Applied Thermal Engineering 62 (2014) 470–480

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Infrared thermography of a pulsating heat pipe: Flow regimes and multiple steady states

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HIGHLIGHTS

- PHP tested with varying heat powers under vertical orientation.
- Tube wall and inside fluid temperatures measured in the evaporator.
- Infrared temperature visualization correlated to internal fluid motion.
- Multiple pseudo-steady states are identified during long operation.
- Occurrence of multiple operating states depends on input heat power.

ARTICLE INFO

Article history:
Received 16 July 2013
Accepted 23 September 2013
Available online 12 October 2013

Keywords:
Pulsating heat pipe
Infrared thermography
Temperature oscillations
Multiple-steady states

ABSTRACT

Understanding of the operational characteristics of a closed loop Pulsating Heat Pipe (PHP) with non-intrusive spatial and temporal measurement of tube wall temperature by high resolution infra-red thermography (IRT) has been attempted in this work. The PHP is made of a copper capillary tube of internal diameter of 2.0 mm and has eight turns each in the evaporator and condenser section. It is operated in vertical heater down position with water as the working fluid. The local temperature field of the PHP surface is measured by IRT while a micro-thermocouple is used to measure the local fluid temperature. IRT field information throws light on several important operational features and helps, not only to correlate the temperature foot-print with thermal performance but also to qualitatively identify the internal flow characteristics as the heat power input to the system is increased. The PHP displays different flow behaviour, viz., no-flow, intermittent oscillatory flow, oscillatory flow with bulk circulation, with corresponding unique thermal performance. In addition, this study clearly reveals that PHPs exhibit multiple steady states at intermediate heat input powers. While this phenomenon has been observed for single-loop PHP system earlier, it is reported here for the first time in a multi-turn device. The overall thermal resistance of the device decreases from ~1.90 K/W to 0.24 K/W, with increasing input heat power from 30 W to 500 W. The overall thermal performance of the device makes is quite an attractive solution for many potential high heat flux thermal management applications.

1. Introduction

A pulsating heat pipe/oscillating heat pipe is essentially a passive two-phase heat transfer device, which also belongs to a special category of wickless heat pipes. In the contemporary times, thermal management poses demanding challenges in many domains of technology, such as microelectronics, refrigeration, HVAC, automobile sector, space, nuclear and other emerging systems. While in many applications effective handling of the quantity of heat power is an issue, in other systems, the heat flux is critical. In some systems, such as power electronics thermal management must address both these challenges simultaneously. PHPs were introduced in the mid-1990s by Akachi [1,2], incorporating the concept of self-sustained thermally driven oscillating two-phase, single component systems, for transfer of heat along an applied thermal gradient. The concept involves no wick structure, it is extremely simple to construct (only requires a long tube of capillary dimensions) and is inherently suited for high heat flux thermal management [3–5]. Several possible manifestations of the primary heat transfer structure can be easily obtained. Moreover, it has been

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http://dx.doi.org/10.1016/j.applthermaleng.2013.09.041

Nomenclature

A	Area (m^2)
d	Diameter (m)
K	Thermal conductivity (W/mK)
L	Length (m)
n	Number of parallel channels (–)
Q	Heat power (W)
R	Thermal resistance (K/W)
T	Temperature (°C)
$\overline{T}$	Average temperature (°C)

Subscripts

a	adiabatic
avg	average
c	condenser
e	evaporator
cr	cross-section
eff	effective
tot	total
out	outer
w	wall
∞	cooling medium/ambient

effectively shown that the device can be designed to operate at any orientation without substantial penalty on overall thermal resistance [6–8]. In recent times, several groups have envisaged a range of applications for pulsating heat pipe, sometimes as a stand-alone system and on other occasions, in combination with a regular wicked heat pipe or a loop heat pipe [8–13]. It is now known that, while the structure and construction of the system are relatively easy, the system dynamics is not so straightforward and depends on several intertwined operational, thermo-physical and geometrical characteristics [4,5,14,15]. In the past decade, there has been a spurt of research activity, primarily on two fronts (a) Experimental approach to better understand the system dynamics and generate global and local data to help construct a mathematical model [6–8,14–18] and (b) Suggesting governing equations for motion and heat transfer to better predict the heat transfer rates [19–24].

Based on the existing literature survey, it is clear that even though a PHP has a simple structure, it has a complex thermo-hydrodynamic operational characteristic due to combination of several two phase flow instabilities involved. Hence, several researchers have worked on understanding the device operation in the last decade. These experiments have revealed that the internal fluid oscillations are coupled with the ensuing temperature oscillations of the device. It is important to understand the coupling between the fluidic motion and the resulting temperature oscillations which drive the system dynamics. The infrared thermal imaging technique is relatively new and also gaining importance as a powerful non-intrusive method. In this context, this paper focuses on understanding the pulsating heat pipe operation with spatial and temporal measurement of temperature by high resolution infrared thermography. In addition, the PHP system has been operated for continuous period of over 11 h and multiple steady states have been observed. The IRT data is correlated with the thermal performance and possible internal flow oscillation characteristics have been proposed. Results of the present study are expected to augment the present understanding of the device operation.

2. Experimental setup description and procedure

The major sub-parts constituting the experimental set-up are as shown in Fig. 1. It consisted of a PHP assembly, a multichannel PC-DAQ (National Instruments® NI-9213, NI-cDAQ 9162), an IR video-camera (FLIR® SC6000, 640 × 512 @30 Hz, wave length range 3–5 μm, 25 mK sensitivity) for spatio-temporal thermographic measurements and a constant temperature thermostatic cooling water circulator bath (Haake ®, DC-30, K200). The PHP was made of copper capillary tube having ID = 2 mm and OD = 3 mm, with eight turns (each in the evaporator and condenser) forming a closed loop. The inner radius of each U-turn was about 6 mm. The total length of the capillary tube used was about 3942 mm and the total internal volume was equal to 12.5 ml. DI water was used as the working fluid (by 60% of total internal volume of tube). The PHP had a total height of 245 mm and length of 185 mm. The U-turns of the copper capillary tube in the evaporator section were embedded within an aluminium block (220 mm × 60 mm × 4 mm) having suitable engraved channels. The fit was interference type, with the application of thermal heat sink compound (RS Component® #554-311). A flat surface mountable mica heater (MINCO® with R_{int} = 22.4 Ω) was fixed behind the aluminium block as shown, and was supplied by a stabilized AC power source. The condenser section was also similarly embedded within another aluminium block (220 mm × 90 mm × 4 mm). The back side of the condenser aluminium plate was exposed to cooling water coming from the thermostatic circulator at sufficiently high mass flow rate so as to maintain near isothermal conditions.

