An Experimental Study towards the Practical Application of Closed-Loop Flat-Plate Pulsating Heat Pipes

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Abstract

The thermal performance of a flat-plate closed-loop pulsating heat pipe (PHP) is experimentally obtained. The PHP is manufactured by means of CNC-milling and vacuum brazing of a stainless steel 316L bottom plate and lid. Each channel of the PHP has a 2×2 mm² square cross section. In total 12 channels (6 turns) fit in the 50×200 mm² effective area of the PHP. During the experimental investigation, the power input is increased from 20W to 100W through a 50×50 mm² evaporator section, while cooling is performed through a 50×50 mm² condenser section with the use of a Thermo-Electric Cooler (TEC). The PHP is charged with methanol with 40% filling ratio. The thermal resistance is obtained for different inclination angles. It is observed that the 6-turn device operates well in vertical orientation. It however does not operate horizontally. Moreover, experiments have shown that the operating orientation is between 15-30°. The overall thermal resistance was determined at 0.48 K/W for a 100 W power input in the vertical evaporator-down orientation.

1 Introduction

In the recent past, Pulsating Heat Pipes (PHPs) have attracted the attention of many researchers as viable candidates for enhanced heat transfer through passive two-phase heat transfer mechanism [1, 2]. Although a complete theoretical understanding of operational characteristics of this device is not yet achieved, there are many emerging niche applications, ranging from electronics thermal management to compact heat exchangers [3]. The current study is carried out to provide renewed insight in the practical application of PHPs.

The concept of a PHP was first introduced and patented by Akachi in 1990 [4]. The device basically consists of a pipe or channel of capillary dimension bent in a serpentine manner. The channel of a PHP is evacuated and then partially filled with a working fluid. By applying heat to the evaporator section (and cooling the condenser section), a train of liquid slugs and vapour plugs naturally forms inside. With sufficient power input, evaporation and condensation of the fluid, pressure differences, and perturbations in the system initiate oscillatory motion of the slugs and plugs [5]. The oscillating flow provides the transport of heat from the source towards the sink and the PHP acts as a passive thermal link.

In this study, the thermal performance of a closed-loop flat-plate PHP is experimentally obtained. The power input and inclination angle are varied in the tests. The PHP features a channel with a square cross section of 2×2 mm² that is CNC-milled into a 2.5 mm thick plate of 53×207 mm². A cover plate of 50×200 mm² and 1 mm thickness is fastened on top by means of vacuum brazing. The bottom plate is wider than the lid, as it is used for the positioning method in the brazing process.

Stainless steel 316L is selected as the substrate material. Due to the low thermal conductivity of the substrate material, the PHP performance can be well distinguished. Also, stainless steel is preferred for vacuum brazing. The stainless-steel plates are brought to a temperature of 1050°C in a vacuum furnace with BI2 nickel brazing foils in between the bottom plate and the lid, while small weights are placed on top. This way, metallurgical bonding of the plates is ensured.

The channel spacing and turn radius are equal to the 2-mm channel width. Hence, 6 turns fit into the substrate. Finally, a 1/16” filling tube is inserted sideways to complete the device. The tube is shrink-fitted and subsequently soldered for extra solidity of the joint. The part of the PHP where the filling tube is inserted is intended to be the (colder) condenser section. This means that the tube will be predominantly filled with liquid, which has less effect on the PHP operation than vapour [5].

The bottom plate of the manufactured PHP is shown in Fig. 1(a). After vacuum brazing, X-ray imaging was used to check whether the device was properly manufactured and all internal channels were open. As shown in Fig. 1(b) this was the case. Finally, the closed device with filling tube is shown in Fig. 1(c). The filling tube features a 1/16” Swagelok® fitting to connect it to the charging system.

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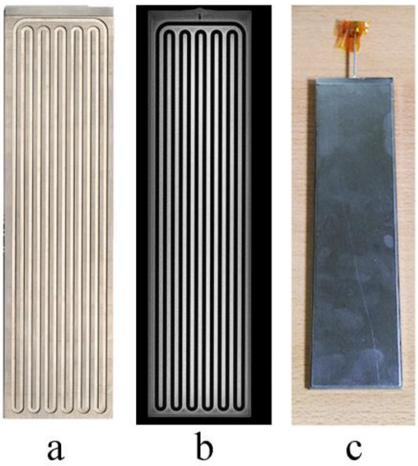

Figure 1: a) CNC-milled PHP channels in the bottom plase, b) X-ray image showing the interior after vacuum brazing and c) the closed device with filling tube after manufacturing.

