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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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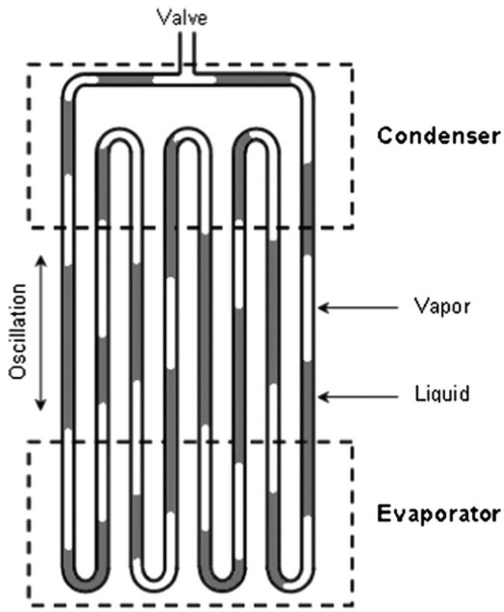

Fig. 1. Flow pattern for a pulsating heat pipe.

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.

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

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 for channel size, surface tension and fluid density effects on flow within these devices. Some studies have referenced a *Bo* number of 1.84 [14,19], others have used a value of 2 for diameter calculations [3,5,15,16] while others examined a range of *Bo* numbers [8].

For this study a *Bo* of 2 was used, as Akachi et al. [3] originally suggested. The critical diameter was calculated for each of the three fluids tested. Calculations were also made for various temperatures since the PHP was exposed to a range from ambient to 120 °C. The smallest critical diameter calculated for all conditions was found to be 0.2592 cm, which is still larger than the 0.1651 cm inner diameter of the copper tube used.

The design consists of fifteen total turns, 0.6350 cm in diameter, and a size of 46.80 cm long and 14.70 cm wide, as seen in Fig. 2. The width was predetermined by the chosen number of turns and turn radius. The height was chosen such that each section: evaporator, adiabatic, condenser; was square, and equal to one another, similar to the designs of Ma et al. [14] and Dmitrin and Maidanik [20]. Two ports were deemed necessary: one to evacuate the loop, and the other to inject the chosen working fluid.

2.2. Testing apparatus

Procedures for testing the pulsating heat pipe require that the system has an evaporator section for heat input and a condenser section for heat removal. With the heat pipe in a vertical orientation, the evaporator section was chosen as the lower one-third of the system. In order to achieve a uniform heat input to the section, an oil bath was constructed to suspend the section into thermally conductive XCEL THERM® oil, which was heated using four individual cartridge heaters controlled by a power regulator. The tank housing the oil was constructed from aluminum; it was then encased in a wooden box with a layer of Styrofoam™ insulation to minimize heat loss to the surroundings as seen in Fig. 3. Directly above the evaporator was an adiabatic section exposed to atmospheric conditions. Although some natural convection occurs within this section it is not a primary mode of thermal energy exchange within the system and may be considered “optional” [12,26]. For the application of interest this region will not be entirely adiabatic, however it was designated as such to distinguish temperature measurement locations. The upper third of the heat pipe, the condenser section, removed heat from the system through forced convection with a standard desktop fan placed roughly 30 cm from the section. Ambient air at approximately 21 °C was forced normal to the plane of the condenser section.

Temperature difference between the evaporator and condenser sections is a critical measurement to determine whether or not a pulsating heat pipe is functioning correctly. To obtain accurate readings, T-type thermocouples were soldered directly to the copper tubing exterior of the PHP. To ensure accuracy, a calibration test was first performed by heating a beaker of water and recording temperature readings from a bare thermocouple, a thermocouple soldered to a piece of copper tube, and a Resistance Temperature Detector (RTD). The results, verified the temperature acquisition method was accurate with a maximum temperature deviation of 2.25% relative to the RTD reading.

