FLAT PLATE PULSATING HEAT PIPE FOR ELECTRONICS COOLING

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ABSTRACT

Pulsating heat pipes are simple passive devices with excellent heat transfer capabilities, presenting low thermal resistance. Its thermal performance is mainly influenced by the thermophysical properties and volume of the working fluid. In this context, the impact of ethanol on the thermal performance of a diffusion-bonded flat plate pulsating heat pipe, composed of round channels with lateral grooves in the evaporator, is experimentally studied in this research. The experimental results of the pulsating heat pipe are compared with a previous study using distilled water. The grooved flat plate pulsating heat pipe is specially designed for cooling large-scale electronics (208x150x4.4 mm^3), including those for space applications. Its thermal behavior is investigated in three different orientations: gravity-assisted, horizontal and against-gravity. The device with ethanol works satisfactorily in all tested positions. The most notable impact of the ethanol was in the thermal enhancement of the PHP operating in the against-gravity orientation, reducing the thermal resistance and the evaporator temperature by 10 °C. Besides, ethanol promotes early startup in the horizontal and against-gravity positions. This research extends the operating range of the pulsating heat pipe for cooling large-scale electronics, enabling the device for future microgravity tests aboard a sounding rocket.

1. INTRODUCTION

Throughout the 21st century, the technology industry advances made possible the production of high-performance electronic components. Likewise, the heat generation produced by these devices during their operation has increased, becoming the thermal management an issue in electronic gadgets, such as those for the space satellites and computer processor applications (Ayel et al., 2015). Therefore, higher-performance heat exchangers must be explored. Heat exchangers based on phase change are highly efficient, being the most common the conventional heat pipes, loop heat pipes, thermosyphons, and vapor chambers. Heat pipes are able to operate independently of the gravity force because of the capillary effect promoted by the porous wick (Mantelli, 2021). On the other hand, thermosyphons requires gravity assistance for proper operation. In the last few years, a new biphasic device has been highlighted in the literature, named Pulsating Heat Pipe (PHP). The PHP is a simple passive device with excellent heat transfer capabilities, which may work without gravity aid, presenting low thermal resistance even in high heat power loads (Bastakoti et al., 2018).

In pulsating heat pipes, confined liquid plugs and vapor slugs, at saturation temperature, are constrained in a channel array. Liquid-vapor mixture flows inside the system, transferring heat from a heat source (evaporator) to a heat sink (condenser) in a two-phase chaotic displacement by convection and phase change mechanisms, as shown in Figure 1 (Nikolayev, 2021). The simplest way to manufacture a PHP is by meandering a small tube to form interconnected parallel channels, named tubular PHP. Flat plate PHP accomplishes the same function as the tubular; however, channels are formed by machining channels

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in their faces, so that the channels are formed after they are joined. Moreover, flat plate PHP is more suitable for cooling electronic gadgets due to the better coupling with the heat source, reducing contact resistance, and, consequently, increasing heat transfer capacity.

There are several joining methods to manufacture flat plate PHPs, including simple processes, such as conventional welding, or advanced techniques, such as additive manufacturing and diffusion bonding.

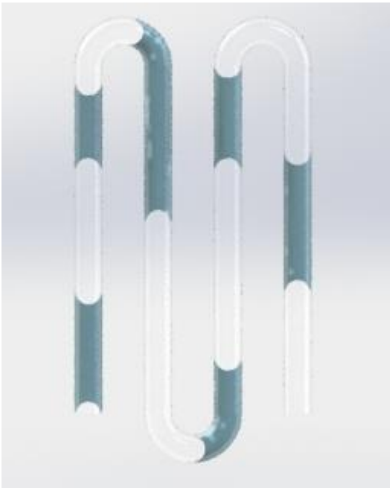


Figure 1. Oscillation motion inside a pulsating heat pipe.

The thermal performance of flat plate PHPs can be improved by changing parameters such as working fluid, filling ratio, number of turns and channel size. Besides that, researchers have stated that the internal channel characteristics may enhance the heat transfer capability of PHPs, including surface roughness modifications (Betancur et al., 2020), grooves addition (Krambeck et al., 2022) and wick structure insertion (Betancur et al., 2021). However, the thermal performance of a PHP is mainly influenced by the thermophysical properties and volume of the working fluid.