1.1 Influence of channel cross-sectional shape

The cross-sectional dimension is determined by the Bond (Eötvös) number criterion. This criterion states that the fluid's physical behaviour adheres to a pulsating mode, meaning that plug-slug flow is occurring inside the PHP and agglomeration leading to phase separation is avoided. The critical Bond number is this case is four [1]. In this case, the critical inner diameter is given by:

$$D_{crit} = 2\sqrt{\frac{\sigma}{g(\rho_l - \rho_v)}} \tag{1}$$

For methanol, the critical hydraulic diameter is a little larger than 3 mm for the complete temperature range from 20°C to 100°C. Yang et al. [3] however reported that for rectangular cross-sectional channels, the sharp angled corners have an important bearing on the flow pattern transitions and the acceptable inner diameter. They reported different operation modes. They observed traditional pulsating plug-slug flow, but in vertical orientation their PHP also performed as an interconnected array of two-phase thermosyphons. This was explained by the capillary action in the sharp angled corners that counteracts the probability of having a naturally formed train of liquid slugs and vapour plugs inside the channel.

As the PHP of this study also features a squared cross-sectional channel, this behaviour is to be expected in the current research. As the Bond-number criterion only provides a tentative first order estimate, a 2 mm hydraulic diameter was applied.

To start operation, the PHP is evacuated and then charged with methanol. A Fill Ratio of 40% is applied in this study and the effects on the temperature variation and the thermal performance are observed.

2 Experimental setup & methodology

After charging the device, it is placed in the test setup. Here, heat is applied to the evaporator section using four heaters (Caddock MP9100 power film resistors, 2Ω ±1% accuracy). The heaters are connected to 50×50×3 mm^3 copper plates to provide uniform heating to the PHP. They are powered by a variable power source to deliver step-by-step elevated power input from 20W to 100W in steps of 20W.

The condenser temperature is controlled and maintained at a constant level using Peltier-elements and a controller (TC-XX-PR-59, LairdTech). This part of the system is referred to as the thermo-electric cooler (TEC). The copper blocks between the TEC and PHP contain thermocouples that record the condenser temperature. In operation, the Peltier-elements cool down at the PHP side and heat up at the opposite side, where the heat is dissipated through a custom-made 3D-printed titanium heat exchanger. A water-glycol mixture cooling liquid controlled at 2°C is pumped through these heat exchangers. The effective interface surface of the heat exchangers is 50x50 mm^2, which is also the area of the TEC and the copper blocks. The PHP is clamped in a sandwich-like construction between the heating and cooling elements, as shown in Fig. 2. Hence, double-sided heating and cooling is performed. Note that the thermostat bath alone would be able to provide sufficient cooling, but the addition of the TEC (that is able to heat up and cool down more rapidly) allows for a careful control of the internal PHP working temperature.

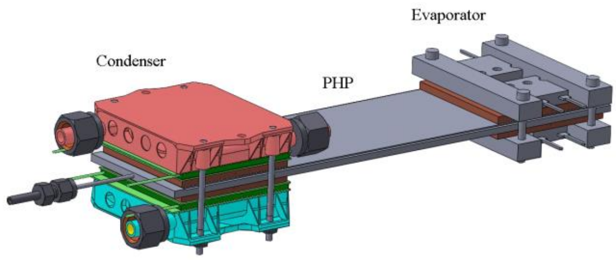

Figure 2: CAD-model of the test setup.

Between the condenser and the evaporator sections, there is a 100×50 mm^2 adiabatic section. As the temperature response of the PHP is of interest, a total of 14 thermocouples is used to measure the temperature: 4 in the evaporator section, 8 on the PHP body, and finally 2 in the condenser section. The thermocouple locations are schematically shown in Fig. 3. The TEC-bubble in this figure indicates where the reference temperature for the TEC is measured. A UNIK 5000 (GE) 0-10 bar absolute pressure sensor completes the setup (Green 'P' bubble in Fig. 3). This sensor is used to determine whether the PHP is charged correctly and to monitor the pressure variation during in the experiments. The PHP is tested in several orientations from vertical (evaporator down mode) to horizontal. The power is increased from 20W to 100W and the condenser temperature is maintained at 10°C by the TEC.