Before the experiments, the PHP was first evacuated to less than 10^{-4} mbar by the combination of rotary pump (Varian®, DS1020) followed by turbo-molecular pump (Varian®, V-70), after which the working fluid was partially filled (60% by total volume of the tube) through a micro-metering filling valve. Four micro-thermocouples (Omega®, K type, 0.3 mm, accuracy = ±0.2 °C after calibration) were located in the middle of adjacent tubes of evaporator section for measuring the evaporator wall temperature as shown in Fig. 1a, and one more thermocouple was located inside the PHP capillary tube through a micro-hole sealed with high temperature thermal cement (see Fig. 1a); this was used to measure the local fluid temperature inside the PHP tube. The whole setup bench was placed in a dark black screen enclosure to minimize external and reflected radiation to interfere with IR thermography. The front exposed surface of the PHP was coated with a special high emissivity (Nextel®; emissivity = 0.965) black paint coating for getting consistent IR energy from the exposed surface of the PHP structure. The heat power to the evaporator was increased and temperatures were recorded with a frequency of 10 Hz. The IR video was also recorded for each test at a frequency of 30 Hz. All reported tests are for vertical bottom heat mode.

To evacuate the PHP capillary tube, it was connected to a rotary roughing pump (Varian®, DS1020) followed by a turbo-molecular pump (Varian®, V-70) through a micro-metering PEEK® value. After reaching a desired vacuum level of 10^{-4} mbar, the metering valve was closed and the vacuum pump set up was disconnected. The PHP tube was then connected to a container filled with degassed and deionized water. Appropriate quantity of the working fluid was then administered into the system. Condenser cooling water was set at the desired level and heat input was given in specified steps. At each heat input level, the PHP was operated till a quasi-steady state temperature profile was obtained; this typically takes about 40–80 min depending on the applied heat input. IRT and thermocouple data were recorded simultaneously.

For data reduction, the primary data from IRT and thermocouples were processed to get the total thermal resistance and the

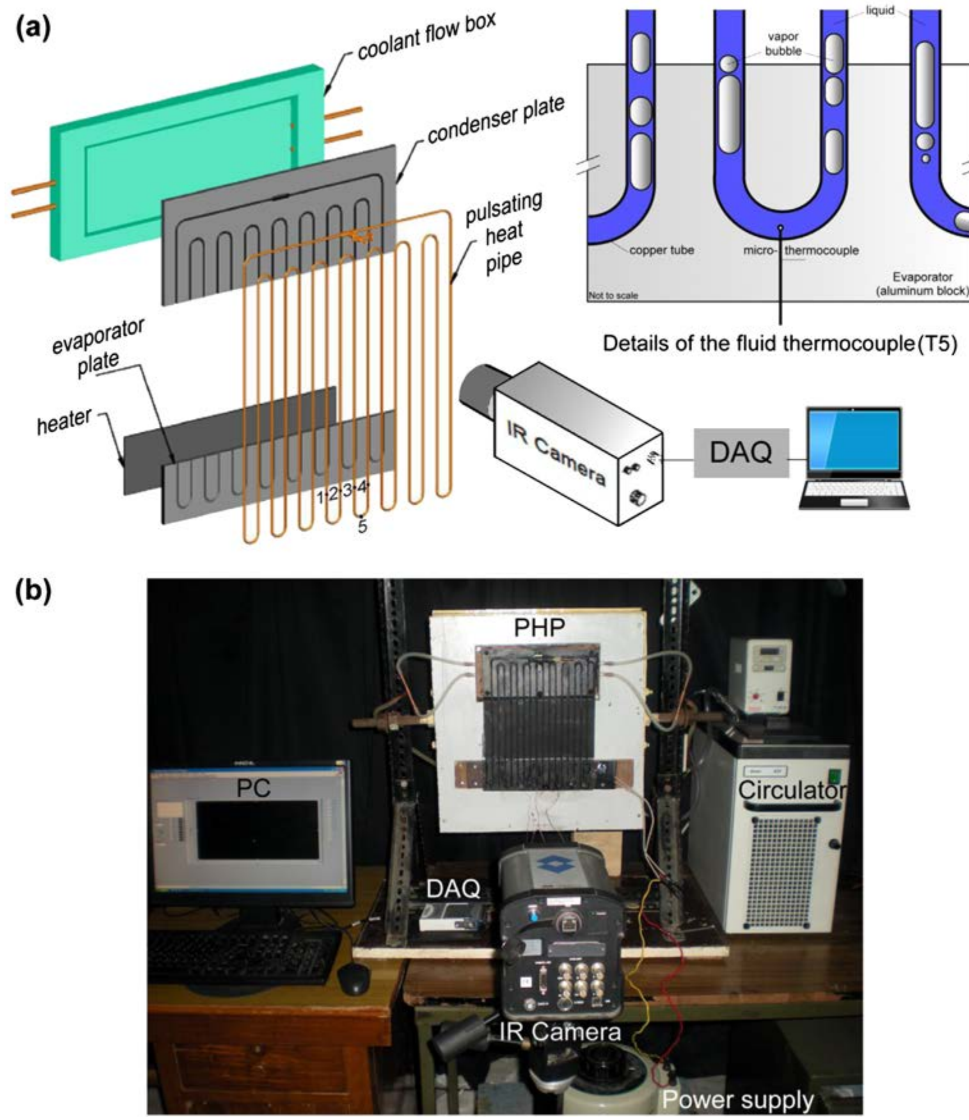

Fig. 1. (a) Schematic diagram of the PHP experimental setup along with the details of the thermocouple T5 embedded in the evaporator U-turn for fluid temperature measurement and (b) Photograph of the entire setup with all the peripheral systems.

effective thermal conductivity of the PHP system. The total thermal resistance of PHP (R_{tot}) is defined as the ratio of temperature difference obtained between evaporator wall and cooling medium of condenser section ($\overline{T}_w - T_\infty$) to the heat power ($Q$), given by:

$$R_{tot} = \frac{(\overline{T}_w - T_\infty)}{Q} \quad (1)$$

$$\text{where,} \quad \overline{T}_w = \frac{T_1 + T_2 + T_3 + T_4}{4} \quad (2)$$

All the thermocouples embedded on the evaporator wall were calibrated in-situ and the average temperature obtained by them was equivalent to the average temperature obtained from the IR thermographs. The effective thermal conductivity of the composite PHP tube system can therefore be obtained as:

$$K_{eff} = \frac{L_{tot}}{A_{cr}}\frac{1}{R_{tot}} = \frac{L_{tot}}{A_{cr}}\frac{Q}{(\overline{T}_w - T_\infty)} \quad (3)$$

$$\text{where,} \quad A_{cr} = n\cdot\pi\cdot d_{out}^2/4 \text{ and } L_{tot} = \frac{1}{2}(L_e + L_c) + L_a \quad (4)$$

3. Results and discussion

3.1. Temperature oscillations and corresponding fluid movement

The profile of the wall temperature oscillations (fluctuations) obtained by the thermograms provides a clear indication of the possible flow behaviour of the working fluid inside the PHP tube during the tests. Therefore, series of experiments are performed with varying heat powers to understand the PHP behaviour. As noted, the device is always mounted in the vertical bottom-heat orientation, in which the evaporator section is at the bottom and condenser section is at the top.