Krambeck et al. (2022) investigated two diffusion-bonded PHPs, one with a simple round cross section channel and another round with ultra-sharp lateral grooves in the evaporator section, for the thermal management of large-scale electronic gadgets in a wide range of applied heat loads. Although water is an excellent working fluid for copper PHPs, Krambeck et al. (2022) concluded that, for both PHPs, water delayed the startup, characterized by the operation in a slug-plug flow mode, restricting their operation range.

In this context, the impact of ethanol on the thermal performance of a diffusion-bonded flat plate pulsating heat pipe is experimentally studied in this research. The cross-section of the evaporator is composed of round channels with ultra-sharp lateral grooves. The thermal behavior of the PHP with ethanol is compared to the same grooved PHP using distilled water (Krambeck et al., 2022) in order to investigate the impact of the working fluid on the device's operation, especially the startup and evaporator temperatures. This research should extend the operating range of a flat plate pulsating heat pipe for cooling large-scale electronics, enabling the device for future microgravity tests aboard a sounding rocket.

2. EXPERIMENT

In this research, a flat plate PHP of 208 x 150 x 4.4 mm^3, specially designed for electronics cooling, was experimentally investigated, as shown in Figure 2. Two copper plates of 2.2 mm in thickness with 13 U-turns channels (machined by CNC) were diffusion bonded to form the 26 interconnected parallel round channels for the working fluid circulation. The PHP evaporator has a unique cross-section geometry consisting of a round channel (1.25 mm radius) with an ultra-sharp chamfer on both lateral sides. Figure 2 presents the proposed lateral grooves of an angle of 20°. More details of the manufacturing procedure can be found in Krambeck et al. (2022) and Betancur-Arboleda et al. (2020).

2.1 Working fluid selection

In order to properly select the working fluid for the proposed PHP, four liquids (distilled water, acetone, ethanol and methanol) were investigated using the Bond number. This dimensionless parameter evaluates the relationship between the gravitational force and the surface tension of the working fluid. The Bond number (Bo) is defined by the following expression:

$$\mathrm{Bo} = \frac{g(\rho_l - \rho_v)}{\sigma} \qquad (1)$$

where ρ_l is the density of the liquid, ρ_v is the density of the vapor, D is the diameter of the channel, σ is the surface tension of the working fluid and g is the gravitational acceleration. According to the literature, to operate as a PHP (oscillating /pulsating condition), the Bond number must be less than a critical value, i.e., $Bo_{crit} \leq 4$ (Czajkowski et al., 2020; Khandekar and Groll, 2003; Takawale et al., 2019).

Besides evaluating the relationship between the gravitational force and surface tension, the Bond number estimates the confinement of the working fluid inside the PHP, i.e., the confinement increases with decreasing the Bond number. Figure 3 presents the *Bo* for all selected working fluids as a function of the temperature. Distilled water presented the lowest *Bo* of the tested working fluid, which means that the PHP working with water should be highly confined and operate in an oscillation mode for all considered temperatures.

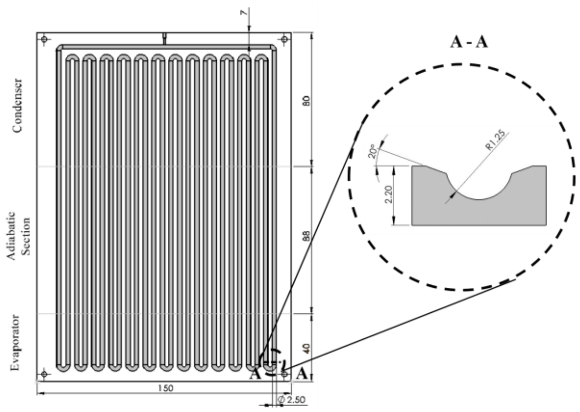


Figure 2. Proposed PHP and the channel cross-section view of the evaporator section.

