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Experimental Study of Start-up in a Closed Loop Pulsating Heat Pipe with Alternating Superhydrophobic Channels

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Abstract

A Pulsating Heat Pipe has been designed with alternating hydrophilic/superhydrophobic channels and tested at different heat power inputs. The device consists in a copper tube (internal/external diameters of 3.18/4.76 mm), bent into a planar serpentine of ten channels and five U-turns in the heated zone. The tube is partially functionalized with a superhydrophobic coating, in such a way to create an alternation of hydrophilic and superhydrophobic tubes along the loop. The aim is to investigate how the wettability affects the start-up, the fluid motion along tubes with different wettabilities and the overall performance of the device. Then, the overall behavior is compared to another PHP, having the same geometry and under the same working conditions, but completely hydrophilic. The PHP is evacuated and then filled with distilled water, with a filling ratio of 50%. The heating section is equipped with two heating elements that supply up to 350W. A cold plate, directly connected to a thermal bath, keeps the condenser at a constant temperature of 20°C. 16 T-type thermocouples are located on the external tube wall at the evaporator and at the condenser zones, while the fluid pressure is measured at the cooled region by a pressure transducer directly mounted in contact with the flow. Input power has been increased from 20W up to 350W in 10 steps, and then decreased following the same heating steps. Temperature evolution recorded both at the condenser and at the evaporator zones allows to obtain the overall PHP thermal performance for all the tests performed. It is found that the alternating wettability of tube sections strongly affects the flow motion, the start-up and the overall performance. Comparing the results obtained with such a functionalized pulsating heat pipe to a completely hydrophilic pulsating heat pipe, the thermal resistance of the functionalized pulsating heat pipe is all the times higher than the hydrophilic one. Moreover, the start-up is achieved for higher heating power levels for the functionalized pulsating heat pipe. Local temperature measurements at the hydrophilic sections are lower than the temperature recorded on the superhydrophobic tubes. In addition, temperature fluctuations are more noticeable at the hydrophilic inserts, synonym of a pulsating flow able to dissipate heat in those regions. On the contrary, the temperature measurements at superhydrophobic surfaces exhibit a flat trend, as if the flow is blocked within the functionalized inserts. The superhydrophobic coating, hindering the liquid film formation, decreases locally the flow motion. Enhancing the inner wettability, the flow motion is improved, since the liquid film can cover the inner surface, acting as a sort of lubricant that facilitates the liquid plugs and vapor bubbles passage. These experiments point out the importance of the wettability wall for pulsating heat pipes.

Keywords: Closed Loop Pulsating Heat Pipes; Alternating Channels; Wettability; Hydrophobicity

1. INTRODUCTION

The use of high performance electronic components has increased the amount of heat to dissipate during their operation. The aim is to maintain the maximum temperature of electronics below a critical threshold value; otherwise, both the performance and the lifespan will decrease abruptly. Therefore, higher performance heat exchange systems for higher heat fluxes cooling must be explored. Currently, some applications produce fluxes that can vary from 10 to 40 W/cm^2 [1]. In most applications, such as terrestrial and space, reliable, low-weight, high heat transfer capacity devices are required. Several different types of heat transfer devices such as conventional heat pipes, loop heat pipes and capillary pumped loops [2] can be applied. However, the major problems regarding these solutions are related to the complexity of their manufacturing processes. In this context, the pulsating heat pipes (PHP), a relatively new two-phase passive heat exchanger proposed in the early 1990s by Akachi (1990) [3], with very promising advantages such as flexibility, low costs, reproducibility and, above all, the possibility to extract efficiently high heat fluxes can meet all these requirements. The use of PHP for electronics thermal control is promising for high power level and high heat flux density cases [4][5][6].

PHPs are highly efficient heat exchanger devices; basically consisting of an evacuated small diameter closed tube, bent in multiple turns, where a certain amount of working fluid is inserted. PHPs are composed of two main regions: evaporator, where heat is inserted, and condenser, where heat is removed, as shown in Fig. 1. An adiabatic section, a thermally insulated region located between the evaporator and the condenser, may have a variable dimension or even not exist. PHPs operate in closed

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two-phase chaotic cycles. Confined saturated liquid, when heated, forms slugs of liquid and plugs de vapor as shown in Fig. 2. Due to the confinement, PHPs use latent heat of vaporization to generate vapor, expanding the bubbles and pushing the liquid slugs to the condenser region. The high-speed cycles are responsible for the efficiency of the working fluid latent and sensible heat transportation.

