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Abstract. A promising solution in the field of passive two-phase heat transfer devices is represented by Pulsating Heat Pipes (PHPs). They are undoubtedly appealing due to the high heat transfer capability, efficient thermal control, adaptability and low cost. In the last years they are raising concern for space applications that are characterised by extreme environmental conditions, strictly constrains in terms of compactness, reliability and the need to dissipate efficiently heat in microgravity conditions. In this study, the thermal performance of oscillating heat pipes that consists of extra-thin metallic pipes are investigated: the adoption of metallic pipes with an inner diameter less than 0.4 mm permits to couple flexibility and compactness with high heat transfer performance. HFC-134a is used as working fluid. Many authors have investigated the pulsating behaviour of this type of heat transfer devices only considering the average temperature of the evaporator and condenser. In this work, to deeply investigate the oscillating behaviour of the proposed PHP, it is adopted an approach based on the study of the local temperature distributions on the wall of the PHP, acquired with a high-speed and high-resolution infrared camera. The local analysis of the temperature trends is of fundamental importance in the understanding of the complex phenomena that govern the pulsating field.

Introduction

One of the main current issues of technological development is represented by thermal management and energy saving. A primary dare is constituted for example by the cooling of the electronic components considering the rapid and constant process of miniaturization of the chips associated with a continuous growth of the dissipated power: these requirements feed the race for the rising of innovative technologies that guarantee the coupling between high thermal performance and reduced dimensions [1]. A rapidly expanding field of research certainly concerns space applications that additionally are characterised by extreme environmental conditions, strictly constrains in terms of compactness, reliability and the need to dissipate efficiently heat in microgravity conditions [2,3].

A high potential response to these needs is represented by a promising solution in the field of passive two-phase heat transfer devices: the Pulsating Heat Pipes (PHPs). They were invented in the 1990s [4] and they quickly attracted the interest of both researchers and companies thanks to the elevated heat transfer capability, efficient thermal control, adaptability and low cost. They are essentially constituted

by bending a capillary tube alternatively connecting the heating and cooling sections, named evaporator and condenser, respectively. The pipe is partially filled with working fluid which is arranged internally as an alternance of liquid slugs and vapor plugs. The vapor plugs and liquid slugs scattered in the pipes are made self-oscillated due to the temperature difference between the both ends of the PHP [5].

Nevertheless, the noteworthy benefits, the mechanisms that rule PHPs are not yet entirely conceived. To investigate and fully understand the basic principles of their thermal behaviour, many researches have been conducted in recent years [6-10]. However, almost all the studies carried out with the aim of analysing the principles of thermal operation of PHPs, involved the study of the average heat transfer rate over the entire heat transfer area (evaporator or condenser) or the study of the overall thermal resistance of the system.

To improve the knowledge of these devices, in the present work the temperature distributions on the wall of the PHP acquired with a high-speed and high-resolution infrared camera were analysed to deeply investigate the oscillating behaviour of the proposed PHP. The local analysis of the temperature trends is of fundamental importance in the understanding of the complex phenomena that govern the pulsating field.

In particular, in this study it is considered a PHP realised by extra-thin metallic pipes [11] with an inner diameter less than 0.4 mm that permits to couple flexibility and compactness with high heat transfer performance.

Experimental Setup

In figure 1 it is reported a picture of the studied pulsating heat pipe: it is constituted by a stainless-steel capillary tube with inner and outer diameters of 0.32 mm and 0.52 mm, respectively. The pipe is bended 7 times in two directions resulting in 14 turns.
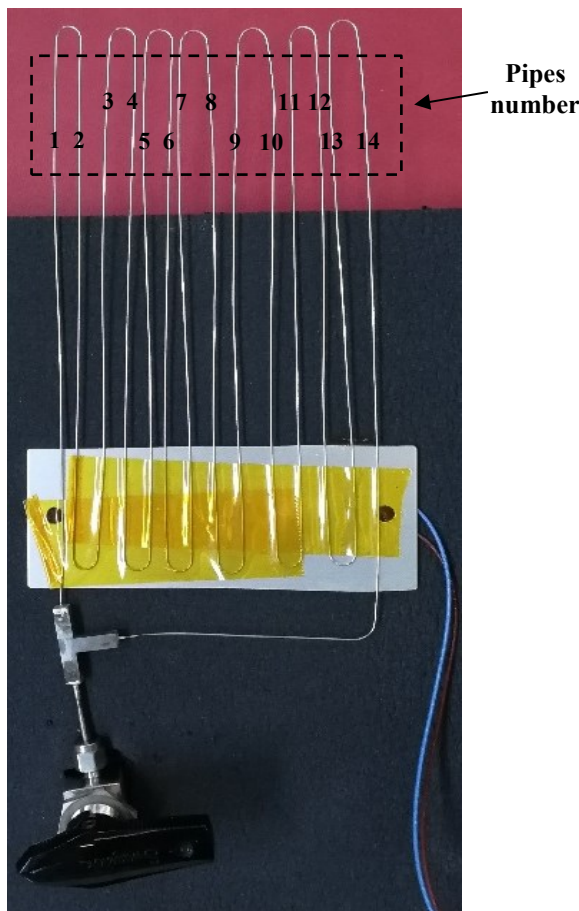