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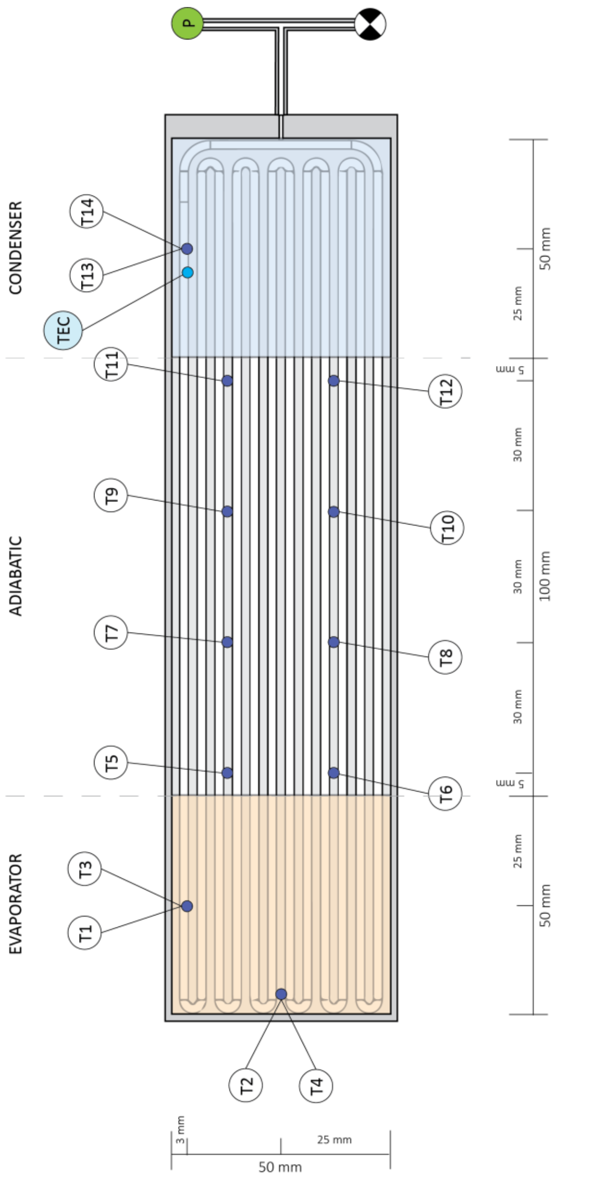

Figure 3: Schematic of the PHP with evaporator, adiabatic, condenser, thermocouple and pressure sensor locations.

3 Results & discussion

3.1 Reference empty-body measurement

Before the PHP is charged with methanol, the thermal resistance of the empty body is determined. To this end, the empty PHP placed in the thermally isolated test setup and a power input of 2W is applied, while the condenser temperature is not controlled. The temperature response in this case is shown in Fig. 4.

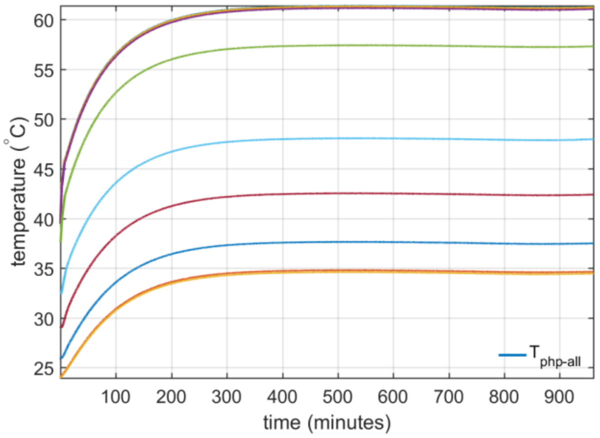

Figure 4: Temperature response of the PHP empty body for a 2W power input.

As shown in Figure 4, the PHP reaches a steady state situation after about 400 min. At this point, the effective thermal resistance can be determined by:

$$R = \frac{T_e - T_c}{Q_{in}} \qquad (2)$$

where, T_e and T_c are the average evaporator and condenser temperatures, respectively, and Q_{in} is the input power. The thermal resistance of the empty body is 13.9 K/W.