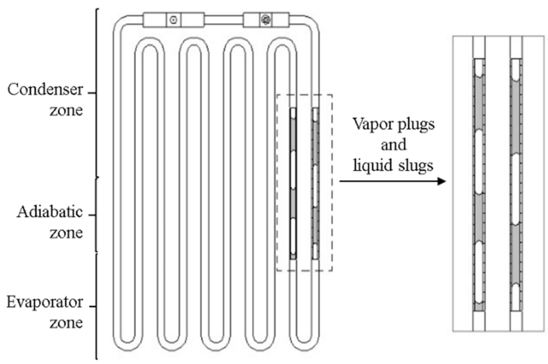

Fig. 1. Schematic of a pulsating heat pipe.

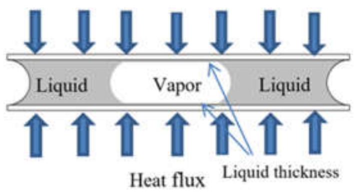

Fig. 2. Fluid pattern inside a pulsating heat pipe.

Considering the PHP family, the closed loop pulsating heat pipes (CLPHP) have better thermal performance than the open loop pulsating heat pipes (OLPHP), as they provide the possibility of fluid circulation. Numerous techniques were studied to enhance the flow circulation in a preferential direction within CLPHPs. In order to improve the thermal performance of CLPHP, some researchers studied the influence of increasing the number of turns and of introducing valves in the circuit [7]. Although efficient, check valves increase the manufacturing complexity of the device as highlighted by [8]. However, there can be geometry limitations for the number of turns in actual applications. Other works point out that hydraulic asymmetries could enhance the flow circulation and, thus, the overall performance of the device. Recent works as [8] are focused on the visualization of the PHP hydrodynamic behavior and on the heat transfer measurements of a CLPHP with variable cross section area channels. They noticed that CLPHP with uniform channels are more sensitive to inclination. However, non-uniform CLPHPs worked in all inclinations tested.

On the other side, different researchers showed that the surface wettability influences the vapor and liquid slug motion and so, the thermal performance of PHP [9] [10] [11]. Actually, the presence of thin films over internal surfaces, surrounding the vapor plugs, is related to the surface wettability. These films usually improve the heat transfer capacity when applied to the evaporator sections of the device [10]. Works as [9], [10] show that the heat transfer capacity of PHPs can be improved with different wettability patterns along the channels. Also, the literature reports a performance improvement in phase change heat exchangers by using a hydrophobic surface in condensers, so that condensation happens in dropwise mode [12] and by improving the wettability in evaporators, to avoid dry patches [13] and creating a liquid film around the vapor plug [9]. The idea behind the concept of using different cross section area channels is to create unbalancing capillary pressures by receding and advancing contact angle hysteresis [14] [15].

The literature shows improvements of PHPs based on wettability modification and capillary unbalancing, although it was never tested the effect of alternating channels with hydrophilic and superhydrophobiic coatings to create capillary unbalancing. The present work is focused on the study of the start-up of a closed loop PHP with alternating hydrophilic–hydrophobic channels (functionalized PHP, bare copper-chemical coating) under different experimental conditions, which is compared to a bare PHP reported by Betancur et al., in 2017 [16].

2. EXPERIMENTAL SET UP

In order to quantify how such coating procedure affects the wettability, a copper surface is functionalized, spreading Glaco® coating to form a thin layer. Then, the advancing (θ_A), receding (θ_B) and the hysteresis contact angles ($\Delta\theta$) of a water-air mixture are measured at the superhydrophobic surface and at a not-functionalized one (hydrophilic) [17]. The measurements are repeated in 5 different points of each surface. Results, in terms of averaged measurement and standard deviation, are shown in Table 1:

Table 1. Wetting properties of Superhydrophobic and Hydrophilic copper surfaces.

