to 12 W, corresponding to 1.8 W/cm$^2$ at evaporator section, ensuring a suitable PEMFC operation.

## 1. Introduction

The technical feasibility of proton exchange membrane fuel cell (PEMFC) still relies on technology solutions to solve problems associated with their operating limits. PEM fuel cells have a strong appeal in the use of automobiles, portable devices and even distributed electricity generation.

Fuel cells work through an electrochemical process, converting the chemical energy of a substance into electrical energy. The PEM fuel cell is, basically, composed of two electrodes (anode and cathode) separated by an electrolyte (polymer membrane), which form the membrane electrode assembly (MEA). On the anode side hydrogen is supplied and dissociated, then the ions $H^+$ move through the membrane toward the cathode. Electrons flow externally through an electrical circuit up to the cathode side, where they recombine with $H^+$ ions and $O_2$ to form $H_2O$ as the reaction product. In order to avoid problems related to the operation, the temperature needs to be in the range of 70–90 °C, once an overheating leads to the membrane drying and corresponding collapse of the fuel cell.

An existing 200 W Electrocell fuel cell in operation at LabCET was taken as reference in this work. Ten units 20 W fuel cells are combined to form the fuel cell stack. In this work, the efficiency was considered 50%. Therefore 20 W is the thermal power to be absorbed by the heat pipes in each unit cell. The stack dimensions are 55 × 140 × 170 mm.

The commercial PEMFC cooling has been usually performed by forced convection of air or water. However, this technique can generate high thermal gradient inside the fuel cell, especially at high loads. Experiments have shown differences up to 23 °C between the inlet and the outlet of a cooling channel and up to 10 °C between channels [1]. One way to increase the performance of the cell is by reducing the temperature difference between the inlet and outlet of the cooling channels. Basically, this is achieved by managing the cooling fluid flow velocity [2–4]. The cooling

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**Nomenclature**

| | |
|---|---|
| $a_0 - a_{10}$ | constants, Eq. (B.5) [−] |
| $A$ | cross-sectional area [m$^2$] |
| $C_1$, $C_2$ | inner heat pipe dimensions [m] |
| $d$ | diameter [m] |
| $d_*$ | dimensionless diameter [−] |
| $D_1$, $D_2$ | outer heat pipe dimensions [m] |
| $f$ | friction factor [−] |
| $FR$ | filling ratio [%] |
| $H$ | height [m] |
| $h_{lv}$ | latent heat of vaporization [kJ/kg] |
| $k$ | thermal conductivity [W/(m K)] |
| $L$ | length [m] |
| $L_x$ | half-length of active area [m] |
| $m$ | mass [kg] |
| $\dot{m}$ | mass flow rate [kg/s] |
| $n$ | fluid control volumes number [−] |
| $N_*$ | dimensionless area [−] |
| $P$ | pressure [Pa] |
| $p$ | perimeter [m] |
| $\dot{q}$ | power [W] |
| $\dot{q}_{el}$ | electric power [W] |
| $\dot{q}_{th}$ | thermal power [W] |
| $q''$ | heat flux [W/m$^2$] |
| $r$ | radius [m] |
| $R_{th}$ | thermal resistance [K/W] |
| $Re$ | Reynolds number [−] |
| $T$ | temperature [°C] |
| $t$ | wall thickness [m] |
| $u$ | velocity [m/s] |
| $V$ | volume [m$^3$] |
| $Y$ | half the spacing between heat pipes [m] |
| $Z$ | flow plates assembly thickness [m] |
| $Z_1$ | cathode side flow plate thickness [m] |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | groove opening angle [°] |
| $\beta$ | auxiliary angle [°] |
| $\eta$ | efficiency [%] |
| $\mu$ | dynamic viscosity [Pa s] |
| $\psi$ | parameter for pressure drop [m$^2$] |
| $\rho$ | density [kg/m$^3$] |
| $\sigma$ | surface tension [N/m] |
| $\tau$ | shear stress [N/m] |
| $\theta$ | contact angle [°] |
| $\varepsilon$ | convergence criterion [−] |

*Subscripts*

| | |
|---|---|
| $AA$ | active area |
| $C$ | condenser |
| $E$ | evaporator |
| $f$ | fluid |
| $F$ | fraction |
| $h$ | hydraulic |
| $HP$ | heat pipe |
| $ins$ | inscribed |
| $L$ | liquid |
| $max$ | maximum |
| $min$ | minimum |
| $out$ | outside |
| $sat$ | saturation |
| $T$ | total |
| $th$ | thermal |
| $V$ | vapour |
| $w$ | wall |

channels may be arranged in different ways, so the cell performance is maximized through the cells with higher temperature uniformity [5].

Some designs have been proposed as alternatives for conventional systems. Vasiliev and Vasiliev Jr. [6] presented several thermal management solutions, which could be applied in fuel cells of different sizes and powers. Among the proposed systems are mini and micro heat pipes, loop heat pipes, pulsating heat pipes and sorption heat pipes. The article only introduces the ability of each system. In patents applied by Faghri [7,8] there are two settings of bipolar plates for fuel cells, which utilize the heat pipe technology for thermal control, however no results were presented.

Recently, a few papers have been presented with good results for different PEMFC thermal control ways. Joung et al. [9] proposed the use of a flat evaporator loop heat pipe (FELHP) comprising a bifacial wick. Two-phase heat spreaders (TPHS) have been proposed by Rullière et al. [10], where different TPHS types were successful tested, including with longitudinal grooves. A combined system comprising a set of heat pipes coupled to a capillary pumped loop (CPL) was proposed by Silva et al. [11], using deionized water and acetone as the working fluid for heat pipes and CPL, respectively. The preliminary results reported by Oro and Bazzo [12] demonstrated the promising application of the proposed cooling system.

Microgroove has demonstrated to be reliable to work under ground and microgravity applications as reported by Bazzo et al. [13], where results of CPLs with a circumferentially microgrooved capillary evaporator were presented using water, ammonia, acetone and freon 11 as working fluids.

A few papers have been reported referring to the mathematical models of heat pipes, including micro grooved heat pipes. Suman and Kumar [14] presented an analytical model developed for fluid flow and heat transfer applied to micro-heat pipes of polygonal shape. As study case, the proposed model was used in two heat pipes of different geometries, triangular and rectangular, showing among other parameters the corresponding liquid velocity, heat flux and capillary limit. Later, Suman [15] presented a discussion related to start-up and shutdown of a V-shaped micro-heat pipe, a detailed analysis of the fill charge and a sensitivity analysis of design parameters and properties of the working fluid on the transient operation. In this regard, as reported by other authors no experimental results were presented.

This paper presents theoretical model and also experimental results concerning the use of mini flat heat pipes as a reliable alternative for thermal control of PEM fuel cells, at the industrial viewpoint assuring technical feasibility and expecting low manufacturing cost.

## 2. Theoretical analysis

This section presents the geometric characteristics of the heat pipe under study, the fundamentals related to capillary limit, as well as simplifying assumptions and boundary conditions necessary for installation of the heat pipes in the flow plates used in PEMFC.