Figs. 2 and 3 show the temperature oscillations profiles of the wall and fluid of the evaporator section for different heat powers. The data in Fig. 2 corresponds to heat power from 20 W to 150 W, while that reported in Fig. 3 corresponds to 175 W–250 W. Several observations regarding the internal fluid behaviour can be

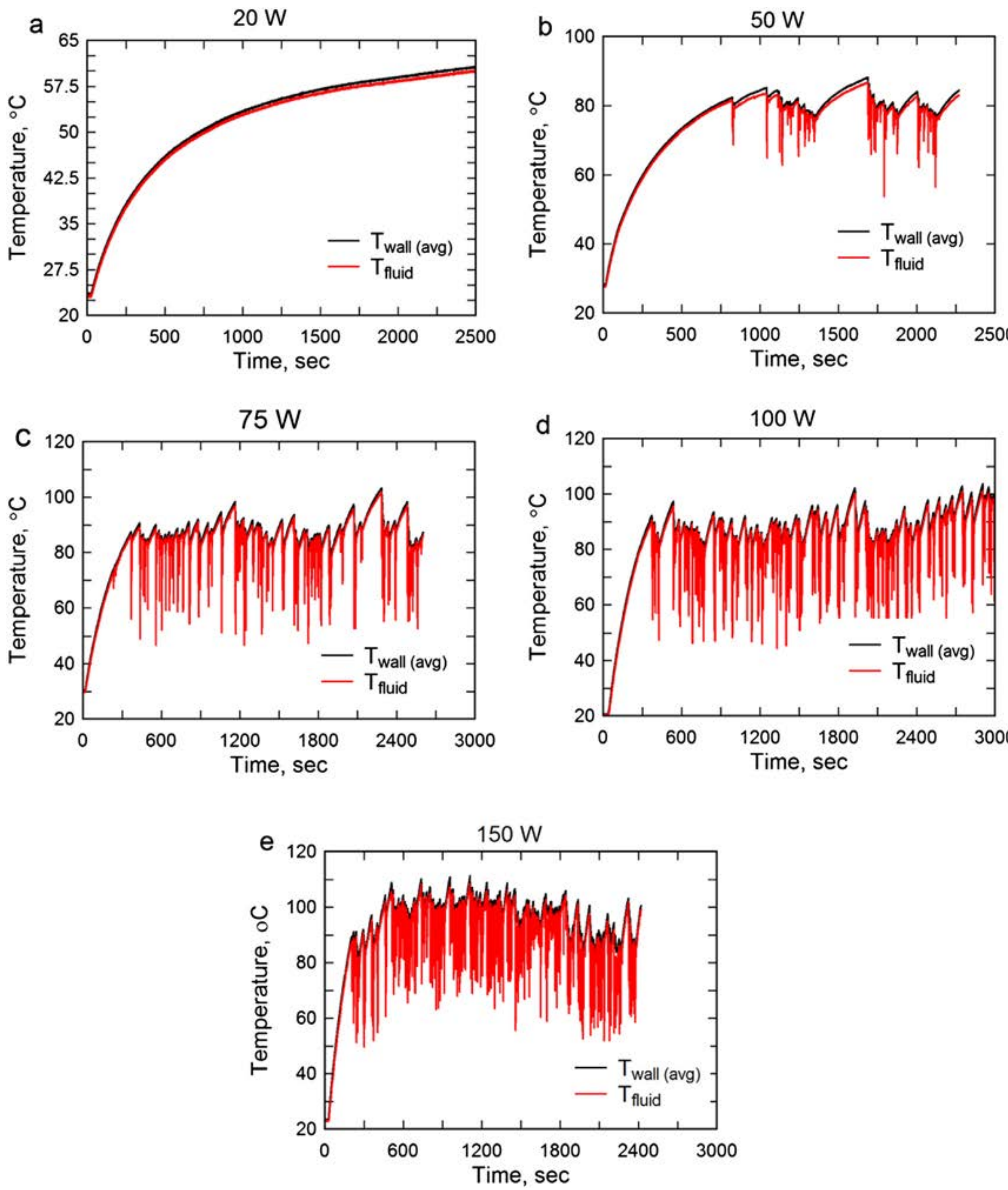

Fig. 2. Temporal evolution of temperature oscillation profiles of wall average and fluid temperatures in the evaporator section for different input heat powers (a) no oscillation (b) start-up oscillations and (c) to (e) intermittent oscillations.

ascertained by the temperature data. At low heat input (e.g., 20 W), the device fails to start-up due to insufficient power to generate bubble pumping action, as will be discussed further in detail below. As the heat flux increases, fluid temperature oscillations are clearly seen, indicating the start of internal oscillations, which are intermittent at low heat powers (50 W–150 W), thereafter becoming more uniform. The internal oscillations of the cold fluid exposed to the condenser section and the hot fluid exposed to the evaporator lead to the oscillations of the fluid temperature. Thus, the local fluid temperature variation corresponds to real fluid oscillations of working fluid inside the PHP capillary tube. It is found that the temperature oscillations of wall and fluid temperature, reach a pseudo-steady state within about 3–5 min at higher heat powers and the oscillation frequency increases with increasing heat power. It is further observed that there is more vigorous oscillation in fluid temperature compared to that of wall temperature due to thermal capacity of the tube material (and the adjoining evaporator block), which damps the oscillations.

In the next test, the heat power is increased from 175 W to 250 W (Fig. 3). Simultaneously, IR visualization of the device is also recorded at different heat power inputs, in order to better understand the device behaviour (Fig. 4); this will be elaborated in the subsequent sub-sections. Here again, it is interesting to note that the ‘footprint’ of the internal fluid motion can be ‘seen’ through the spatial temperature distribution of the tube temperature obtained by IR thermography. There is a clear synchronization found between the tube wall temperature oscillation and internal working