Surface	θ_A	θ_B	$\Delta\theta$
Hydrophilic	89°±3.6°	45.5°±5.1°	45.2°
Superhydrophobic	164.5°±2.1°	159.3°±5.1°	5.2°

The alternating functionalized PHP studied in this paper, consists of a copper capillary tube with 4.76 mm of outer diameter (OD) and 3.18 mm of inner diameter (ID), bent in a planar geometry in order to have 5 U-turns at the evaporator. The tube consists of ten alternating channels as shown in Fig. 3.

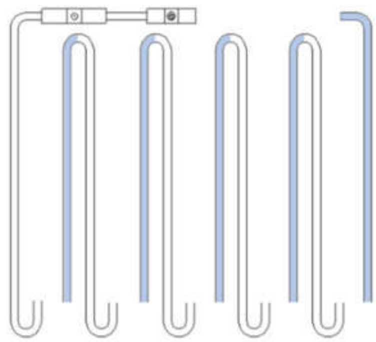

Fig. 3. PHP functionalized (hatched) alternating tubes.

Part of the inner surfaces of the tubes are coated with Glaco®, to create the alternating wettability channels. The selected parts to be functionalized were treated according to the following procedure: 1) Volume of the region to be functionalized was calculated to be 1 ml; 2) At the right end, a pipette containing a minimum of 10 ml of distilled water was connected. A recipient containing Glaco® was located at the left end. The pipette was connected to the pipettor and then to the tube through a silicon hose as shown in Fig. 4a; 3) The pipettor was scrolled up to dislocate the liquid column in 1 ml, as showed in Fig. 4b. When the column of water is dislocated and Glaco® is sucked, it starts to be displaced into the channel to be functionalized; 4) The pipettor was scrolled down until it returned to its initial position allowing, also, that the excess of Glaco® leaves the functionalized channel (Fig. 4c); 5) The tube was disconnected and then placed in vertical position for minimum 15 minutes until the functionalized coating dried. This process was repeated at the other four functionalized channels.

All the hydrophilic and superhydrophobic inserts are connected using a low-outgassing glue (Torr Seal®), in such a way to alternate the hydrophilic and superhydrophobic sections (Fig. 5), building the functionalized closed loop PHP. When the glue dries, the device is vacuumed down in a Vacuum pump (Edwards RV8®) up to $1x10^{-6}$ [mbar]. An Edwards Spectron 5000 Leak Detector® equipment is used to check the device sealing. Finally, the PHP is charged with distilled water in a volume ratio of 50% [8.2±0.1ml]. The water was first degassed by continuous vacuuming cycles, utilizing a volumetric pump. The internal pressure is monitored by a high accuracy pressure transducer (Keller M5-HB®) located at the condenser zone.

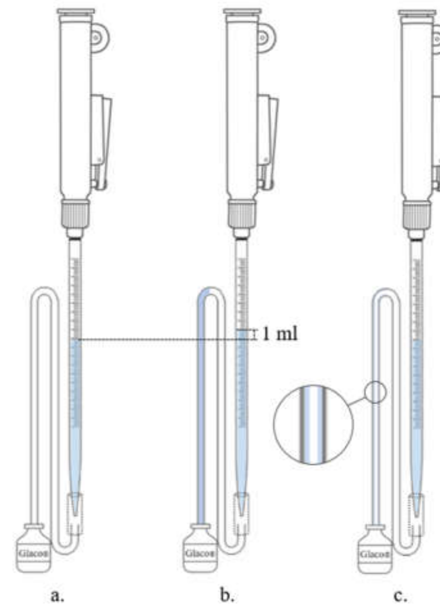

Fig. 4. Functionalization steps.

Temperature distribution of the functionalized PHP is monitored by 16 type T thermocouples (±0.9°C of maximum uncertainty) as shown in Fig. 5. A DAQ-NI SCXI-1000® data acquisition system is used to record data during the experiment. The PHP is assembled in a cold plate formed by two aluminum blocks as shown in Fig. 6. The cold plate is connected to a thermal bath (Lauda® Proline RP855), able to control the bath temperature (±0.1°C).