Three thermocouples were then soldered to each section as seen in Fig. 2. To obtain an accurate average temperature for each trial, temperature readings were taken every 5 s and were recorded using a Keithley data acquisition device and ExceLINX™ software.

For each trial the pulsating heat pipe was evacuated to the lowest attainable pressure by the vacuum pump, and then injected with a working fluid. A pressure between 12.00 and 13.33 kPa absolute (measured as 660–670 mmHg vacuum) was obtained for each trial. Before any trials were conducted however, the design

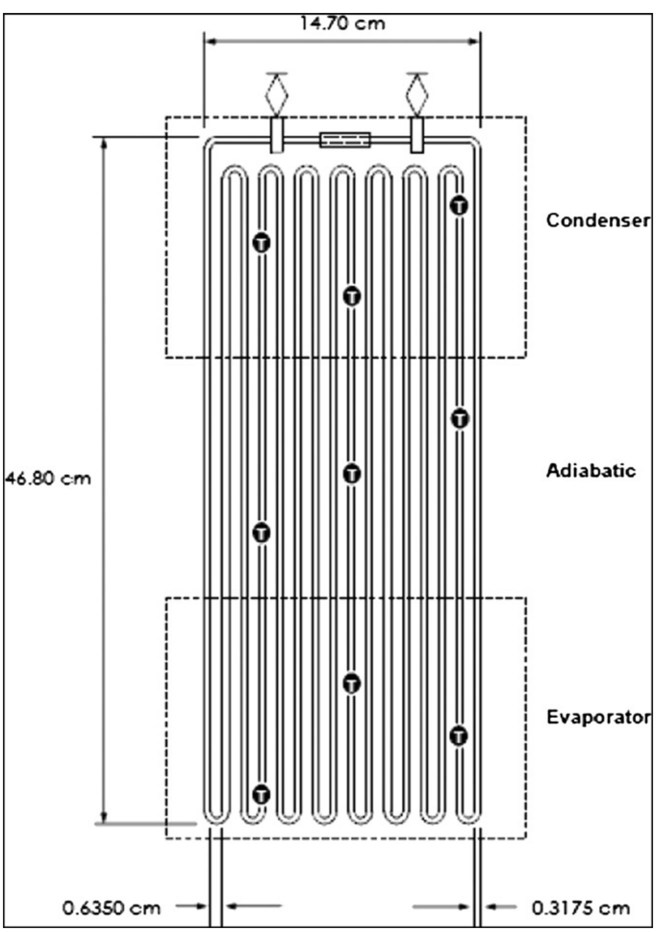

Fig. 2. Pulsating heat pipe design with thermocouple locations.

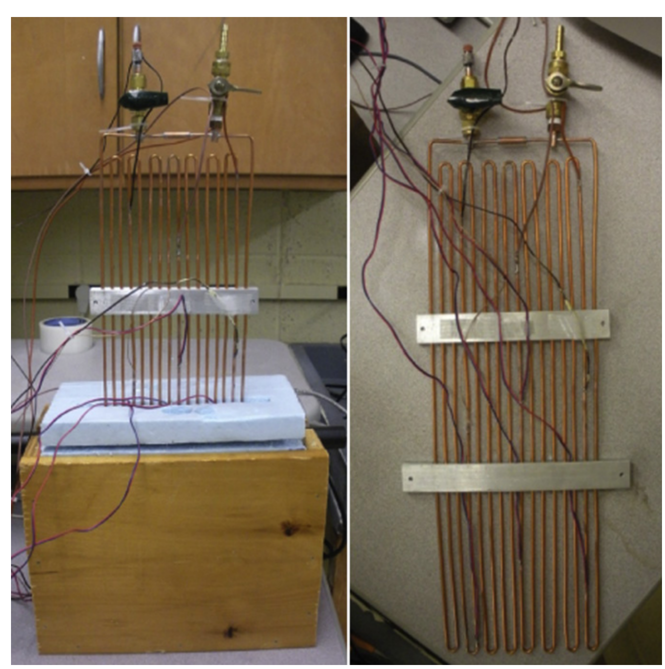

Fig. 3. Test apparatus and pulsating heat pipe.

was tested for leaks to ensure that it would hold a vacuum and reduce variations due to pressure. Constant vacuum pressure was successfully held within the sealed tube for 24 h, thus proving initial pressure would remain consistent throughout the duration of each trial. A shut-off valve was used on each port to ensure a proper seal within the tube.