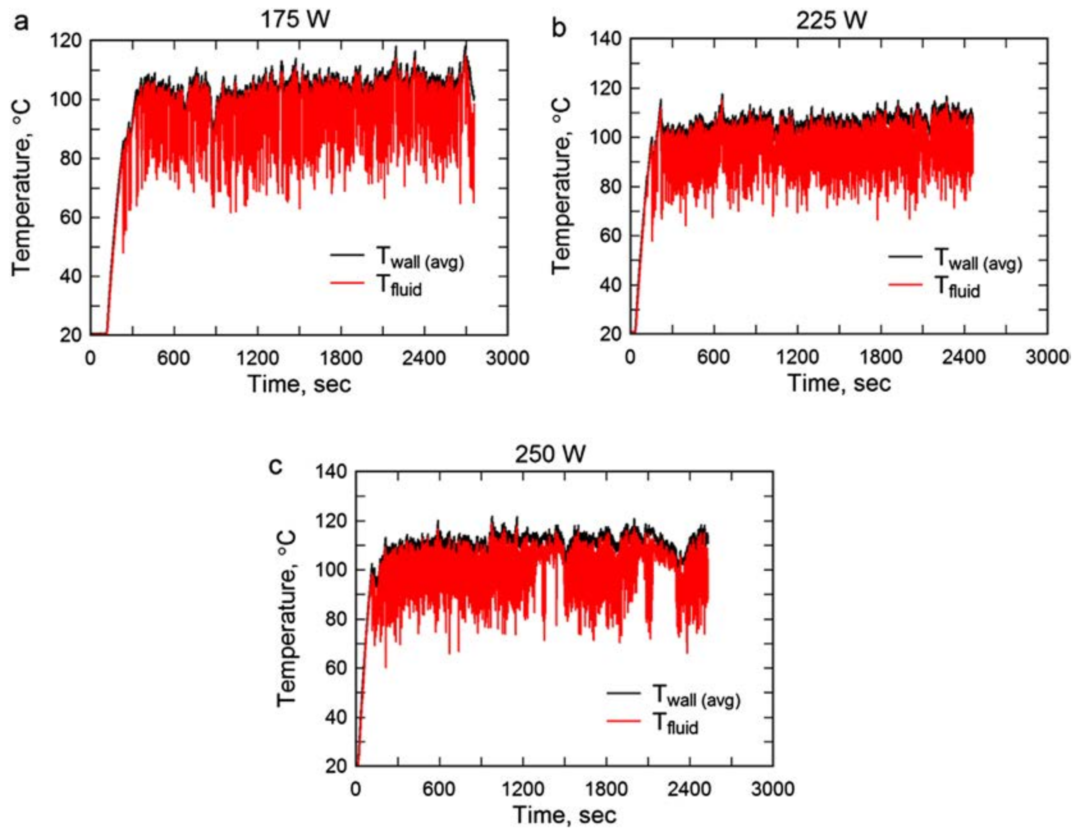

Fig. 3. Temporal evolution of temperature oscillation profiles of wall average and fluid temperatures in the evaporator section for different input heat powers for continuous oscillations of the working fluid.

fluid movement, which can be inferred by the IR data as well as fluid thermocouple data. Based on series of experimental runs, three different broad temperature oscillations profiles have been clearly identified, which will be discussed next, namely – start-up failure (Section 3.1.1), start-up and intermittent oscillations (Section 3.1.2) and, continuous fluid oscillations with or without circulation (Section 3.1.3). In addition, multiple pseudo-steady states have been recorded at intermediate power levels (Section 3.2). Preliminary data also indicates that increasing the input heat power suppresses the possibility of getting multiple steady states in the system, as the flow tends to take up circulatory motion in one direction with superimposed flow oscillations (Section 3.3). Finally, the overall thermal performance of the device is discussed (Section 3.4).

3.1.1. Start-up failure of PHP

There is no temperature oscillation seen at 20 W of heat power (Fig. 2a), either for fluid or for the PHP tube wall. The spatial temperature profile of the evaporator section obtained from IR thermography shows just a plain simple static temperature rise, attributed to simple conduction type of heating. As has been observed by many earlier studies, which use a transparent material for visualization [8–10,13], the fluid remains nearly stationary if there is no sufficient motive thermal power for generating the necessary bubble pumping action for creating self-sustained oscillations of the internal working fluid. It is evident that this level of input heat power is not able to cause sufficient pressure perturbation inside the device to start-up the fluid oscillations i.e., the device fails to initiate any fluid action and effectively, there is no heat transfer operation observed in the system.

3.1.2. Start-up and intermittent temperature oscillations of PHP

The wall temperature oscillations commence i.e., initiates at about 50 W heat input (Fig. 2b), corresponding to a heat flux of about 1 W/cm^2 based on the PHP tube ID. Intermittent oscillations are seen thereafter, wherein a 'start-stop' behaviour [5] is clearly observable. The evaporator wall temperature starts rising, followed by a sudden dip (which is also correlated with the fluid thermocouple temperature suggesting fluid motion), and then again a rise. In other words, the fluid movement is initiated suddenly at a specific time, and then the fluid movement stops for some time, and then it starts again. The 'stop-over' time period gets shorter with increasing heat power input. The corresponding thermographs for such an intermittent operation are seen in Fig. 4b. In addition, each tube behaves somewhat differently as regards temperature oscillation, which, in fact is a characteristic feature of PHPs which is responsible for ensuring sufficient perturbation levels. This essentially means that there is slight variation of heat transfer coefficient in adjacent tube sections due to natural mal-distribution of the two phases of the working fluid inside the device. From the thermographs it can also be inferred that bulk circulatory with oscillating flow takes place intermittently. However, the bulk circulatory flow changes direction in an arbitrary fashion. In the 'stop-over' time interval, the fluid waits for a while to get sufficient energy before it can possibly push adjacent liquid slugs towards the condenser section. This qualitative operations behaviour goes on till about 150 W heat input (Fig. 2b, c, d and e). As the heat power increases, the oscillating frequency keeps on increasing.

3.1.3. Continuous temperature oscillations of PHP

Further increasing heat power from 175 W to 250 W (Fig. 3a–c), there is a qualitative as well as quantitative change in the