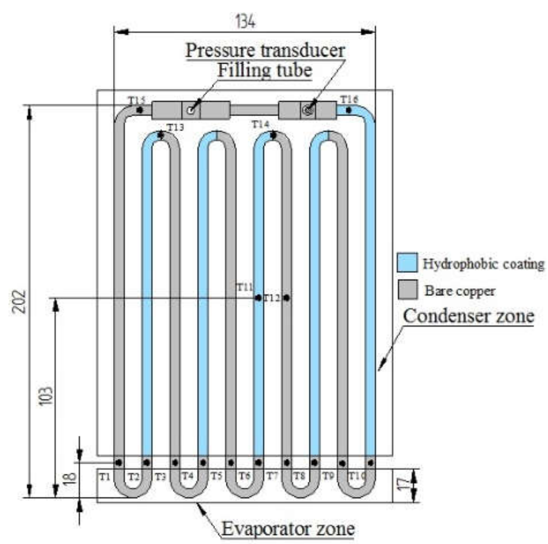

Fig. 5. PHP with superhydrophobic alternating channels.

In order to assure the contact, circular cross section channels are milled on both heat sink plates.

The thermal contact between the functionalized PHP and the cold plate is improved by spreading a thin layer of Omegatherm® 201 thermal grease over the heat exchange contact surfaces. Heat is provided to the evaporator by two cartridge heaters (HLP® type, OD 10 mm and 100 mm length) embedded in the copper block, which are thermally insulated by mineral wool. Heaters are connected to a power supply (TDK-Lambda GEN300-17®) that can provide an electric power input up to 5000W. Complete experimental setup is shown in Fig. 7.

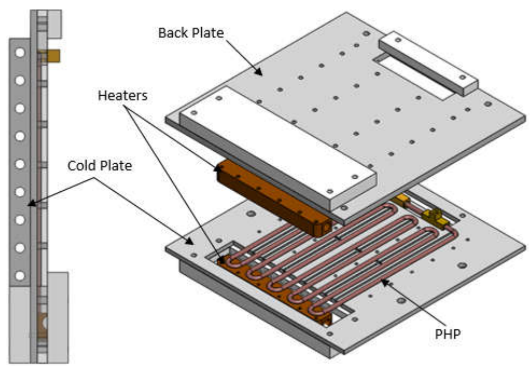

Fig. 6. Experimental block.

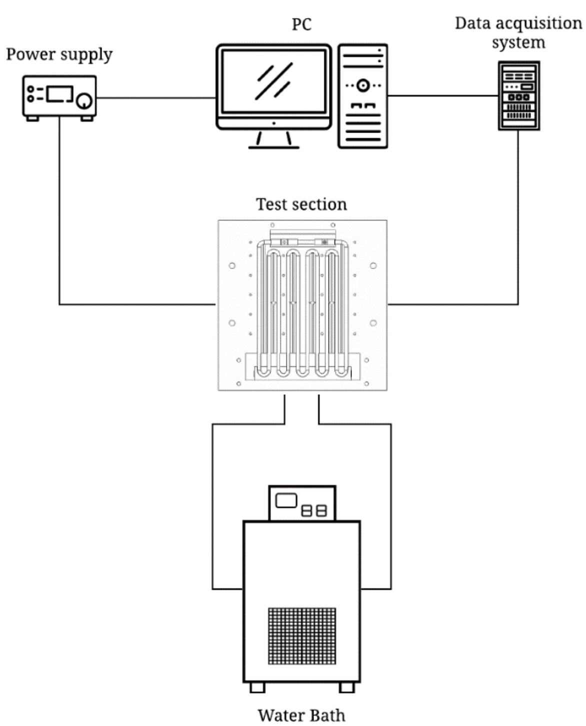

Fig. 7. Experimental setup.

3. EXPERIMENTAL PROCEDURE

The condenser temperature is set at 20°C by the thermal bath control system. Time is given until all the temperatures, both at the evaporator and at the condenser zone, stabilize. Tested power levels are increased and decreased as follows: 20, 40, 60, 80, 100, 140, 180, 230, 290, 350, 290, 230, 180, 140, 100, 80, 60, 40, 30 and 20 [W]. Each power level is maintained for 900 seconds. Experimental procedure was selected to compare to obtained results by Betancur et al., (2017) to analyze the effect of alternating pattern of wettability.