Various testing procedures were conducted. Initially the heat pipe was inserted into oil at room temperature, and then supplied with a power input, as seen in Fig. 4. This method was a simulation of starting up a fuel cell from ambient conditions to ensure that the PHP would operate properly. This procedure, however, proved to be very time consuming because the initial power input was utilized towards heating the oil before it could be applied to the PHP. The system was not operating in steady state and took several minutes to an hour for the heat pipe to show signs of oscillation, as indicated by state point 1 of Fig. 4a. To avoid this issue, with an ultimate goal of exploring steady state operating conditions, the oil was then preheated to 80 °C before the heat pipe was inserted. This method proved to be very effective and was used for nearly all of the subsequent trials.

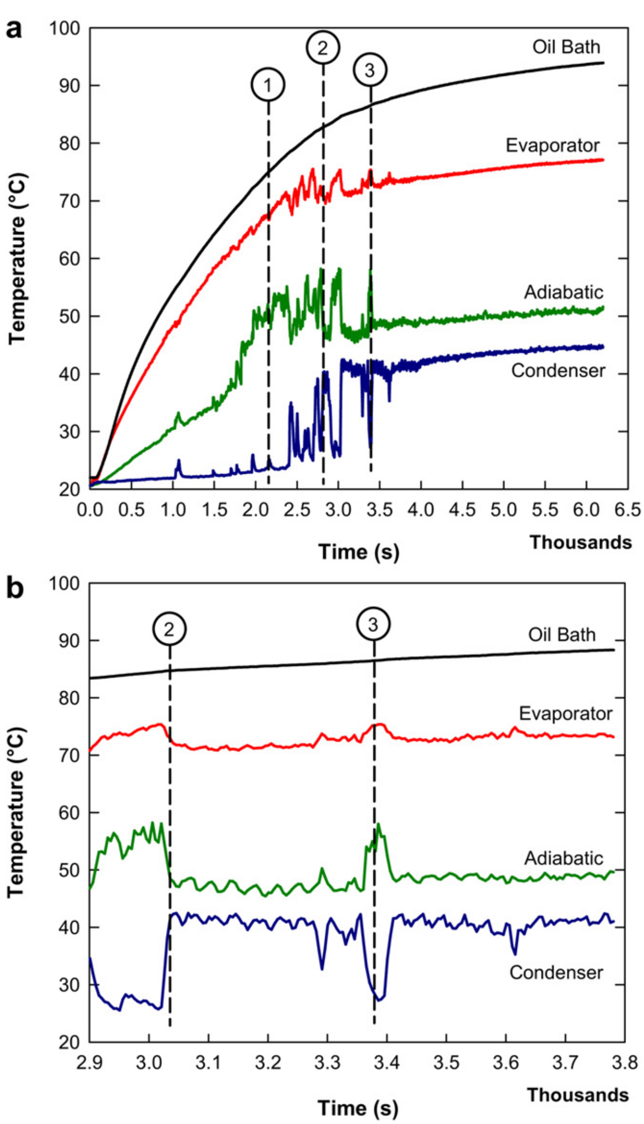

Fig. 4. Heat pipe operation – 45% methanol fluid fill ratio, 120 W power input, from ambient conditions: (a) full experimental results; (b) steady state start.