Methanol and ethanol have similar properties and, for this reason, the Bo curve for both working fluids presented almost the same trend, staying below the Bo_{crit} for temperatures lower than 150 °C. Despite acetone showed similar Bo for temperatures lower than 50 ºC, above this value, the Bond number sharply increased until reaching the critical Bo at 135 °C. Since the main application of the proposed PHP is to remove the heat excess from electronic gadgets, there is a limitation in the evaporator temperature, that in such cases can be estimated as 100 °C (Maydanik et al., 2011). In this way, all presented working fluids should be selected to be used for this application.

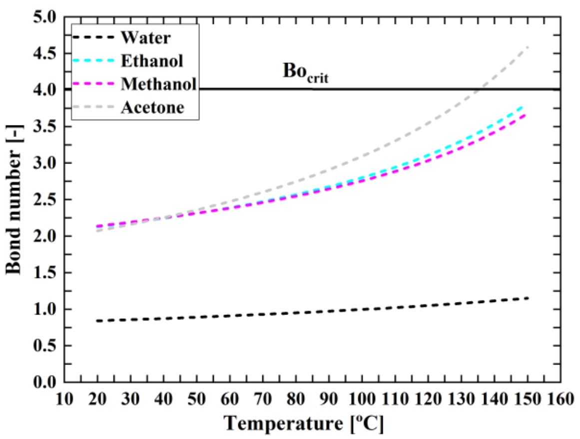
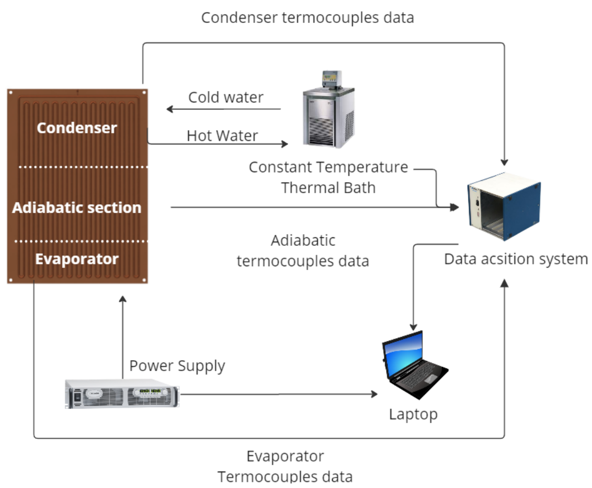


Figure 1. Bond number for the proposed working fluid as a function of temperature.

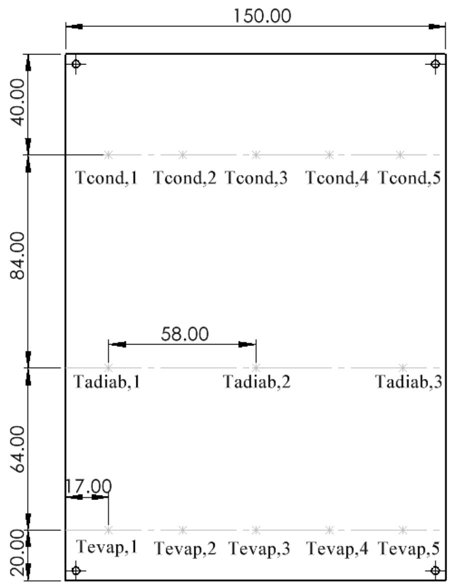
In previous work, Krambeck et al. (2022) studied the proposed PHP using distilled water as the working fluid. Although presented satisfactory results, it showed a delayed startup, especially in the horizontal (no assistance of gravity) and against-gravity orientations. A possible reason for the lateness is high boiling temperature and surface tension of water. Considering the mentioned above, as distilled water was already extensively tested, ethanol is selected for the present investigation, considering its Bond number is lower than acetone and, besides, it has lower toxicity than methanol. Thus, the grooved PHP, using ethanol as the working fluid, is experimentally tested and its thermal behavior is compared to previous experimental results obtained by Krambeck et al. (2022).