4. RESULTS AND DISCUSSION

Experimental results of functionalized PHP were obtained in the same experimental parameters presented by Betancur et al., (2017)[16] for a conventional PHP. Figure 8 shows temperature measurements for thermocouples 11, 12 and 14, located at the hydrophobic coating tube, bare copper tube and at the transition point between both tube regions, following a single turn inside the condenser, as shown in Fig. 5. For the studied functionalized PHP, thermocouples measurement allows to analyze the difference between a bare channel and alternating channels.

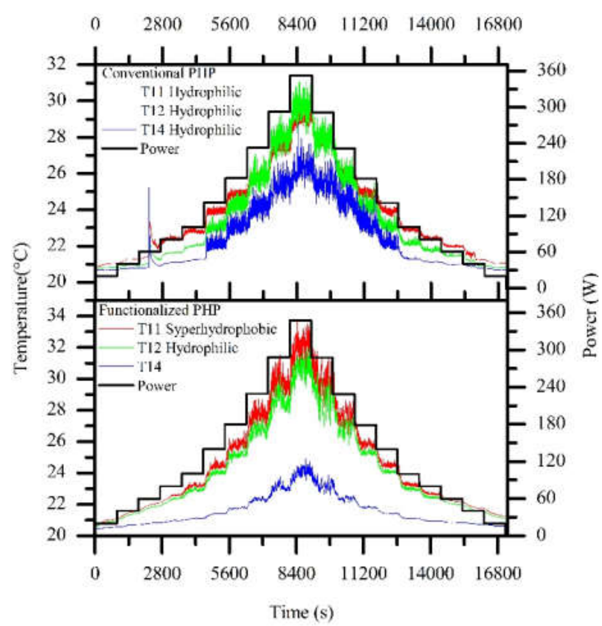

Fig. 8. Temperatures of a single turn for conventional and functionalized PHP.

For the conventional PHP, T14 shows a smaller temperature, due to its distance from the evaporator; a temperature difference between T11 and T12 is observed, with T11 higher for power levels lower than 140W. After this level, T11 and T12 oscillate under similar temperature levels, showing a full activation of the device as PHP. The same performance is observed for decreasing power levels.

However, Fig. 8 depicts that functionalized PHP operation mode was different from the conventional one. T11, which is located on the functionalized with hydrophobic coating tube region, always presents a higher temperature than T12. Moreover, the temperature oscillations are larger for the superhydrophobic inserts rather than those at the bare (hydrophilic) tube regions. These temperature measurements suggest that the flow is following a local preferential direction, which means that the chaotic two-phase flow motion is hindered at the functionalized PHP.

Furthermore, Fig. 8 also shows that conventional PHP needs less time to achieve start-up conditions, observed when the temperatures start to oscillate. For all power inputs, the evaporator temperatures were higher for functionalized PHP (see that the ranges of temperature for the vertical axis are different for the two graphics).

In addition, for the functionalized PHP and for the power decreasing trend, at low power levels, the oscillations stop abruptly and the liquid phase remains in the evaporator, as no fluid oscillations are detected in the condenser.

Figure 9 presents the difference between evaporator and condenser mean temperatures, for both functionalized and non-functionalized (conventional) PHPs as a function of time. This figure also presents the fluid pressure at the condenser zone. One can notice that the PHP oscillations and temperature differences are strongly affected by wettability. Also, in the conventional PHP, oscillation starts after a peak of high pressure that characterizes the PHP activation, which happens at a power of 60W. However, for the functionalized PHP, the initial pressure oscillations happened at almost double heating power level (80W). In addition, the pressure trends are different between the two cases. In the conventional PHP, there is a vigorous peak of pressure during the start-up and, at the same time, all the temperatures at the evaporator decrease abruptly, due to the full activation of the two-phase oscillating flow between the heated and the cooled region. In the functionalized PHP, the pressure peak does not exist, only some oscillations of the average values of temperature can be recognized, without a drop in the heated section.

The low wettability in some sections of the loop hinders a proper full start-up. This could be attributed to the intensification of pressure drops along the superhydrophobic sections. As already pointed out in previous works, the decreasing of the wettability in a capillary tube results in an increment of the pressure drop, as the liquid film formation is delayed within the superhydrophobic tube. Therefore, the heating power needed to activate liquid-vapor phase change is higher than the case in which the loop is all hydrophilic.