3. Results and discussion

Different variables were examined to determine their effect on performance of the pulsating heat pipe, some of which included: working fluid, filling ratio, and power input. A control trial was conducted with the PHP having a no-fluid vacuum to ensure that the observed results were a genuine result of the fluid's presence as seen in Fig. 5. Slight fluctuations of the adiabatic temperature were observed, however, the variation was less than 5 °C. The trend proceeded along a trajectory of increasing temperature and at no point during the trial did the temperature drop off as was characteristic of a properly functioning PHP. In addition, the temperatures of interest, condenser and evaporator, remained steady.

When comparing various conditions, the performance indicators included: time to reach steady state operation and average temperature difference between evaporator and condenser sections.

This temperature difference can be seen in Fig. 4a (at state point 2) once the PHP was activated and reached steady state. By expanding the section, as Fig. 4b illustrates, one can see the relationship between evaporator and condenser. State point 2 highlights the exact point where steady state was reached. Steady state was initiated at this point because each of the three sections jumped simultaneously to create the roughly 30 °C temperature difference. State point 3 of Fig. 4b represents a momentary relapse in oscillations soon after the PHP had begun steady state operation, but after that point the system was very consistent.

The preliminary evidence of a functional PHP was sufficient to justify further investigation of other fluids as well as various operating conditions.

3.1. Effects of filling fluid

Acetone, methanol, and water were all chosen as potential working fluids for the pulsating heat pipe. Some physical properties of these working fluids are listed in Table 1. Acetone was initially believed to be an effective choice for successful oscillations and performance because of its low boiling point, low viscosity, low sensible heat and relatively low surface tension. Nevertheless, acetone as a working fluid failed to produce data to support a claim

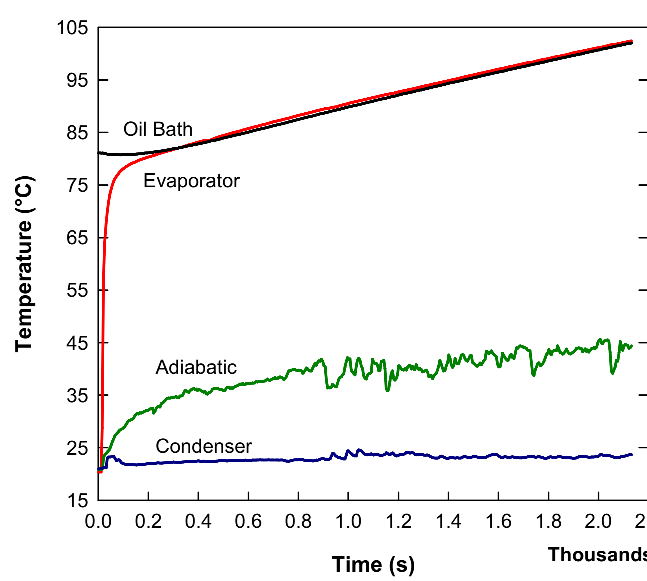

Fig. 5. Heat pipe operation – empty vacuum, 100 W power input, and 80 °C preheated oil bath.

Table 1
Selective physical properties of working fluids at STP (atmospheric pressure and 20 °C).

Working fluids	Boiling temperature (°C)	Dynamic viscosity (kg/m-s)	Surface tension (N/m)	Density (kg/m^3)
Acetone	56.5	3.27E−4	2.52E−2	788
Methanol	66	5.98E−4	2.27E−2	799
Water	100	1E−3	7.28E−2	998

that the PHP was successfully operating in this study. The ultimate indicator for success was operation at steady state; while some oscillations were present within the system for acetone, the lack of steady state operation over several trials deemed the fluid unsuccessful.

Acetone also has corrosive tendencies with respect to copper, thus it was replaced by methanol, which proved to be very successful in subsequent trials. Its success was measured by its capability of reaching steady state operation. Steady state was determined by a distinct temperature transition within each section, generating a narrow temperature difference between evaporator and condenser sections relative to the difference outside of steady state (as depicted in Fig. 4).