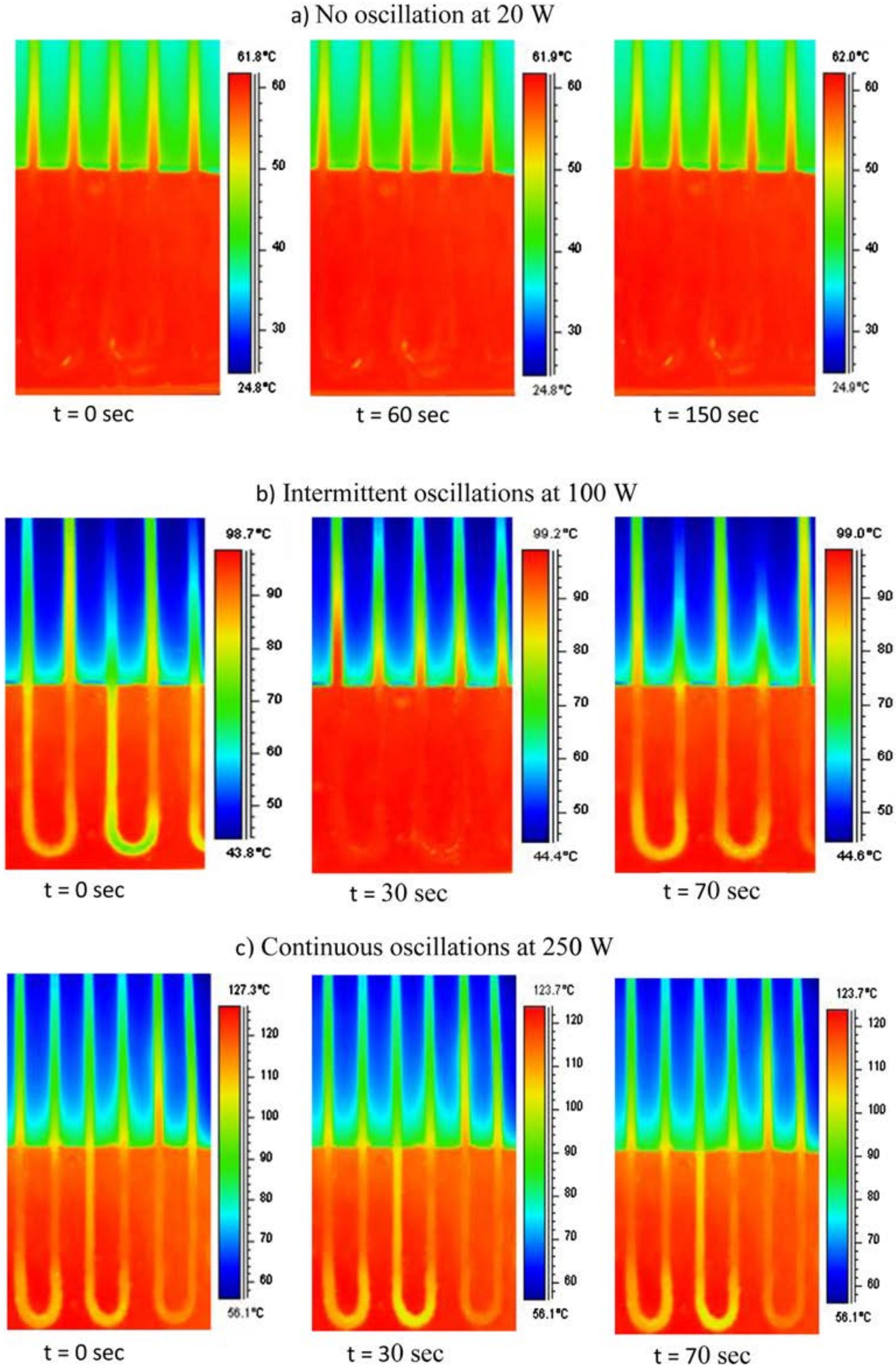

Fig. 4. IR temperature profiles for increasing thermal input power: the temperature scale is given alongside.

temperature oscillations of the fluid and wall temperature. Firstly, it is observed that the thermal resistance of the fluid dramatically improves as the device continues to absorb heat power without substantial increase in the evaporator temperature. This is attributed to occurrence of continuous fluid movement inside the tubes of the device, as depicted in the corresponding thermographs (Fig. 4c). The fluid oscillatory movement is fully and vigorously initiated in this stage, coupled with some degree of circulations. The thermographic video observation clearly reveals this behaviour. However, even at this stage, complete circulatory flow is not observed through the thermographs or the fluid thermocouple measurement. Also, as noted earlier, different tube sections have different temperature fields at any given instant of time, suggesting randomness in the system dynamics.

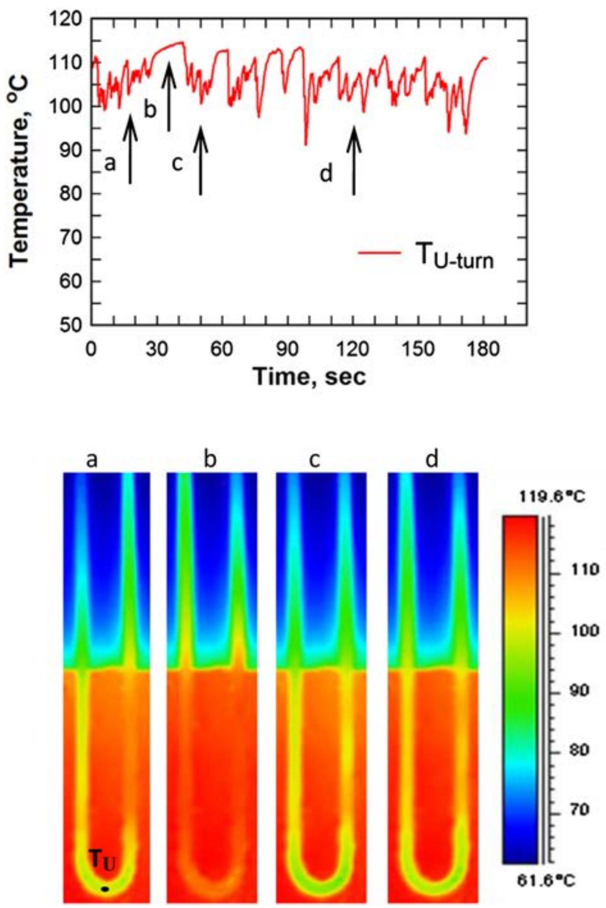

Fig. 5. Temperature oscillation profile and IR thermo-grams of a U-turn in the evaporator at a specified pseudo-steady state for 250 W of heat power.

Fig. 5 shows temperature oscillations profile with different IR images of a U turn of evaporator section at a pseudo-steady state for 250 W of heat power. The different IR images represent various stages of fluid movement during the operation. In the figure, a, c and d clearly imply occurrence of fluid movement i.e., oscillation (yellowish light green) in the tube and then b represents absence of fluid movement (red) in the device. Further, it is noted that as the fluid movement takes place, the wall temperature comes down and when there is an absence of fluid movement, the wall temperature goes up, clearly suggesting that oscillation of the working fluid, generated due to the heat input power, is the major mechanism contributing to the heat transfer occurring in the system.

Supplementary video data related to this article can be found online at http://dx.doi.org/10.1016/j.applthermaleng.2013.09.041.

3.2. Multiple pseudo-steady states

It is interesting to note that in our experiments too, multiple pseudo-steady states could be observed, the occurrence of which as has been previously reported by Khandekar et al. [15]. During such a phenomenon, the system dynamics spontaneously goes from one 'steady-state' to other, without any external stimuli. However, the present result is novel, as the previous study by Khandekar et al. [15] reported such behaviour for a single turn PHP device. The results of the present study indicate that even multi-turn PHP system can indeed exhibit multiple steady states, if they are allowed to run for long periods of time. Such characteristics may have adverse effects in real-time engineering systems and occurrence of such behaviour needs to be carefully studied and avoided for reliable operation.