Results of ΔT in Fig. 9 allow identifying the start-up and oscillation onset. Functionalized PHP starts up at higher power levels and at higher mean temperature levels. It is possible to identify two different start-up modes for the two PHPs, as explained for Liu et al, 2013 [18]. For both PHPs the heat transfer mechanism before the start-up was conduction.

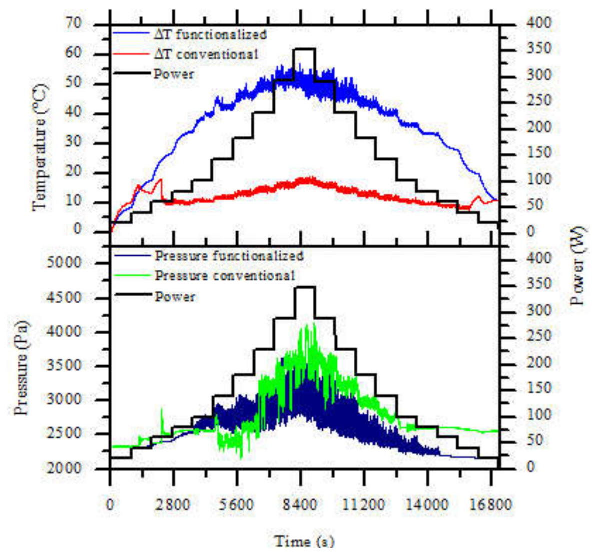

Fig. 9. Mean ΔT and pressure at condenser zone.

Figure 10 presents the behavior of T15 and T16 temperatures (located at the end of the condenser zone) for both PHPs. The observation of these temperatures allows an indication of when the oscillating fluid reaches the condenser upper position, where the pressure transducer is installed.

The temperatures readings for thermocouples T15 and T16 for the conventional PHP, presented in Fig. 10, show that the temperatures are strongly affected by the fluid oscillations, especially when the device achieves start-up conditions, where the oscillations amplitude increase.

On the other side, T15 and T16 temperatures (Fig. 10) for functionalized PHP show a completely different behavior, as the condenser upper region is only slightly affected, for power inputs lower than 140W. One can see clearly a temperature increase with power increase, but the oscillations were almost imperceptible, especially for power levels below 140W. For higher power inputs, T15 and T16 temperatures start to oscillate, but at low amplitudes.

This small temperature oscillation shows that the flow possibly tends to be unidirectional. Further visualization experimental work is necessary to determine the type and direction of flow. Furthermore, T15 (located at the bare cooper tube) shows lower temperature fluctuations than those of T16. Conventional and functionalized PHPs show a different oscillation pattern where the low wettability of the functionalized tube hinders the flow motion.

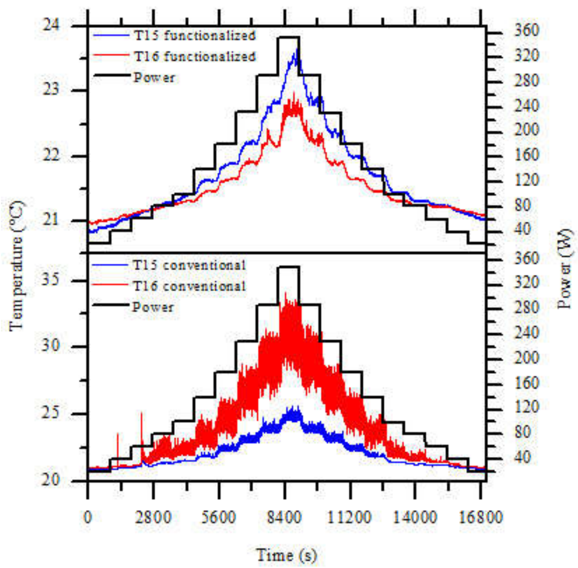

Fig. 10. Temperature performance of T15-T16.

As already mentioned, the pressure losses increases with decreasing the wettability of capillary tubes, as liquid films have difficulties to be formed along the tube. The liquid film is extremely important for the overall flow motion, in the sense that it acts as a lubricant, helping the flow to move along the serpentine. Hampering the liquid formation causes start-up delays and holds back the overall flow motion, decreasing the PHP thermal performance, when compared with traditional PHP operating under the same conditions.

