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Experimental investigation of pulsating heat pipe performance with regard to fuel cell cooling application

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HIGHLIGHTS

► Methanol as a working fluid outperformed both acetone and water in a pulsating heat pipe.
► Performance for the PHP peaked with methanol and a fill ratio of 45 percent fluid to total volume.
► A smaller resistance was associated with a higher power input to the system.

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ABSTRACT

A pulsating heat pipe (PHP) is a closed loop, passive heat transfer device. Its operation depends on the phase change of a working fluid within the loop. Design and performance testing of a pulsating heat pipe was conducted under conditions to simulate heat dissipation requirements of a proton exchange membrane (PEM) fuel cell stack. Integration of pulsating heat pipes within bipolar plates of the stack would eliminate the need for ancillary cooling equipment, thus also reducing parasitic losses and increasing energy output. The PHP under investigation, having dimensions of 46.80 cm long and 14.70 cm wide, was constructed from 0.3175 cm copper tube. Heat pipes effectiveness was found to be dependent upon several factors such as energy input, types of working fluid and its filling ratio. Power inputs to the evaporator side of the pulsating heat pipe varied from 80 to 180 W. Working fluids tested included acetone, methanol, and deionized water. Filling ratios between 30 and 70 percent of the total working volume were also examined. Methanol outperformed other fluids tested; with a 45 percent fluid fill ratio and a 120 W power input, the apparatus took the shortest time to reach steady state and had one of the smallest steady state temperature differences. The various conditions studied were chosen to assess the heat pipe's potential as cooling media for PEM fuel cells.

1. Introduction

The heat pipe concept was developed nearly seven decades ago, as patented by Gaugler in 1944 [1,2]. The traditional heat pipe design consists of a small diameter straight tube with a porous wick material lining the inner wall. One end serves as the evaporator with a heat input to the system while the other, the condenser, with a heat sink. Heating one end results in a fluid phase change within the tube from liquid to vapor. The other end causes condensation and the wick allows the liquid to traverse back to the evaporator section.

The oscillating, or pulsating heat pipe (PHP) was first developed by Akachi et al. in the mid-1990s based upon a similar passive two-phase fluid energy exchange [3]. Consisting of a serpentine loop design with capillary-sized passages, the PHP is evacuated, filled partially with a working fluid, and then sealed for operation. The structure is classified by two distinct sections, evaporator and condenser where thermal energy is transferred into and out of the system, respectively. When heat is applied small segments of liquid and vapor develop and then oscillate while traversing from evaporator to condenser section as seen in Fig. 1. Two-phase fluid transport in a capillary tube combined with conjugate heat transfer results in a very complex and dynamic system involving surface tension, shear stress, gravity and pressure forces [4]. Oscillation and some circulation within the device are driven by a pressure gradient induced by the temperature gradient.

Two general structures of pulsating heat pipe have emerged; the flat plate design has machined channels in a metal substrate [5,6], while the tube design consists of capillary-sized diameter tubes. PHPs also have several different configuration options: an open

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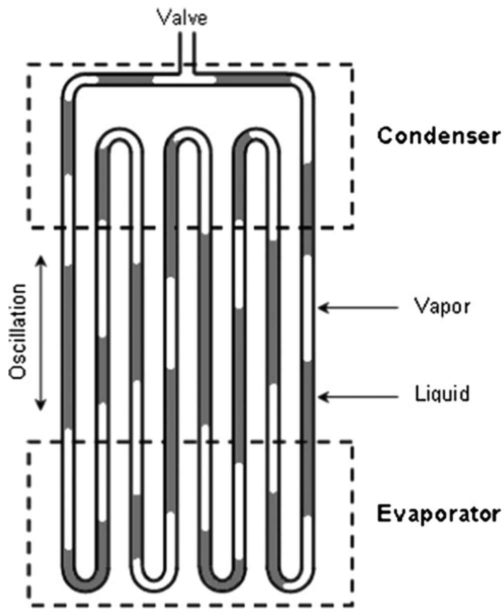

Fig. 1. Flow pattern for a pulsating heat pipe.

loop having separately sealed ends, a closed loop with connected ends and no termination point, or a closed loop variation having one or several check valves to ensure continuous flow in one direction [7,8]. A closed loop configuration has been proven more effective because termination points on open loop hinder, and can prevent vapor/liquid movement within the loop [9,10].