2.2 Experimental setup

Figure 4a shows the experimental setup used in the present work. The PHP was divided into three regions: the evaporator of 40 mm of length, where heat is supplied, the condenser of 80 mm of length, where heat is removed and, between these two regions, the adiabatic section of 88 mm of length. A TDK-Lambda GEN300-17 programmable source was used to supply power to the heater, composed by cartridge electrical resistors (10 mm in diameter and 100 mm of length), embedded on two copper blocks allocated over one surface of the evaporator, resulting in a total contact area of 5,750 mm^2. Each resistor can supply up to 210 W of power. The condenser consisted of an aluminum block measuring 140 x 80 mm (contact area with condenser of 11,200 mm^2), with two parallel channels for water flow. A Lauda Proline RP1845 thermal bath controlled the water temperature at 20 °C with a flow rate of 7.8 l/min. Thermal grease was used to reduce the contact resistance between PHP external surfaces and the heater and cooler. All apparatus was insulated with an Isoglas™ blanket with a thickness of 30 mm, with thermal conductivity of 0.045 W/m°C at 100 °C.



a) Experimental setup



b) Thermocouples position

Figure 4. Schematic view of experimental apparatus.

To read the temperatures of the PHP, 14 T-type thermocouples were used, as can be seen in Figure 4b, five allocated in the evaporator section ($T_{evap,1}$, $T_{evap,2}$, $T_{evap,3}$, $T_{evap,4}$, $T_{evap,5}$), five in the condenser ($T_{cond,1}$, $T_{cond,2}$, $T_{cond,3}$, $T_{cond,4}$, $T_{cond,5}$), three in the adiabatic section ($T_{adiab,1}$, $T_{adiab,2}$, $T_{adiab,3}$) and one measured the ambient temperature. All thermocouples were placed over the external surface, at the opposite side of the heat source. For fixation, a thermosensitive adhesive strip (Kapton™) was used. To analyze the obtained temperature data and to determine the PHP thermal performance, an acquisition system (DAQ-NI™ SCXI-1000) and a laptop (Dell™) with the software Labview™ were used.

2.3 Experimental procedure

For each test, the same experimental procedure was used. First, it was verified that the PHP did not have any leaks using a leak detector (Edwards Spectron™ 5000 Helium). Then, a compact turbomolecular pumping station (Edwards™ T-Station 85) evacuated the PHP until it reached the ultimate pressure of 4 x 10^{-5} bar. In the meanwhile, ethanol was previously boiled to remove all non-condensable gases. After that, the PHP was filled with the select filling ratio (FR) of ethanol, which was calculated by the following expression:

$$FR = \frac{V_l}{V_t} \quad (2)$$

where V_l is the working fluid volume and V_t is the total void volume. A forceps was used to seal the capillary tube. After that, the PHP was tested using the experimental apparatus seen in Figure 4a. At the end of each test, a pump was used to clean the tube, removing the working fluid and the filling process was repeated again for the next test.

The device was left at each power step for 900s, to allow the PHP to reach steady-state conditions. The following power inputs were used: 20, 40, 60, 80, 100, 140, 180, 230, 290 and 350 W.

The FR used to charge the PHP was of 60% (18 ml), which, according to Hosoda et al. (1999), provides the best thermal performance. The tests were carried out in three different positions: gravity-assisted (evaporator below condenser), horizontal and against-gravity orientation (evaporator above condenser), to analyze the impact of gravity on the PHP's thermal performance. The experiment data were collected at the rate of 1 sample/s.

In this work, the thermal performance was characterized by the PHP thermal resistance, using the following equation:

$$R = \frac{(\overline{T}_{evap} - \overline{T}_{cond})}{q} \quad (3)$$

where q is the heat input, $\overline{T}_{evap}$ and $\overline{T}_{cond}$ are the average evaporator and condenser temperatures, respectively. The average temperature of each of the regions (condenser, adiabatic and evaporator) was determined as the average of the temperatures captured by the thermocouples in that section, by:

$$\overline{T} = \sum_{j=1}^{M} \left(\frac{\frac{\sum_{i=1}^{N} T_i}{N}}{M} \right) \quad (4)$$

where N is the number of samples and M is the number of thermocouples in each section and T is the thermocouple temperature in steady-state conditions. Parameter N is determined by the last 200 measurements of each heat input, which corresponds to 200 seconds of measurement on each thermocouple. It is considered a steady-state condition when the average temperature variation was lower than 0.3 ºC/min.