Figure 1. Picture of the studied PHP.

The device is basically composed by 3 sections, i.e. the evaporator, the condenser and an adiabatic section, as it possible to see from the sketch reported in figure 2. Each element is 50 mm long resulting in 150 mm of total length of the apparatus. Under the evaporator zone a brass T-junction connects the ends of the tube, in order to build a closed loop. The T-junction was fitted with a filling/metering valve (see figures 1,2).

In the experimental set up the PHP is placed in a vertical position (90 deg) with the heating section placed at the bottom (as it is shown in figures 1 and 3): in this section pipes are attached by aluminium tape to a 3 mm plate composed by two layers, 1 mm of aluminium and 2 mm of copper: on the back side of the metal panel it is fixed a Polyimide sheet heater with adhesive 3M Y966. This set up solution permits to obtain both a satisfactory uniform thermal contact resistance between the pipe and the heater, and a uniform temperature of the evaporator section.
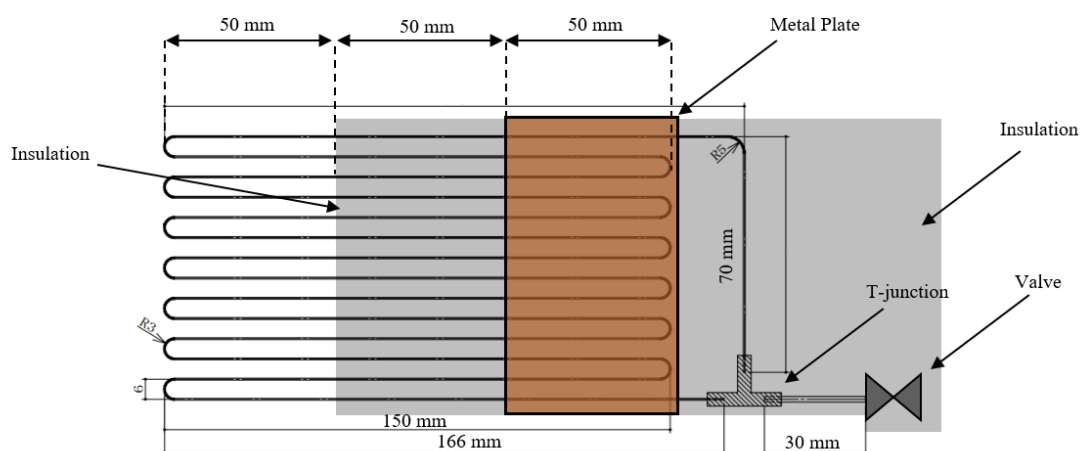

Figure 2. Sketch of the studied PHP.