Water was also explored as a potential working fluid, but it proved to have very violent and drastic oscillations relative to data for methanol. One can tell the difference between methanol and water by comparing the end result of Fig. 4a for methanol, with that of water in Fig. 6, where each had the same fluid fill ratio as well as power input.

The drastic oscillations in the water data appear to suggest that the system never reached steady state; however, closer examination revealed that the PHP seemed to fall in and out of what would be characterized as steady state. These small sections of steady state were often short in duration, the longest period of which was 250 s. For this period, another indicator of performance was calculated: evaporator-condenser temperature difference. Although over a short time, it provided some insight as to the performance of water relative to methanol. The average temperature difference is 49.16 °C. Methanol, however, produced a temperature difference of 23.46 °C under the same operating condition. This higher temperature difference resulted in a higher evaporator section temperature for water, averaging 94.52 °C compared to 68.89 °C for methanol, where both maintained a condenser temperature at roughly 45 °C. This difference explicitly quantifies better performance for methanol, as well as the evident steady oscillations.

Steady state is a desirable condition for this particular device because of the potential application in mind: fuel cell cooling. A constant heat removal rate within a fuel cell is critical because it results in near constant cell temperature, which in turn produces steady performance, reduced chance of overheating, and minimization of cell component damage. Thus, methanol was chosen over acetone and water as the best performer, and was used in remaining trials examining filling ratio and power input.

3.2. *Effects of filling ratio*

Experimental data, with methanol as a working fluid, indicated that fill ratios between 35% and 55% of total volume reached steady state much more rapidly than outside this range, as seen in Fig. 7. Successful operation of the PHP at 45% and 50% fill ratios are displayed in Fig. 8. The determined "optimized range" was consistent with data from other studies that examined the design parameter [3,9–11,15–18,24]. In fact, time to steady state operation outside of that range was, on average, no less than double of that between 35 and 55% as seen in Fig. 7.

At 310 s, the shortest time to steady-state operation was observed at a ratio of 45% fluid fill. For each trial conducted, the average temperature difference between evaporator and condenser sections was calculated throughout steady state operation. This performance variable was a clear indication of successful oscillations within the heat pipe, and measured consistency of the device across different input conditions. As seen in Fig. 9, at fill ratios between 35% and 70%, the temperature difference was within 2.5 °C; this represents a wide filling range for minimal variation in evaporator–condenser temperature difference. In the "optimized range" from 35 to 55%, the gap was 1 °C, an indication of the consistency of this fill ratio range determined from the data on time to reach steady state.

3.3. *Effects of power input*

Various power inputs were tested, to observe their effect on time to reach steady state and evaporator-condenser temperature

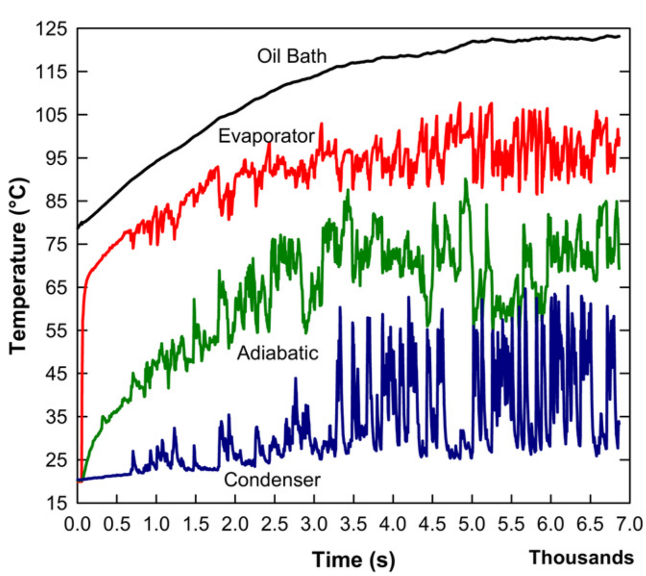

Fig. 6. Heat pipe operation – 45% water fluid fill ratio, 120 W power input, and 80 °C preheated oil bath.