To verify the existence of multiple steady states, experiments are conducted for a continuous period of 8–12 h Fig. 6 highlights multiple pseudo-steady states for different heat powers. Clearly identifiable steady states are seen for heat input of 275 W, one state manifesting better thermal resistance as compared to the other. At 200 W too, the PHP tends to shift its operating point from a higher thermal resistance to a lower thermal resistance, i.e., it is found from these experimental runs that the device operation spontaneously fluctuates between a higher evaporator wall temperature and a lower evaporator wall temperature. As the heat input increases to 275 W, the device tends to dwell at one of these states for a very long period of time, before switching to the other mode spontaneously; it can, however, again come back to the original operating state. The 200 W case shows behaviour, which can be categorized as somewhat in-between that of the two extreme cases.

Based on these experimental runs, it can also be inferred that the pseudo-steady states of device operation correspond to different flow patterns inside the device. At low operating powers, the flow is primarily oscillatory. As the power input to the device increases, the flow pattern changes to transient type flow wherein the oscillatory and bulk circulatory flow undergoes flow direction reversals. As the power increases further, bulk circulatory flow is observed – the flow tending to take a fixed direction for extended periods of time. When the system undergoes a spontaneous change from one operating steady state to the other, it is associated with a particular flow pattern changes also, as indicated in Fig. 6.

To further understand these flow transitions, Figs. 7 and 8 show IR images along with temperature profiles at a specified time period during circulatory and oscillatory flow conditions respectively. These wall temperature profiles are obtained from IR data, at locations 1 through 8 in the adiabatic section, as indicated on the figures. It is found that as the device undergoes circulatory flow, the adjacent tubes temperature profiles in the adiabatic section (Fig. 7) are not overlapping each other. In other words, where one tube is hot (red colour-1,3,5,7) its adjacent tube is cool (blue colour-2,4,6,8). This suggests that the flow is circulatory in nature as cold fluid from the condenser sections flows down and gets heated up as passes in the evaporator U-turn. As will be seen later, such a flow condition is the most effective state, one having the least thermal resistance. When the flow starts taking up a fixed direction, wall temperature drops in the evaporator. Thus, occurrence of a permanent circulatory flow superimposed on local oscillatory behaviour is desirable for best system operation. This is generally achieved at high heat fluxes and therefore a PHP is inherently suited for high heat flux handling. In the lower performing operating state (corresponding to higher evaporator temperature), the PHP undergoes oscillatory flow and bulk circulation tendency gets suppressed. This is shown in Fig. 8, wherein the adjacent tubes temperature profiles of adiabatic section get overlapped onto each other due to frequent flow reversal.

Avoiding such multiple steady states is desirable and more research is needed to understand its origins and subsequent control. As has been suggested in the literature [24–26], density wave oscillations are inherent characteristics of PHP operation and occurrence of meta-stable states cannot be ruled out [19]. Local temperature and pressure measurement are recommended for better understanding of these transitions. Increasing the number of turns and employing fluids having a large saturation pressure gradient with respect to saturation pressure is one of the suggested solutions for avoiding multiple steady states [14,15]. Another important parameter which affects the instability of two-phase

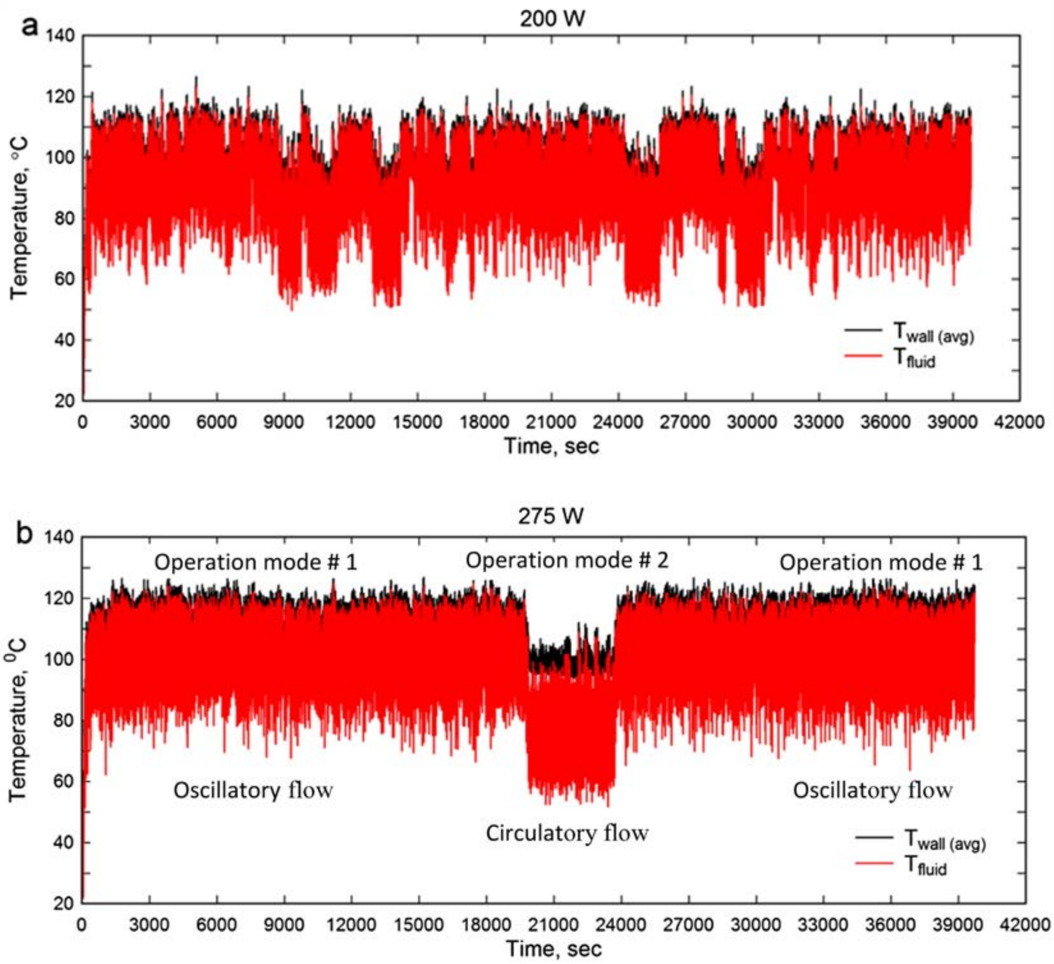

Fig. 6. Multiple pseudo-steady states obtained for different input heat power when the PHP runs continuously for over 11 h (a) at 200 W of heat input and (b) at 275 W of input heat power.