Heating, adiabatic section, T-junction and valve are covered with a thermal insulation layer of 2 cm of expanded polyurethane as it possible to see from figure 3. The cooling section is the only part of the device that is not surrounded by the insulation material: it is exposed to the environment and it is cooled by natural convection. The device is first evacuated and then partially filled (filling ratio = 48.9 vol% , defined as the ratio of the liquid working fluid volume to the total PHP volume at room temperature) through the valve shown in figures 1 and 2 with 1,1,1,2-Tetrafluoroethane (HFC-134a).
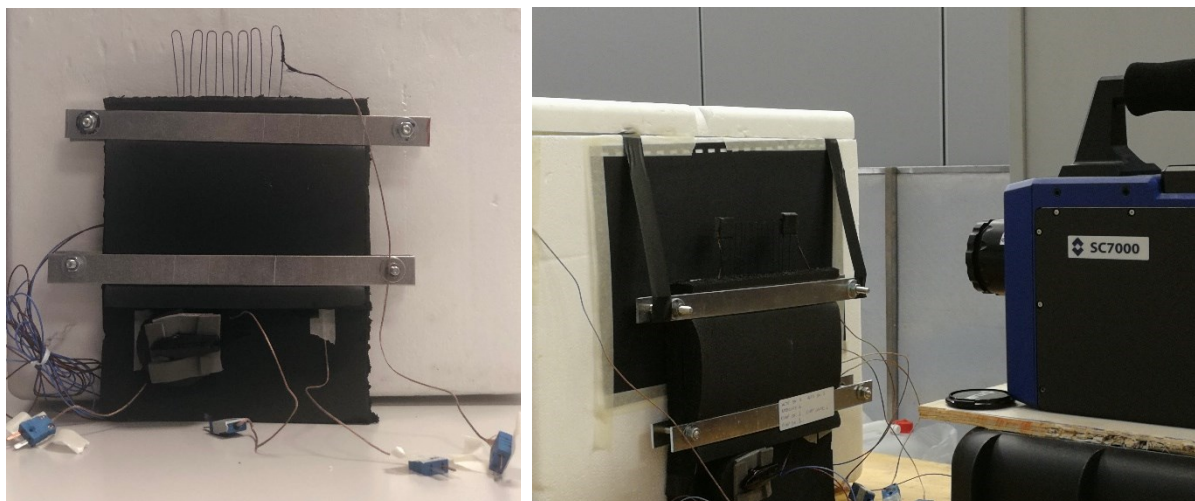
Figure 3. Experimental setup.

Temperature at the heating section is evaluated by means of 3 thermocouples placed on the metal plate; another thermocouple is attached on the sheet heater to detect and prevent overheating.

The temperature of the cooling section is instead monitored by means of an infrared FLIR SC7000 unit, with a 640 x 512 pixels detector array: it permitted to acquire thermal images with an acquisition frequency of 25 Hz. Its thermal sensitivity, as reported by the instrument manufacturer, is 20 mK at 303 K, while its accuracy is ±1 K. As shown in figure 3 the pipes in the condenser section were coated with a thin film of high emissivity paint that changes the surface emissivity without affecting the heat conduction problem in the tube wall. In the present experimental setup, thanks to limiting the viewing angle to less than ± 30°, the surface was considered as a diffuse grey emitter [12].

The effective emissivity of the coating was estimated in situ by shooting a target at different known temperatures, and the value 0.95±0.01 was found. The temperature was also checked in one point by using a thermocouple in order to control the correspondence of the measured values by the two acquisition systems. In figure 1 it is also highlighted the numeration of the different pipes in the condenser section. For the present configuration, the infrared spatial resolution, at target surface, is equal to 0.18 mm/pixel.

The supplied heating power was varied between 0.5 W and 5 W; it corresponds to an average heat flux at the pipe wall between $8 \cdot 10^2$ W/m^2 and $8 \cdot 10^3$ W/m^2. Two different power supplies were employed in order to have acceptable uncertainty values of heating power at both low and high levels. Each heat input step is kept for several minutes to reach the pseudo-steady state. The empty PHP is also tested from 0.5W to 2 W with steps of 0.5W in order to provide a comparison with the purely conductive mode.

Experimental Results

Representative temperature maps acquired by the infrared camera in the cooling section at four instants are reported in figure 4. As expected, the data highlight the pulsating phenomena that characterize the studied device: the temperature distributions exhibit a significant variation along the whole section. This observation confirms that adopting the usual approach based on the computation of the overall thermal resistance of the device starting from the spatially averaged temperature computed by means of few thermocouples located at the condenser and at the evaporator is limiting.