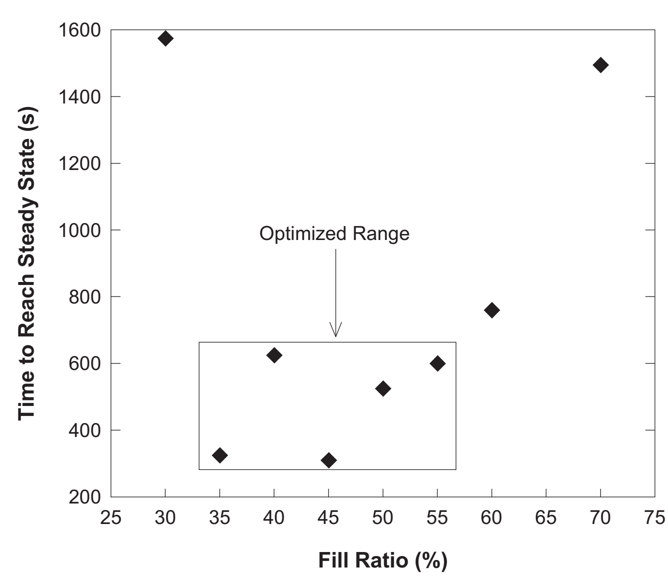

Fig. 7. Time to reach steady state operation at various fill ratios, 120 W power input, and 80 °C preheated oil bath.

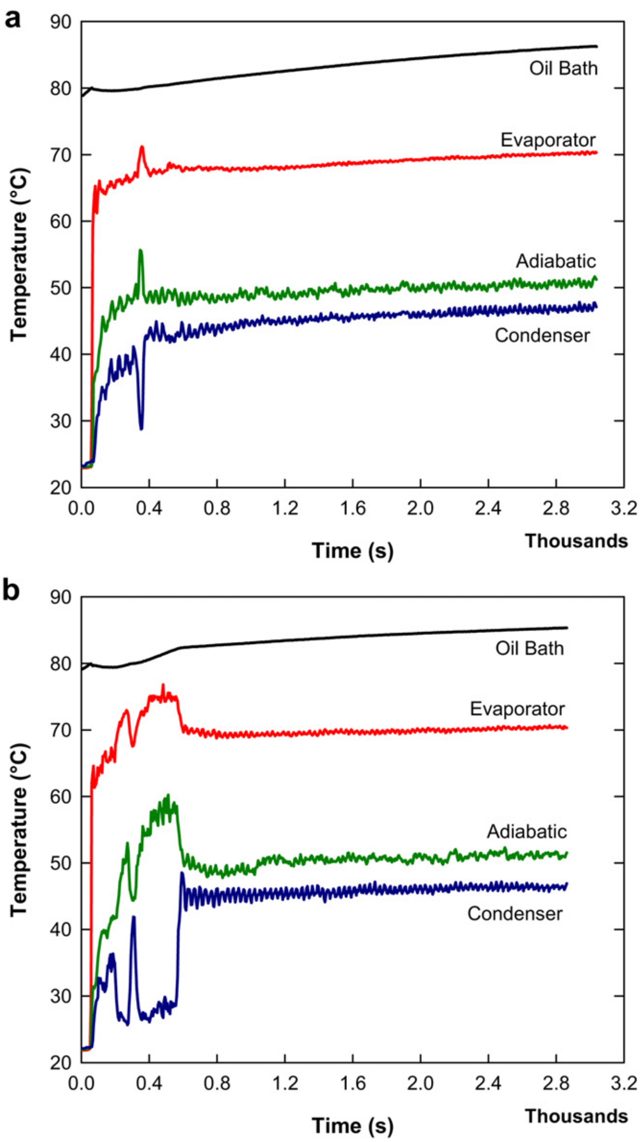

Fig. 8. Heat pipe operation – 120 W power input, 80 °C preheated oil bath and methanol fluid fill ratios of (a) 45% and (b) 50%.

difference. Using the previous fill ratio data, each trial was conducted using a 45% fill ratio of methanol to total volume. Results were not as consistent as with filling ratio variations, however the pulsating heat pipe did not reach steady state operation at a power input lower than 90 W.