Equivalent thermal resistance (R_t) concept is used to express the performance of the PHPs. R_t is defined as the ratio between the mean temperature difference between the evaporator and condenser (ΔT) and the heating power transported by the PHP(Q):

$$R_t = \frac{\Delta T}{Q} \tag{1}$$

In Fig. 11, the overall thermal resistance is plotted against the power input for functionalized PHP and compared with conventional PHP, for both testing conditions: increasing and decreasing power input levels. The uncertainty for the equivalent resistance was calculated as less than 2%. For both cases, the thermal resistance decreases with the increase of the transported heat power, until the maximum experimentally applied power input (350W). Moreover, for all power levels, thermal resistance is higher for functionalized PHP. Only when the power input levels are small and both PHPs are not fully activated, the thermal resistances presents similar values, as expected as, in this level, conduction heat transfer take the most important role. However, an odd behavior is observed for the functionalized PHP at lower decreasing power input levels, when the resistance tends to a plateau. Actually, after the PHP is activated, even with the power supply decrease at levels lower than those required for its activation, the device remains active. Therefore, for the functionalized PHP, the thermal power necessary to reach start-up is higher than the minimum power required to sustain the fluid motion.

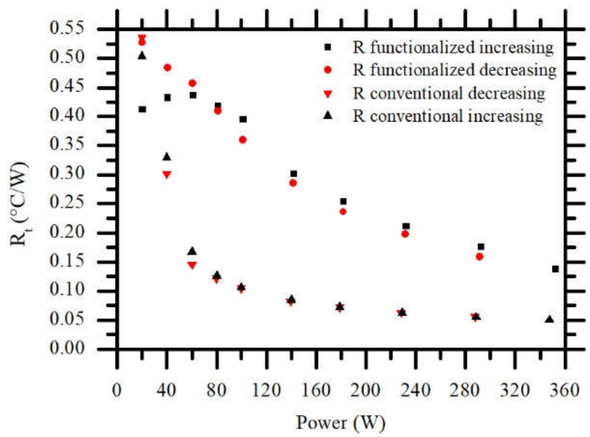

Fig. 11. Thermal resistance.

Figure 11 also shows that, after conventional PHP two-phase flow motion is full activated, the thermal resistance values tend to stabilize in a defined plateau. On the other side, the thermal resistance of the functionalized PHP continues to decrease with increasing supplied power. This can happen because, as the heat transfer due to the oscillation motion is not very effective in this case, the working fluid convection heat transfer, which tends to be the dominant heat transfer mechanism, increases with the temperature increase.

The present testing conditions allow an analysis of the studied PHPs subjected to application of increasing and decreasing powers. A summary of the operating conditions for both PHPs is presented in Table 2. The "Start-up, S" is considered achieved when oscillation is observed in any U-bend, while "full activation condition F", when oscillations are observed in the whole device.

Table 2. Start-up comparison.

	Condenser temperature [20°C]	
Power [W]	Conventional	Functionalized
20	N	N
40	S	N
60	F	N
80	F	S
100	F	F
140-350-140	F	F
100	F	F
80	F	F
60	F	N
40	N	N
20	N	N

N= not working. S=start-up, F=full activation.

The start-up behavior tests results for both PHP under the 80W power application levels are presented in Fig. 12. It is observed that the start-up is quite different for the studied PHPs.

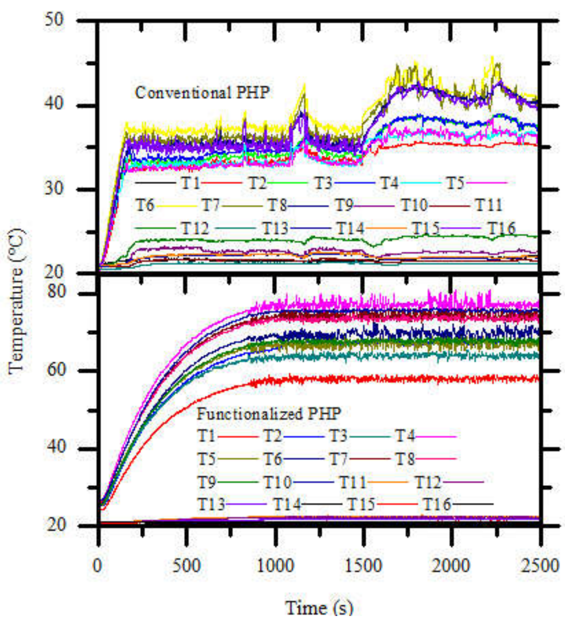

Fig. 12. Comparison of start-up for conventional PHP and functionalized PHP.