In the present work the thermal resistance was evaluated for each pipe adopting the following formula:

$$R_{t,i} = \frac{T_e - T_{c,i}}{Q_{net}}$$

(1)

where $R_{t,i}$ is the thermal resistance of the i$^{\text{th}}$ pipe, Q_{net} is the net heat power provided at the heating section, T_e is the evaporator temperature and $T_{c,i}$ is the condenser temperature of the i$^{\text{th}}$ pipe. In particular, Q_{net} is the electrical heat input reduced by the heat losses to the surroundings, T_e is obtained averaging the values of the three thermocouples placed on the metal plate, $T_{c,i}$ is found averaging the temperature measured by the infrared camera in the central area of every tube. Both the evaporator and condenser temperatures are evaluated by averaging the measured values over a time interval of approximately 30 seconds.

For what concern the evaporator temperature the small differences among the values measured by the different thermocouples confirm the positive effect of the metal plate in terms of temperature uniformity at the evaporator.

In figure 5 the thermal resistance computed for each pipe is reported versus the heat input at the heating section. Applying the propagation of error procedure [13], it was possible to determine the uncertainty on thermal resistance starting from the uncertainties associated to the directly measured quantities (±0.2 K on T and ±5% on Q_{net}): the maximum uncertainty is ±8 %.

From figures 4 and 5 it is possible to see that, at the same time, there are some pipes in which is possible to observe pulsating phenomena as the rising of hot fluid from the evaporator (i.e. pipes 8 and 10 in figure 4a) or the descending of colder fluid from the condenser (i.e. pipe 3 figure 4a) and other pipes

where instead the oscillating flow it is not activated (i.e. pipes 1 and 13 figure 4a). This confirms that, in order to characterize the PHP thermal behaviour, measuring temperatures with a limited number of thermocouples, as many Authors do, could be really misleading since temperature values strongly depend on the sensors' position. It is also possible to see that in the side pipes (i.e. 1,13,14) the pulsating field is not triggered and the fluid inside them presents a limited motion.
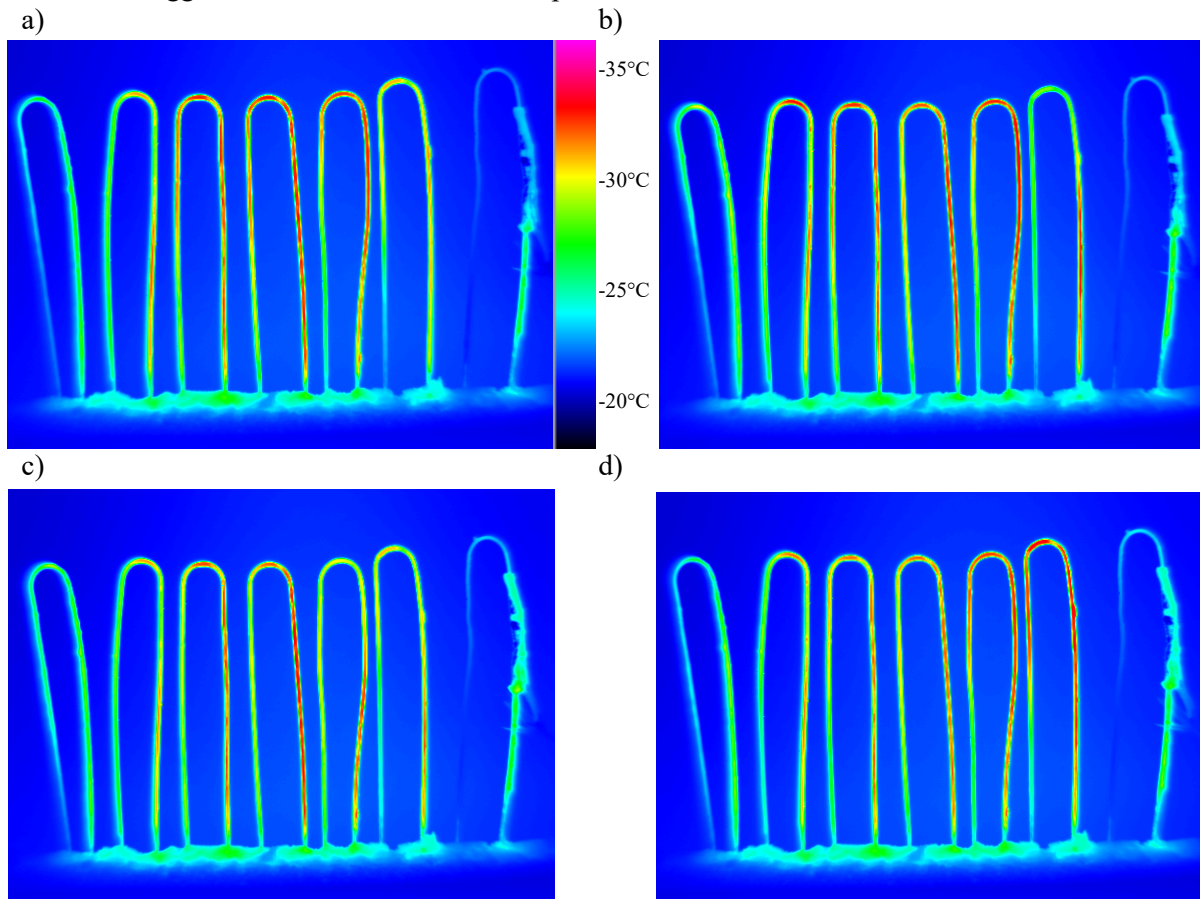