Results suggest that the pulsating heat pipe is capable of removing between 100 and 120 W of power. This was concluded based on steady state oil bath temperature under these operating conditions. For trials with 45% methanol fluid fill, and power inputs of 100 and 110 W, the final oil bath temperatures were 0.31 °C and 0.26 °C different from the initial temperature at which steady state was reached. Each trial consisted of at least 40 min of steady state operating time.

This observation was also supported by Fig. 10 where the design maintained an oil bath temperature between 83 °C and 87 °C, which is within range of optimizing PEM fuel cell performance. The system was self-regulating by commencing and ceasing oscillations several times and maintained this narrow temperature range for over 90 min of operation. Had the PHP been implemented within a fuel cell, that temperature would have prevented overheating, thus providing a successful cooling method.

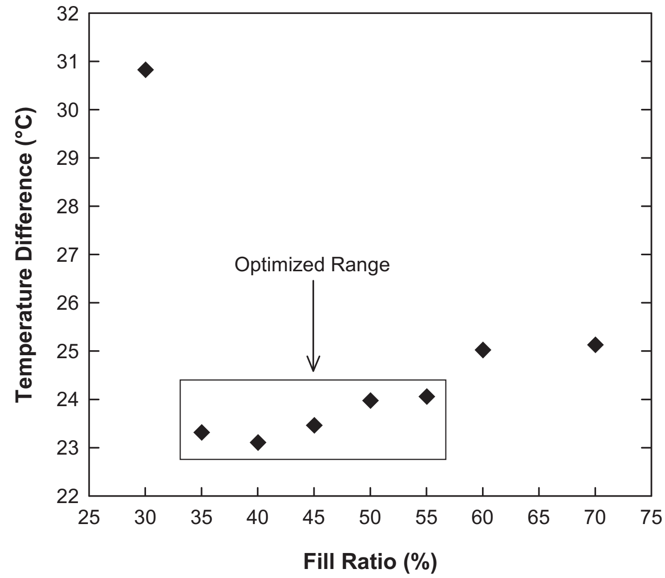

Fig. 9. Average temperature difference between evaporator and condenser section throughout steady state operation, at various fill ratios, 120 W power input, and 80 °C preheated oil bath.

For data collected at 45% methanol fluid fill ratio, and various power inputs between 100 and 150 W, another performance factor was calculated: effective thermal resistance. As a measure of the evaporator-condenser temperature difference with respect to heat flux, thermal resistance was calculated for the duration of steady state operation as explained by the following equation:

$$R_T = \frac{T_{evap.,avg.} - T_{cond.,avg.}}{\dot{Q}} \tag{2}$$

where $T_{evap.,avg.}$ represents the average evaporator temperature and $T_{cond.,avg.}$ the average condenser temperature throughout