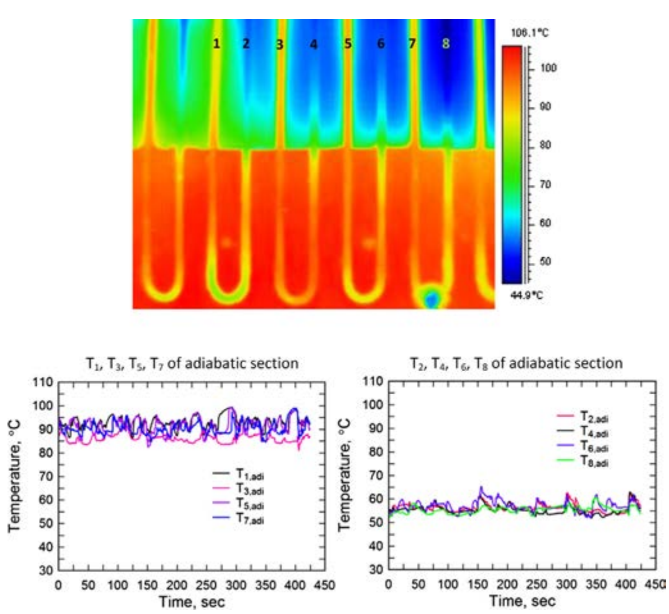

Fig. 7. IR and temperature oscillation profiles during circulatory flow (Steady-state operation mode #2) at 275 W of heat power.

internal convective flows is the applied heat flux, which is scrutinized next. As will be seen, applied heat flux can itself be a control parameter for avoiding multiple steady states.

3.3. Operations at higher heat power

The effect of input heat flux on two-phase flow instabilities (e.g., density wave oscillations) is well documented in classical literature, especially for open channel pressure driven flows [25,26]. These studies clearly suggest the strong role of applied heat flux in determining the regions where the flow becomes inherently unstable. Other factors which affect stability regimes are frictional resistance to flow, flow rate, level of subcooling, operating pressure, etc. These studies provide a clear hint that occurrence of multiple steady states in a PHP should get decisively affected by the applied heat flux, for a given set of other operating conditions.

To check the behaviour of the present system, it was operated at higher powers, from 300 W to 500 W, wherein the heat power was ramped up in steps. Fig. 9 shows the time-series plot of the average evaporator wall and fluid temperature, respectively. It is clearly seen that the device continues to transfer thermal power at increasing efficiencies as the heat power is increased till 500 W. In addition, the corresponding infra-red pictures of the evaporator section at 300 W and 500 W respectively, shown in Fig. 10(a), (b), clearly reveal the fact that the flow pattern shows higher tendency

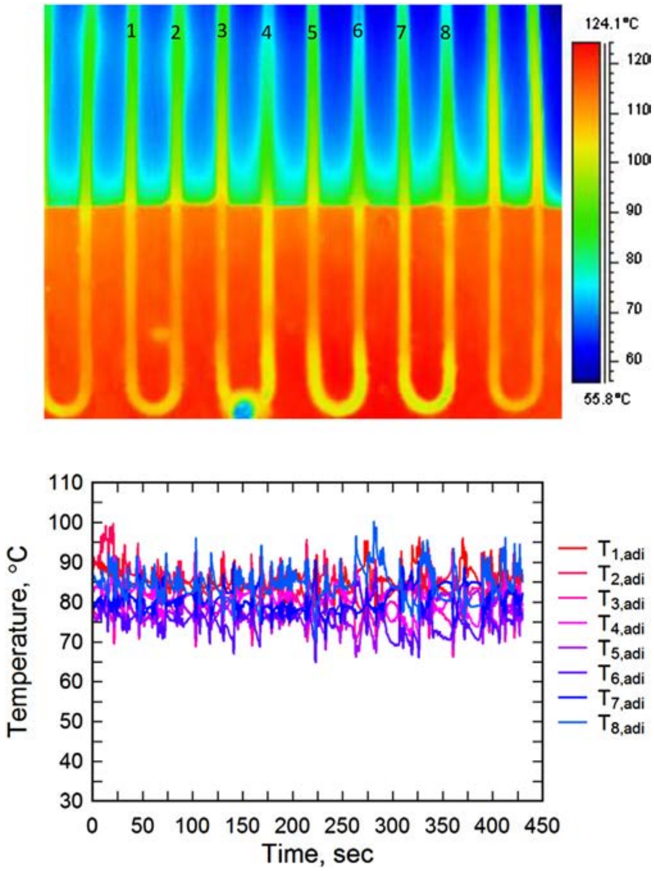

Fig. 8. IR and temperature pulsation profiles during oscillatory flow (Steady-state operation mode #1) at 275 W of input heat power.

towards a transition to uni-directional circulatory flow, as the heating power is increased. At 500 W the flow is circulatory, with superimposed oscillations as seen from the thermal footprint; at this stage, the thermal performance of the device is better than those of all the previous stages. Another interesting feature from the studies at higher heat loads is the preliminary evidence of reduced tendency of the system to show multiple steady states. This has been observed in all the experimental runs at higher

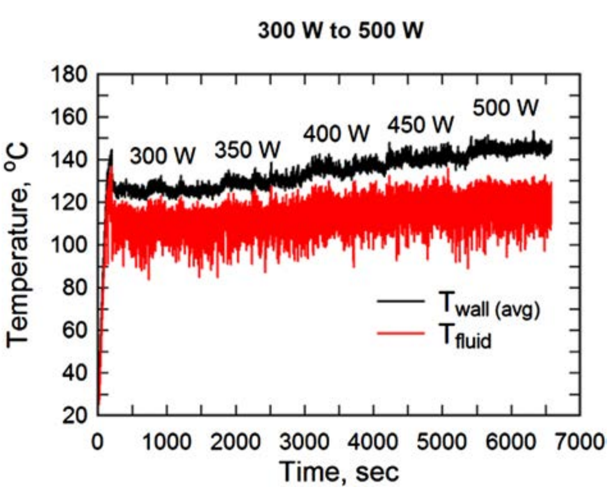

Fig. 9. Time temperature plot of the average evaporator temperature when the PHP was operated at high power (from 300 W till 500 W).

powers; however, this aspect needs further establishment, as only preliminary results are available at this stage. The explicit effect of heat flux on the stability regimes of a PHP needs further dedicated experiments. Unfortunately, the present system could not be tested at higher powers due to safety reasons and no real dry-out phenomena could be observed, as in Ref. [7]. The thermal resistance continued to decrease with power up to 500 W, as will be discussed next.

3.4. Overall thermal resistance

The PHP performance can be explained by calculating the overall thermal resistance. Fig. 11 shows the thermal resistance and effective thermal conductivity as a function of heat power, for the present range of experiments. The thermal resistance trend shows that it decreases drastically with a certain power of heat input, where intermittent oscillations of the working fluid commence. Thereafter, there is a steady decrease of thermal resistance with heat input. As correlated with the IR data, the thermal resistance is directly related to the internal flow patterns, which, in turn are responsible for the thermal oscillations observed on the PHP tube wall and the fluid. With increasing heat power, local thermal oscillations are seen throughout all the U-turns of the evaporator, which indicates efficient exchange of the working fluid between the evaporator and the condenser. As explained earlier, at power input greater than about 400 W, the internal flow tended to become more circulatory in nature. The PHP performance also can be explained by calculating the effective thermal conductivity, as per Eq. (3). The effective thermal conductivity trend shows that it increases with heat power and varies from about 800 W/mK to 6600 W/mK, with increasing heat power input; this is indeed extremely effective as compared to bare copper tubes.