Figure 4. Representative temperature maps acquired by the infrared camera in the cooling section at different instants: a) t = 5.40 s; b) t = 5.64 s; c) t = 5.88 s; d) t = 6.12 s. (Heat input=1.6W).

The reason why the side pipes present this behaviour could be that the big valve connected to the left tube (pipe 1) and the horizontal pipe connected to the right tube (pipe 14) act like cold liquid reservoir. Only when the heat input becomes large, enough heat is supplied to the side pipes and the liquid oscillations start.
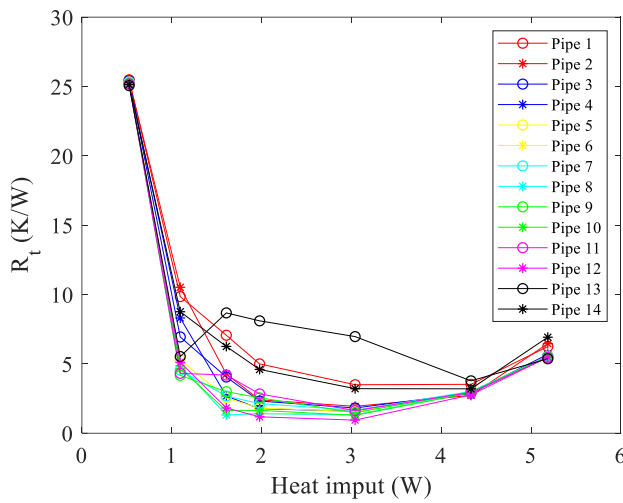
Figure 5. Thermal resistance computed for each tube versus the heat input at the evaporator.

It was computed also an average thermal resistance considering some of the pipes. In figure 6 the average values calculated for two cases are reported: the first considering all the pipes and the second excluding the side pipes. In the same plot it is reported also the value of the thermal resistance obtained in case of empty device.

It is possible to see from figures 5 and 6 that the pulsating heat pipe for heat input values lower than 1 W it is not activated. In fact, the thermal resistance remains almost identical to the one observed for the empty pipe: the small differences are due to the fact that respect to the empty pipe in this case it is also occurring the conduction towards the motionless fluid. This comparison indicates that the device does not start up: the fluid inside is almost motionless and the most relevant phenomenon that governs the heat transfer is conduction. The activation begins for heat input of about 1 W where the transport phenomena, i.e. the thermally induced oscillations, significantly reduce the overall thermal resistance respect to the empty device.
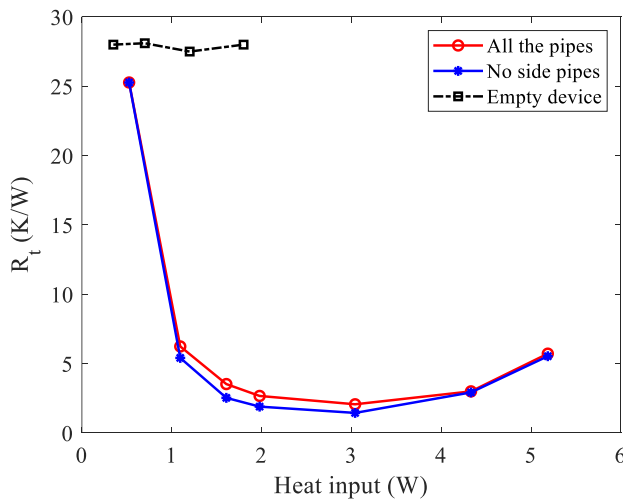
Figure 6. Average thermal resistance.