The heat input can be calculated by the following expression:

$$q = U.I \quad (5)$$

where U is the voltage and I is the electric current, at the cartridge electrical resistor. As the equipment was thermally insulated, the heat leakage to the environment was considered negligible (calculations predicted that this maximum leakage corresponded to approximately 1.5% of total heat load q). All thermocouples were individually calibrated. The method used to calculate the propagation of uncertainties in the calculation of the thermal resistance using Eq. 3 is described in Holman (2011) and is given by:

$$\delta R^2 = \left(\frac{\partial R}{\partial \bar{T}_{evap}}\delta \bar{T}_{evap}\right)^2 + \left(\frac{\partial R}{\partial \bar{T}_{cond}}\delta \bar{T}_{cond}\right)^2 + + \left(\frac{\partial R}{\partial q}\delta q\right)^2 \quad (6)$$

3. RESULTS AND DISCUSSION

The experimental results regarding the thermal performance of the grooved PHP using ethanol as the working fluid are presented in this section. The temperature distributions are used to characterize the PHP thermal behavior under three different positions. In the sequence, the thermal performance of the PHP with ethanol is compared to the same PHP using distilled water (Krambeck et al., 2022) in order to investigate the impact of the working fluid on the device's operation.

3.1 Thermal behavior

Figure 5 presents the temperature distribution for the PHP with ethanol in the gravity-assisted orientation (left vertical axis). In the right vertical axis, the applied heat load is shown, depicted by the full black line. As expected, for all heat loads applied, the temperatures rose until they reached steady-state conditions. Despite the device being capable of transferring heat, it presents difficulties to startup. From 20 to 230 W, the PHP presents a behavior similar to a thermosyphon with high filling ratio, where the heat is mostly transferred by conduction. The device really started up, i.e., showed an oscillatory flow with the formation of large bubbles, at 290 W, at approximately 7300s, when the evaporator temperature dropped suddenly and the condenser temperature increased at about the same instant. After the activation, the device kept working efficiently until 350 W, the highest power tested.

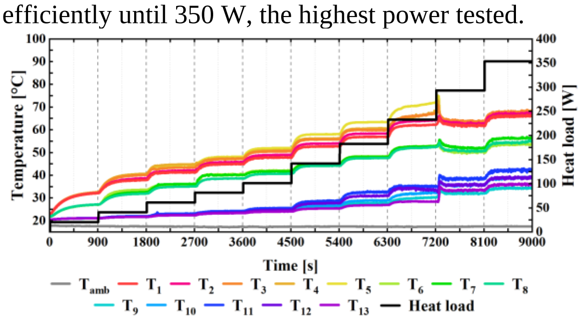


Figure 5. Temperature distribution in the gravity-assisted orientation.

The temperature behavior of the PHP with ethanol, under several heat loads and for the horizontal position, is presented in Figure 6. In this orientation, temperature fluctuations started to be noticed at 60 W, when the condenser temperature increase (purple and blue color lines) showed that the vapor bubbles reached the condenser. At 140 W, the device achieved a stable operation in slug-plug flows, which were maintained for all following heat loads.

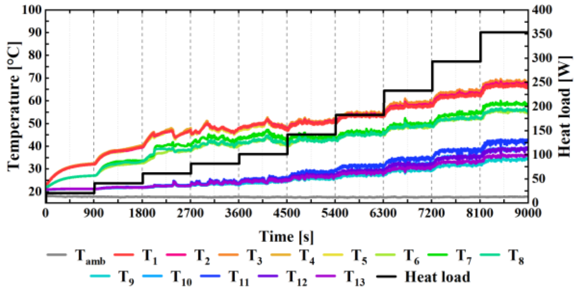


Figure 6. Temperature distribution in the horizontal orientation.

Figure 7 shows the temperature distribution of the PHP operating with ethanol in the against-gravity orientation. The device presents startup difficulties at low heat loads, where quick temperature oscillations showed that some isolated small bubbles were formed at 80 W. The sudden drop in the evaporator and almost simultaneous temperature rise in the condenser, characterizes the activation of the pulsating mode at 140 W, when the evaporator reaches around 80 °C. After that, the PHP operates efficiently until 350 W.