Maximum temperature measurement for conventional PHP was ~37°C before start-up. It is interesting to notice that the evaporator temperatures presented very similar behaviors, in which T6 is the highest and T5 the minimum measured value. These thermocouples are located in close to central regions of the PHP in the same U turn. Besides, the thermocouples located at the condenser zone presented very low oscillations. Oscillations are larger during the start-up, decreasing considerably after 1,500 seconds. T15 and T16 were kept at around 21°C, temperature close to the thermal bath setting.

For functionalized PHP, Fig. 12 results show that the start-up happens without temperature decreasing. In addition, oscillations are observed only for the evaporator temperature reading, while the condenser temperatures remained without visible alterations. The highest measured temperature at evaporator zone is observed in the central region (T4). The other evaporator temperatures decrease in the order: T4, T10, T7, T8, T6, T9, T5, T2, T3 and T1, showing a local unidirectionality trend: T5<T6, T9<T10, T3<T4, T1<T2; however T8<T7. The temperatures at condenser zone are kept almost constant remaining around 20°C and, with oscillations observed for T11 and T12 reading, with T11~T12. T15 and T16 do not oscillate. Although local unidirectionality could be observed, the global one possibly does not exist.

5. CONCLUSIONS

The heat transfer performance of the alternating functionalized PHP partially filled with water is investigated experimentally, keeping the condenser temperature constant at 20˚C. Results are compared to a completely hydrophilic PHP, under the same working conditions. The data obtained showed that the thermal performance of functionalized PHP is inferior, presenting increased thermal resistances, which differ from the conventional PHP resistances that vary from around 0.5, for low power input, to 0.15 [°C/W] for higher heat power supplies.

Due to this low heat transfer characteristic, a relevant wall superheating before start-up is observed, as the major heat transport mechanism is the conduction through the solid material. Besides, functionalized PHP start-up does not show an abruptly pressure increase with consequent temperature decrease as observed for conventional PHP. Therefore, wall temperatures are always higher for functionalized PHP when compared to the conventional PHP.

The results also show that the minimum power level necessary to achieve start-up condition in functionalized PHP is higher when compared to power level necessary for conventional PHP. For higher supplied power, temperature oscillations are stronger at the evaporator of functionalized PHP, while in conventional PHP, the temperatures show stable and low amplitude oscillations. In addition, the functionalized PHP start-up is delayed for higher heat transfer rates. However, when it starts to oscillate, it is possible to maintain the PHP working as full activation even with heat inputs lower than the power level necessary to achieve the start-up.

Thermal behavior hysteresis is observed for conventional PHP as increasing or decreasing power causes different effects in the temperature levels of the PHP. This effect can be attributed to the reduction of the viscous and inertial forces of the liquid slugs, resulting from the operation conditions of both PHPs. Further studies are recommended to analyze the effect of hydrophobic layer in operational mechanisms.

In summary, experimental results point out that the inner wettability is a very important parameter that needs to be taken into account during the PHP design. This aspect is the main contribution of the present work to the state to the art in PHPs, as this conclusion is reported for the first time by means of capillary unbalancing using superhydrophobic coating in alternating channels. It is expected that, going on the opposite direction of the present research, enhancing the wettability will enhance the liquid film formation, enhancing, therefore, the working fluid flow motion within the PHP, improving the overall performance of the device. Furthermore, the PHP start-up would be reached at lower heating power levels. This work just described is left as suggestion for future works.

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NOMENCLATURE

Q	: Thermal power (W)
ΔT	: Difference of temperature (°C)
R_t	: Equivalent resistance (°C/W)
θ_A	: Advancing contact angle (°)
θ_B	: Receding contact angle (º)
$\Delta\theta$	: Hysteresis contact angle (°)
$\bar{T}_e$	: Mean temperature at evaporator zone (°C)
$\bar{T}_c$	: Mean temperature at condenser zone (°C)

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