The best performance of the instrument with the tested filling ratio can be observed for heat inputs of 1.5 W, 2 W, 3 W while instead for a value around 4 W the efficiency starts to deteriorate, and a possible thermal crisis of the system seems to appear for 5 W.

In order to add information on the oscillating behaviour, in figure 7 there are shown the temperature distributions of one representative pipe of the device (i.e., central point in ventral pipe of the adiabatic section) along a time interval of almost 30 seconds for different heat inputs: for all the reported cases

the acquisition starts 10 minutes after the setting of the electrical power in order to reach the pseudo-steady state.

Different types of pulsations (amplitude and frequency) could be observed at different heat loads. For 0.5 W since the pulsating heat pipe not yet start up it is not possible to detect any kind of oscillation.

Around 1 W the device starts up and when the heat input is small with a certain amount of liquid inside the PHP, piping which is liable to be evaporated and piping which is not likely to be interested are generated depending on the gas-liquid distribution state in the PHP: a phenomenon of slow pulsations with great temperature variations is observable for this heat input. The frequency of this slow pulsations is so low that it is not observable in figure 7. A clear oscillatory field is observable also for 1.6 and 2 W with an increasing oscillation frequency and decreasing amplitude.

When larger heat inputs are applied the oscillations become more frequent and they are accompanied by a lower variation of temperature.
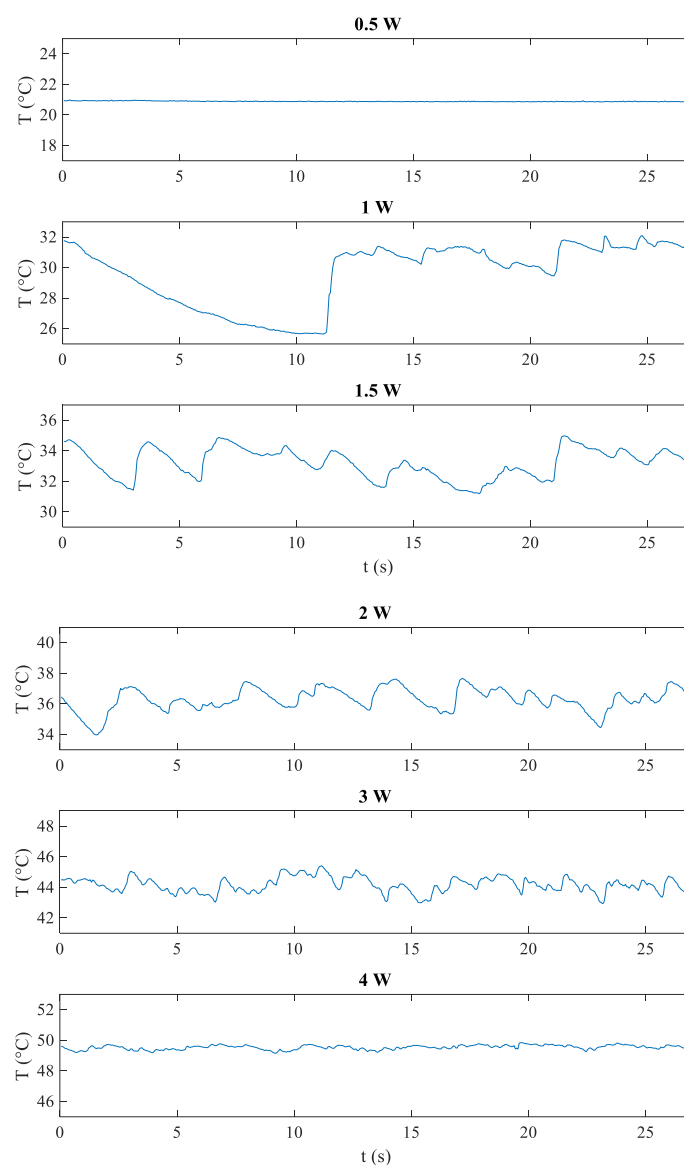

Figure 7. Temperature distributions of one representative pipe of the device vs time for different heat inputs

In order to add details about the different types of temperature oscillations that could be observed by varying the heat loads in figure 8 there are reported the predominant amplitude and frequency of the

oscillations reported in figure 7. As it is possible to see from figure 7 it is not possible to define a unique characteristic frequency or amplitude of the oscillations for a specific value of heat load: nevertheless, it is conceivable to determine predominant frequency and amplitude values by counting the number of the main crests and troughs over 30 seconds and valuing their average amplitude. This approach, although rather coarse, gives repetitive results that are reported in figure 8. A more precise frequency analysis will be performed in further works.