4. Summary and conclusions

A copper tube PHP (ID = 2.0 mm; working fluid DI water) with 8 turns each in the evaporator and condenser section, is fabricated and examined in vertical heater-down position with non-intrusive spatial IR thermographic measurement (of the tube wall temperature), to better understand the operational characteristics of the device. The local fluid temperature in the evaporator section is also recorded by a micro-thermocouple. The following major conclusions are made from this study:

- Self-sustained fluid oscillations are a major mechanism in the device to exchange heat from evaporator to condenser sections and vice versa.
- The thermal imprint of the tube surface temperature observed through the IR camera helps in qualitative identification of the internal flow patterns and underlying thermal behaviour. Depending on the applied heat input, the PHP is characterized by no internal oscillations of the working fluid, intermittent oscillations and continuous local oscillations with superimposition of unidirectional flow inside the tube.
- Multiple steady-states can be identified during long runs of the experiment. These steady-states are clearly identifiable by the wall temperature signal and therefore, the thermal resistance of the system. The operational behaviour of these steady-states can be uniquely associated with internal flow pattern behaviour. The thermally better performing state shows circulatory flow while oscillatory flow without any circulation is comparatively underperforming state. Preliminary results indicate that operating the device at higher heat inputs can lead to reduced tendency of occurrence of multiple operating states at a given condition.

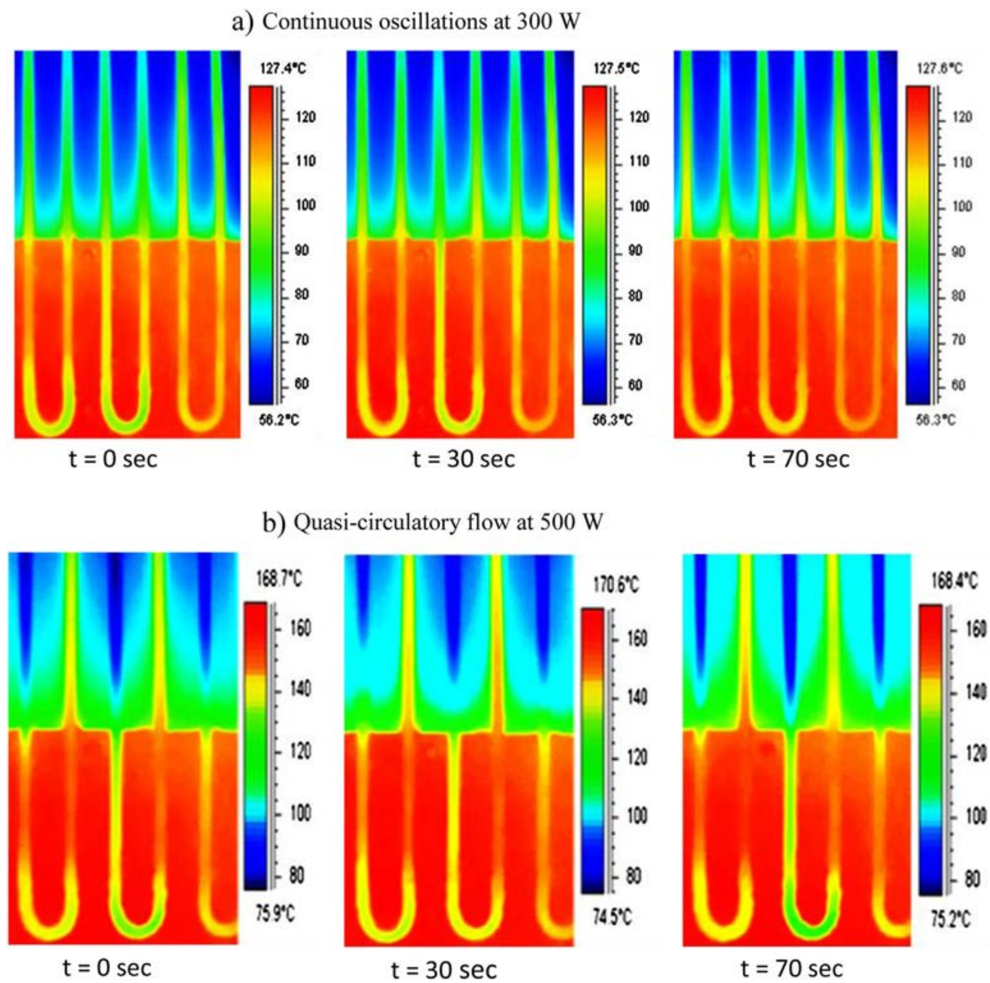

Fig. 10. Infra-red pictures of the evaporator at 300 W and 500 W operations, respectively.

- The thermal performance strongly depends on the heat power which, in turn, affects the internal two-phase fluid dynamics. Overall thermally conductivity of the system is very attractive for many applications.

While IR thermography is a very attractive tool, for transient situations like in a PHP, efforts should be made to minimize the thermal inertia of the tube wall so that attenuation and phase-distortion of the temperature signal emanating at the fluid–wall interface is minimized when recorded on the external tube wall. This will provide much more quantitative local information about the complex internal dynamics. These efforts are presently ongoing.

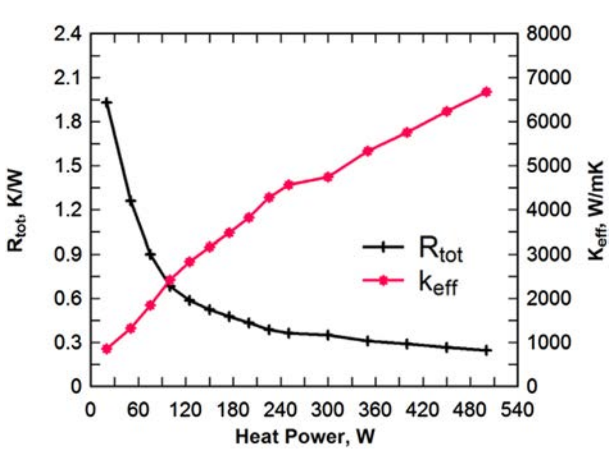

Fig. 11. Total thermal resistance and effective thermal conductivity of the PHP obtained at different input heat power.

Acknowledgements

Partial funding to carry out the experimental program was provided by Bhabha Atomic Research Centre (MoU Project with IIT Kanpur) and Department of Science and Technology (Infra-red camera procured under the FIST Funding Scheme), Government of India. The first author would like to thank the Department of Mechanical Engineering, Indian Institute of Technology Kanpur, India, for giving him the opportunity of a research visit and conduct the reported experiments.

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