This value is lower than computed for a stainless steel plate, when only conduction is assumed. The deviation is a result of unavoidable losses to the environment. The obtained thermal resistance functions as a reference measurement for the methanol-charged PHP experiments described next.

3.2 Vertical 'gravity-assisted' operation

For the first test, the charged PHP is placed in the upright position with the evaporator down. In this orientation, the PHP operates 'gravity-assisted' and is expected to give the best performance of all orientations. Fig. 5 shows the time evolution of the temperature and pressure variation. The pressure corresponds to the methanol pressure at saturation temperature. The increasing power input is indicated between both graphs.

Fig. 5 shows that for each power input increment the temperature rises and stabilizes at a higher level. At 100W of power input the Peltier-elements are not able to provide sufficient cooling anymore. The condenser temperature (T13 & T14) ascends to 17°C, while the TEC set point was set at 10°C. The upper four lines in Fig. 5 show the evaporator temperatures. T2 and T4 are significantly colder than T1 and T3, indicating that the copper blocks at the evaporator section are not uniform in temperature. This is likely due to sideway losses to the environment.

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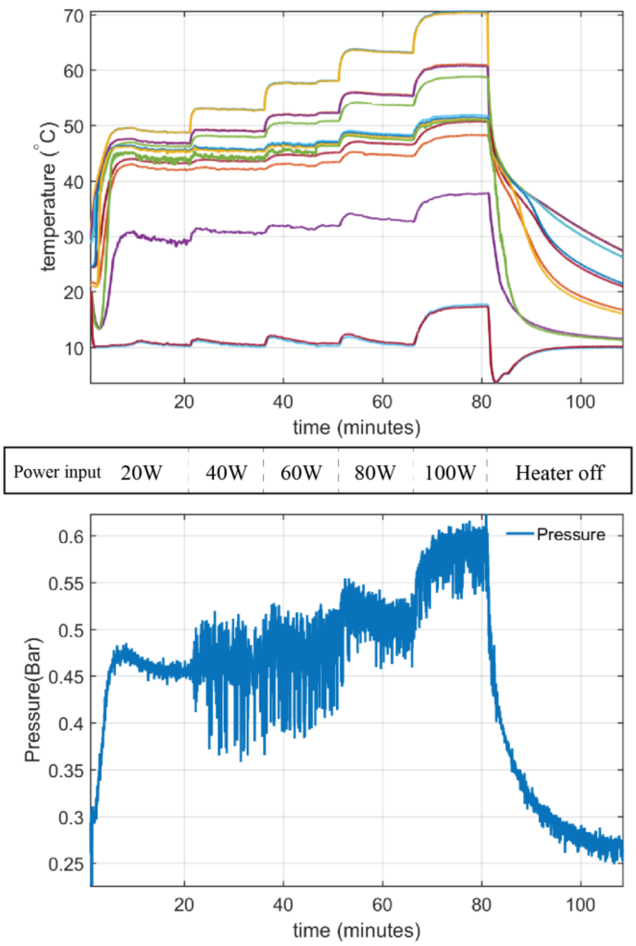

Figure 5: Temperatures and pressure profiles for increasing power input with the PHP in vertical orientation.