The oscillation frequency it is not reported for heat loads of 0.5 W and 5 W: the reason is that at 0.5 W, since the device doesn't start up, there is not any oscillation and that at 5W the oscillations are still present, but they are very difficult to measure.
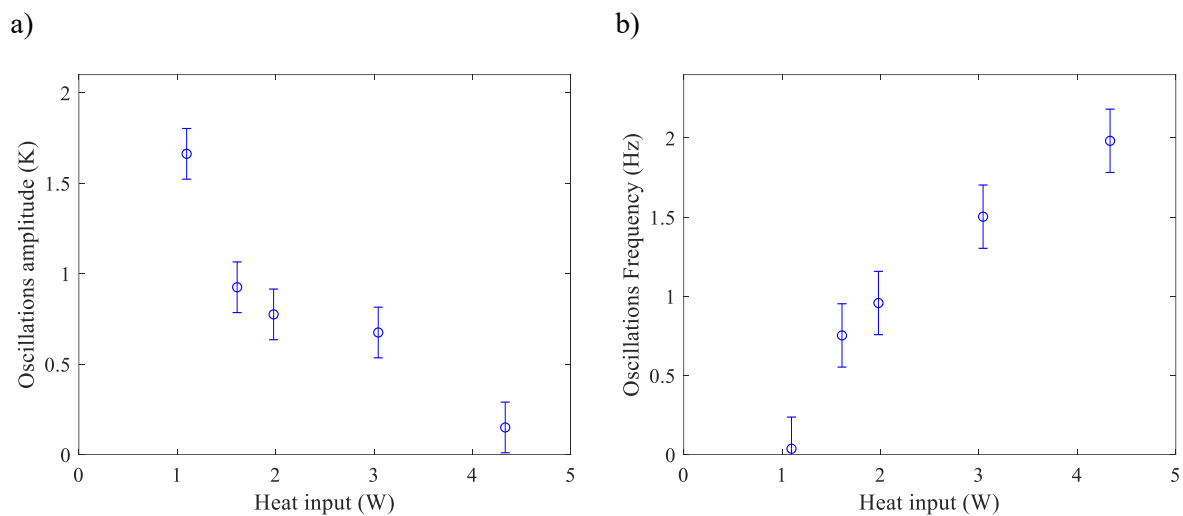
a)   b)

Figure 8. Predominant amplitude (a) and frequency (b) of the temperature oscillations that characterise the pulsating field.

The highest value of amplitude is spotted for the heat input of 1W where the activation of the PHP starts. In this condition a phenomenon of slow pulsations is observable. For this heat load the oscillation frequency presents the minimum value while its amplitude shows the maximum rate.

Increasing the heat input the frequency of the oscillations increase and it is accompanied by a lower amplitude.

Conclusions

In the present work the thermal performance of oscillating heat pipes that consists of extra-thin metallic pipes were studied. In this work to deeply investigate the oscillating behaviour of the proposed PHP it is adopted an approach based on the study of the local temperature distributions on the external wall of the PHP acquired with a high-speed and high-resolution infrared camera. The local analysis of the temperature trends it's of fundamental importance in the understanding of the complex phenomena that govern the pulsating field. The activation of the device began for 1 W where the thermally induced oscillations, reduced significantly the overall thermal resistance respect to the empty device. The best performance of the instrument with the tested filling ratio was observed for heat inputs of 1.5 W, 2 W, 3 W while instead for a value around 4 W the efficiency started to deteriorate, and a possible thermal crisis of the system seemed to appear for 5W. Eventually, different types of pulsations (amplitude and frequency) were observed at different heat load: for 1W the oscillation frequency presents the minimum value while its amplitude show the maximum rate and a phenomenon of slow pulsations is observable for this heat input. Increasing the heat input the oscillations become more frequent but with a lower amplitude.

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