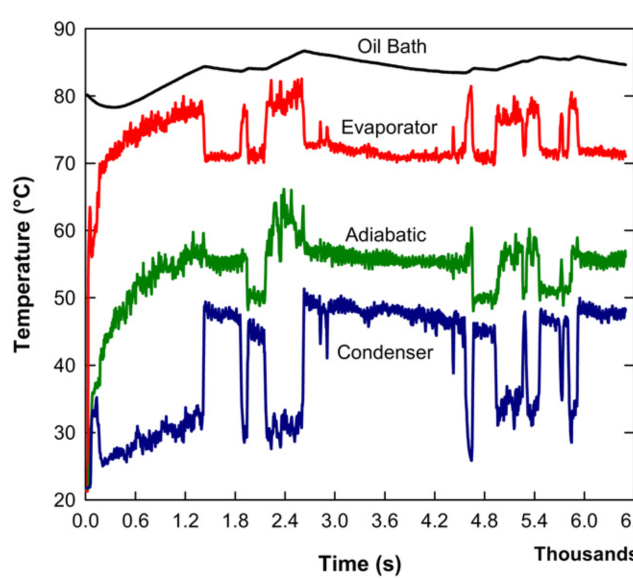

Fig. 10. Heat pipe operation – 50% methanol fluid fill ratio, 100 W power input, and 80 °C preheated oil bath.

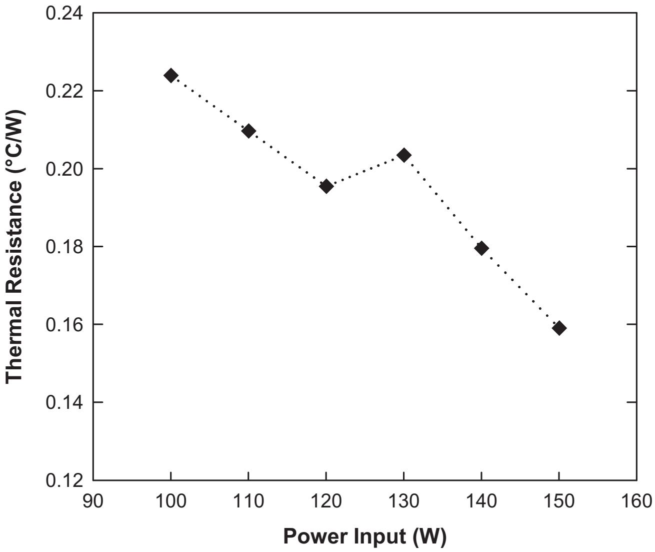

Fig. 11. Thermal resistance for various power inputs – 45% methanol fluid fill ratio, and 80 °C preheated oil bath.

steady state operation, and $\dot{Q}$ is heat input to the system. The calculated data, shown in Fig. 11, produced the same result as that found by others [6,12,13,18,19]: a decreasing thermal resistance with increased power input.

4. Conclusions

The pulsating heat pipe designed was a large-scale working model, but test results proved that it was functional and had the capabilities to self-regulate and maintain a constant evaporator temperature within a small range. Methanol as a working fluid outperformed both acetone and water. Based on the time to reach steady state criteria, and evaporator–condenser temperature difference, performance for the PHP peaked with methanol and a fill ratio of 45 percent fluid to total volume and power input around 110 W. Thermal resistance calculations indicated that a smaller resistance was associated with a higher power input to the system.

The pulsating heat pipe concept has potential to be utilized in a bottom-heated vertical orientation within a fuel cell. A PHP evaporator inserted within bipolar plates of a horizontally configured stack would allow for the condenser to protrude from the stack and transfer heat to its surroundings. Several pulsating heat pipes aligned between cells would remove heat directly from the source and act as an active fin array.

The existing data suggests that this particular PHP design has the potential to be implemented in a 200 cm^2 fuel cell based on its size dimensions, and can remove between 100 and 120 W of power. This estimate aligns closely with the calculated waste heat generated for a fuel cell of that size. With this result and through further testing as well as a greater understanding of PHP operation, these devices could be effectively utilized as a passive cooling method for PEM fuel cells.

Acknowledgements

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Nomenclature

Bo	Bond number
g	gravitational acceleration, N/kg
$\dot{Q}$	heat power input to the system, W
R_T	thermal resistance, °C/W
$T_{evap.,avg.}$	average evaporator temperature, °C
$T_{cond.,avg.}$	average condenser temperature, °C

Greek letters

ρ_l	liquid density, kg/m^3
ρ_v	vapor density, kg/m^3
σ	surface tension, N/m

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