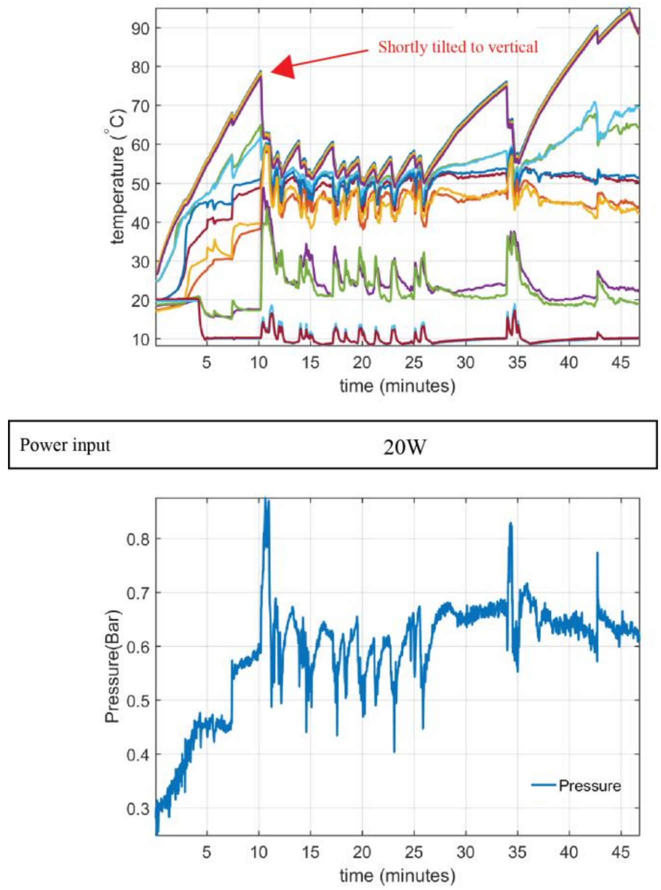

Figure 6: PHP response in horizontal orientation, while tilted shortly to vertical at 10-minute marker.

The PHP is near uniform in temperature, with T12 as the only (colder) outlier. In some tests, T12 was significantly colder, while in other tests T11 was colder. This can be explained by the operating regime acting locally. As no rapid pulsating temperature effects are visible, the PHP is assumed to be in thermosyphon operation mode. In this mode, in each channel the vapour and liquid phases are separated. Liquid pools are formed at the bottom of the PHP that are filled with liquid condensate that runs down along the channel walls. Vapour is expelled from the liquid pool and flows upwards in the centre of the channel, similar as a thermosyphon [6].

At 100W of power input, the thermal resistance of the vertically oriented PHP is 0.48 K/W.

3.3 Horizontal operation

In the horizontal orientation, the PHP did not operate at all. The evaporator temperature increased towards the maximum temperature of 100°C very quickly at the minimum power input of 20W. The power input then shuts off automatically by a limiter, due to safety reasons. The fact that the PHP does not operate horizontally is in line with findings of Charoensawan and Terdtoon [7]. They also reported that a 2 mm (inner diameter) PHP charged with ethanol only started to operate in the horizontal mode at a minimum of 11 turns, which is significantly higher than the 6 turns of this prototype.

The horizontal test was repeated, however this time the device was aided to start-up by shortly (20 sec.) tilting it vertically. The response of the device is observed and the results are shown in Fig. 6. The PHP was tilted at the 10-minute marker during the test. The power input was constant at 20W. After tilting the device, the evaporator temperature drops dramatically and for 15 minutes the device shows intense temperature and pressure fluctuations. A smooth and stable operation similar to the vertical operation was not observed. At the 35-minute marker a sudden temperature drop occurs, as the PHP recovers from evaporator dry-out. Shortly thereafter the evaporator temperature increases to the maximum of 100°C and the experiment was stopped, indicating dry-out of the evaporator section.

The effective thermal resistance was not determined, since the PHP never reached a stable operating condition.

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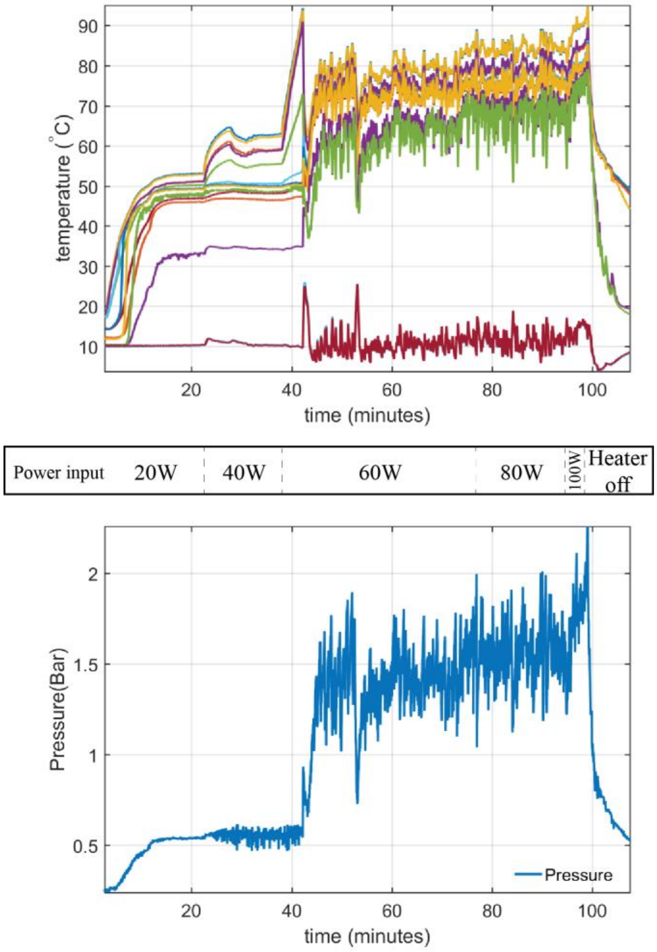