Numerous experimental studies have been conducted to assess several aspects of PHPs such as working fluid, fluid fill ratio, tube diameter, number of turns, heat input and removal, and operating orientation [7–9,11–20]. Ethanol, water, and refrigerant such as R-123 are commonly studied working fluids. Khandekar et al. [12] studied effects of fill ratio and power input for the three fluids. Other fluids have been investigated such as nanofluids [14], acetone, and methanol, among others [15]. Most other working fluid studies involving methanol have studied an open loop design or utilized a single operating point and focused on other parameters rather than effect of input conditions on performance. The work by Tong et al. [21], for example, used methanol at a constant 60% fill ratio and 50 W power input to examine flow visualization. Orientation-dependence studies such as the work by Dolgirev et al. [17] have determined that an evaporator section below the condenser is the most favorable alignment configuration.

The pulsating heat pipe has become a popular topic of interest because of its simple and adaptable design (loop structure, tube diameter, number of turns), combined with its passive heat transfer capabilities. Aside from cooling electronic components, it also has potential as a possible method of cooling Proton Exchange Membrane (PEM) fuel cells. In PEM fuel cells, the electro-chemical process of converting hydrogen potential into an electrical current is nearly 50% efficient and generates the other 50% as waste heat. Some of this heat is removed with the oxidant and byproducts, but not enough to prevent overheating, reductions in efficiency, and damage to the cell membrane. Therefore an alternative cooling method must be implemented to remove the waste heat.

For a fuel cell stack composed of several cells, heat is generated within each cell; this results in a large surface area which must be cooled. An external cooling unit must be employed to prevent overheating and maintain a stack temperature around 80 °C. As discussed by Barbir [22], typical existing methods commonly involve a manifold or channels within bipolar plates, which surround the membrane of the cell, and a cooling fluid such as water, air, or an anti-freeze. This method can be effective, however typically requires a pump to circulate the fluid, resulting in a parasitic loss from the cell. This method also risks cross-contaminating the cooling fluid with the reactant or oxidant fed to the cell. To alleviate the contamination issue natural convection or a fin array may be utilized; however, these methods are less effective as they would be located external to the cell and heat source.

Faghri et al. addressed the concept of using standard heat pipes within fuel cells by utilizing the bipolar plate [22–24]. A solution would be to implement a closed loop pulsating heat pipe between bipolar plates through the use of channels in the back side. Placing the evaporator section within the fuel cell and extending the condenser section upward out of the cell then allow for forced convection heat removal. This proposed solution would require no pump and results in no cell contamination since the pulsating heat pipe has a closed loop design. A PHP would be more effective than natural convection and could be implemented directly at the heat source versus a fin array attached outside of a cell stack. Some have studied the idea of implementing conventional heat pipes within fuel cells, and Vasiliev [25] mentioned the idea of using a PHP, but did not study the idea extensively.

The application of pulsating heat pipes in fuel cells is an advantageous concept. However fundamental understanding needs further development before practical implementation becomes a reality [24]. The objective of this work is twofold: to evaluate methanol as a working fluid for a PHP under various fill ratios and operating conditions compared to other fluids as well as examine PHP performance under conditions to simulate fuel cell operation. This research is the first step to examining the potential of PHPs for fuel cell cooling application. Important criteria for evaluation as a viable fuel cell cooling mechanism include evaporator temperature and steady state performance. Other performance metrics consist of time to reach steady state and evaporator-condenser temperature difference.

2. Experimental design

Pulsating heat pipes have either an open loop, or closed loop design, the latter was selected to be explored. The pulsating heat pipe concept has several design parameters such as size of the PHP, number of turns, channel size, material, working fluid, and fill ratio.

2.1. Heat pipe design

The pulsating heat pipe studied was constructed from copper tubing (alloy 122), having an outer diameter of 0.3175 cm and inner diameter of 0.1651 cm. The material was chosen because of its thermal conductance, as well as malleability for constructing the serpentine design. The tube diameter was chosen based on the limited sizes available, and meets the dimension constraint of Eq. (1) suggested by Akachi et al. [3] for critical diameter.

$$D_{\mathrm{crit}} = Bo\sqrt{\frac{\sigma}{g(\rho_{\mathrm{l}} - \rho_{\mathrm{v}})}} \quad (1)$$

Based on gravitational acceleration (g), surface tension (σ), liquid and vapor densities (ρ_{l} and ρ_{v}), Bond number (Bo) relates surface tension force to gravitational force, which has been used for numerous studies, but variation exists with relation to what Bond number should be used for PHP calculations. Khandekar et al. [4] acknowledged the issue and mentioned relevant parameters from other studies such as the Laplace constant and Confinement number for defining channel size since Eq. (1) is not a universally accepted criteria. They also noted that each classification accounts