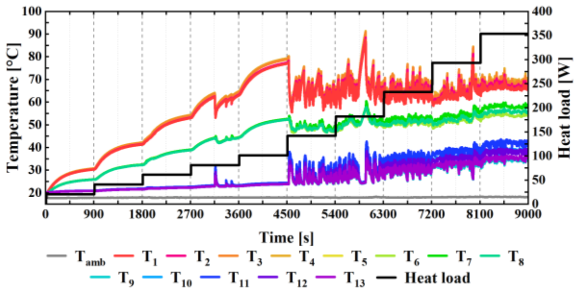


Figure 7. Temperature distribution in the against-gravity orientation.

By comparing Figure 5, Figure 6 and Figure 7, the gravity influence over the device operation mode can be clearly observed. As the confinement is small for ethanol, the gravity force delayed the slug-plug flow in the gravity-assisted orientation, which tried to operate as a thermosyphon. However, without or against the gravity assistance, the PHP operates effectively as an oscillating heat pipe after 140 W. Also, it was observed that the temperature amplitudes of the oscillations in the against-gravity orientation are larger than in other positions. No dry-out is noticed for the tested parameters.

3.2 Impact of working fluid

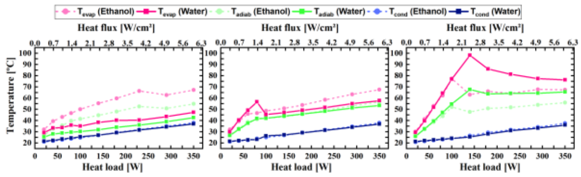
As already mentioned, Krambeck et al. (2022) investigated the same grooved PHP (26 round channels with lateral grooves) using distilled water as the working fluid. In this section, their results for a PHP with FR of 60% are compared to the present experimental data for a complete understanding of the working fluid effect.

The average temperatures of PHP regions, at steady-state conditions, for ethanol and water, under heat loads from 20 to 350 W, are compared in Figure 8. In gravity-assisted orientation (Figure 8a), water shows lower operating temperatures for all regions throughout the thermal load range, even when the oscillating cycle started at 290 W.

In horizontal position, the PHP with these different fluids showed different startup powers. The PHP with ethanol started up earlier when compared to water, as demonstrated by the evaporator temperatures (pink lines), in Figure 8b. The PHP with ethanol started at 60 W, while the PHP with water required 100 W to start. However, after startup, the device with water worked better, at a reduced temperature for the sane power input.

The major differences between PHPs with water and ethanol are in both startup power inputs and temperatures of the adiabatic sections (green lines) and evaporators (pink lines) in the against-gravity orientation (Figure 8c). The PHP with water activated at 180 W, reaching almost 100 °C in the evaporator region at 140 W (dark pink line). On the other hand, the device with ethanol started operating earlier, at 140 W, achieving the maximum evaporator temperature of 80 °C (light pink line). After the startup, the PHP with water operated at temperatures nearly 10 °C higher, in the adiabatic section and evaporator, than ethanol. For instance, at 350 W, ethanol operated at temperatures 67.5 °C and 56 °C in the evaporator and adiabatic section, respectively, while, for water, these temperatures were 76.3 °C and 65.5 °C. The lower adiabatic section and evaporator temperatures show that the ethanol can transfer heat more efficiently when the gravity is unfavorable to the PHP operation.

Figure 9 shows the PHP thermal resistances as a function of the heat load for both working fluids, ethanol and water, operating in gravity-assisted, horizontal, and against-gravity orientations. In Figure 9a, in the gravity assisted positions, as the heat loads increased, the thermal resistances reduced. Clearly, the PHP with water had a better thermal behavior, observed by its lower thermal resistance during the tested range.