Figure 7: PHP behaviour at 15 degrees inclination angle, at 60W of power input the PHP switches to a pulsating mode.

3.4 Operation at a small inclination angle

To find out what the minimal operating angle is, the experiments were repeated at 30° and 15° inclination angles. In the first case, 30°, the PHP operates successful and shows a similar response as in vertical orientation. The evaporator reaches a maximum temperature of 75°C at 100W of power input, which is a ±5°C increase compared to the vertical orientation. The effective thermal resistance in this case is hence slightly higher: 0.51 K/W.

At 15° inclination angle the PHP starts to operate differently once 60W of power input is reached. This is shown in Fig. 7. The evaporator temperature increases fast towards the maximum here, but at 95°C the PHP recovers and a sudden 30°C temperature drop occurs. Thereafter, temperature and pressure fluctuations dominate the system, and the PHP operates in the pulsating regime. The change to another operating mode can also be inferred from the fact that the 'colder' T11 (in purple) increases towards the mean PHP temperature. The TEC also has trouble to maintain a stable condenser temperature, due to the rapid temperature fluctuations.

At 80W of power input the system has an effective thermal resistance of 0.88 K/W. Hence, in this case, the pulsating operating regime gives a lower thermal performance.

4 Conclusions and outlook

A 6-turn, 2 mm inner diameter flat-plate PHP is presented. Experimental results have shown that the PHP is gravity dependent. The PHP operates well in the vertical orientation and at a 30° inclination angle. Horizontally however the PHP fails to operate. At 15° inclination angle and 60W power input rapid temperature and pressure fluctuations occur, as the PHP switches to the pulsating mode.

Yang et al. [3] already observed such an operation mode in their 2 mm inner diameter PHP with square cross-sectional channels for low filling ratios: the device does not act as a PHP in this situation, but as an interconnected array of closed two-phase thermosyphons. The rectangular cross-section increases capillary action in the sharp corners, counteracting the distinct formation of liquid slugs and vapour plugs. The latter are needed for the pulsating mode.

Following the Bond number criterion and Eq. (1), plug-slug flow should always occur for methanol up to a critical diameter near 3 mm. This is however not the case for the reported 2 mm square cross-sectional channel in all operating conditions according to the test results. This confirms the findings of Yang et al. [3] that the Bond number criterion is rather inappropriate for rectangular channels.

Although the PHP does not operate in the pulsating mode, Yang et al. found the best thermal performance for their PHP in the thermosyphon mode, a trend that is also observed in the present work. The fact that PHPs feature the best performance for thermosyphon or (semi-)annular-type flows (in case of circular cross-sections and high input heat fluxes) is reported more often; for instance, by Khandekar and Groll [8]. They remark that the flow is then ironically not *pulsating* anymore.

All found thermal resistances for the stable operating cases were significantly lower than found for an equivalent 3 mm thick aluminium plate, measured in the same setup. In the case of an aluminium plate, a thermal resistance of 3 K/W was measured at 10W of power input with a 42.2°C evaporator temperature. The empty-body PHP had a thermal resistance of 13.9 K/W and reached already high temperatures at a low power input of 2W. The charged PHP in stable operation can transfer a power input of 100W well within the temperature limit, with a thermal resistance as low as 0.48 K/W in the thermosyphon mode and 0.88 K/W in pulsating mode.

Future work will extend towards a larger study in which more parameters are varied, such as the fill ratio and working fluid, for a variety of PHPs. Also, the distinction and switching between the two operating modes are topics of further investigation.

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