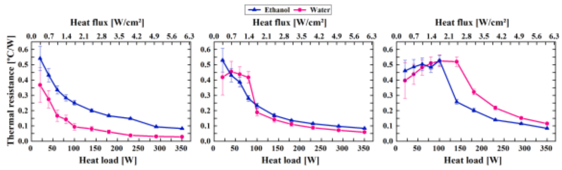
a) Gravity-assisted b) Horizontal c) Against-gravity

Figure 8. Comparison between the temperature of regions at steady-state of the PHP with ethanol and water (T_{evap} = evaporator temperature, T_{adiab} = adiabatic section temperature, and T_{cond} = condenser temperature).

In the horizontal position (Figure 9b), ethanol presented a better thermal performance at low heat loads (below 100 W), with the thermal resistance decreasing with the power input, since the heat load applied, 20 W, achieving a stable operation. However, the PHP with water presents difficulties in the activation from 20 to 80 W, operating with a high thermal resistance, which value is close to that of the empty device (Rempty= 0.51°C/W), i.e., the heat was transferred only by conduction. At 100 W, the water PHP started a proper operation, and the thermal resistance shows a drastic reduction, maintaining its stable operating mode up to 350 W. After startup, when both working fluids were in stable operating mode, water showed lower thermal resistances than ethanol. The lowest thermal resistances were 0.060 ± 0.006 °C/W for water and 0.084 ± 0.003°C/W for ethanol at 350 W.

According to Figure 9c, ethanol shows a higher overall heat transfer capacity than water in the against-gravity orientation. Firstly, the ethanol device started up at a lower heat load, 140 W, while, for the water, 180 W were required. After the activation, both fluids worked as expected: the thermal resistance reduced as the heat load increased. Second, ethanol operates with lower thermal resistances than water. The lowest thermal resistances achieved for the PHP with water and ethanol are 0.115 ± 0.007 °C/W and 0.084 ± 0.003 °C/W, respectively, at 350 W. The change of the working fluid resulted in the thermal resistance reduction of about 28%, for this heat load. Then, it should be noted that the thermal improvement provided by the ethanol in this position seemed to be significant.

The thermal tests showed that the ethanol provides a satisfactory operation for the PHP in all tested positions. When compared to water, the alcohol anticipates the PHP startup in horizontal and against-gravity orientations.



a) Gravity-assisted b) Horizontal c) Against-gravity

Figure 9. Comparison of the thermal resistance between the PHP with ethanol and water.

Besides that, the thermal behavior enhancement in against-gravity orientation is notable by the lower operation temperature in the evaporator (almost 10 °C of reduction if compared to water) and the lower thermal resistance (28% of reduction). This improvement in the against-gravity position is regarded to the higher bond number for ethanol, which enables a large bubble motion.

Therefore, for the studied geometry, the choice of the best working fluid depends on the application conditions: operating positions and power input levels.

4. CONCLUSIONS

The impact of the working fluid on the thermal performance of a flat plate pulsating heat pipe of 13 U-turns was experimentally investigated. The PHP, specially designed for large-scale electronics gadgets, had a unique evaporator channel geometry, with very sharp chamfers in both lateral sides of the circular cross-section channels. The criterion for the selection of the ethanol was the bond number. The experiments were conducted with the PHP operating in three orientations: gravity-assisted, horizontal and against-gravity. The experimental results were compared to the same PHP with distilled water as the working fluid, which was thermally characterized in a previous study.

The main conclusions of the present research are:

• The thermal behavior of the grooved PHP with ethanol is highly influenced by gravity. However, it operates satisfactorily in all tested positions, reaching the oscillatory motion mode earlier in the horizontal and against-gravity position than in the gravity-assisted.

• When compared to water, ethanol anticipates the PHP startup in horizontal and against-gravity orientations.

• In the gravity-assisted position, the PHP with ethanol presents lower thermal performance than the PHP with water.

• The thermal behavior enhancement of the PHP with ethanol operating in against-gravity orientation is notable by the reduction of the operating temperature in the evaporator (almost 10 °C decrease if compared to water) and the thermal resistance (28%).

• The lower adiabatic section and evaporator temperatures show that ethanol can transfer heat more efficiently when the operating position is unfavorable.

In this context, this research extends the operating range of a flat plate pulsating heat pipe for cooling large-scale electronics, especially against-gravity orientation, proving better alternatives for future microgravity tests aboard a sounding rocket.

5. ACKNOWLEDGEMENTS

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