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ORIGINAL

The combined effects of filling ratio and inclination angle on thermal performance of a closed loop pulsating heat pipe

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Abstract
In the present study, a series of experiments are conducted to investigate the thermal performance of a copper made pulsating heat pipe consisting of uniform flow passages with the cross section of 2 mm × 2 mm. Test conditions cover two orientations (0° and 90°) and six different filling ratios (10%, 25%, 40%, 55%, 70% and 85%). The working fluid used in the experiments is methanol. Heat inputs are applied by 7 W intervals up to an upper safe temperature limit (mean evaporator temperature of nearly 110 °C). In addition to temperature measurements and relevant thermal resistance values, the flow behavior is analyzed via high speed video images. It is concluded that at vertical bottom heating mode (90°), the filling ratio plays a key role in the results, and thus, obvious differences occur in thermal performance depending on the filling ratio. As a general trend, at vertical position, thermal resistance increases with increasing filling ratio for a given heat input value. As an exception, the lowest filling ratio (10%) significantly disobeys this generalization. Thus, the worst thermal performances are obtained for the lowest and topmost filling ratio values (10% and 85%). Nearly for every filling ratio, the system can operate at vertical position, while the system cannot start up and/or properly operate at horizontal position (0°). When the heat pipe is placed horizontally, the effect of filling ratio on the thermal behavior significantly diminishes. As an overall evaluation (including flow patterns and evaporator temperature), the optimum thermal performance is obtained for the filling ratio of 40% in existing conditions.

Nomenclature

c_p Specific heat [J kg^{-1} °C^{-1}].
$\dot{m}$ Cooling water mass flow rate [kg s^{-1}].
Q_i Heat load supplied to the evaporator region [W].
Q_o Rejected heat from the condenser region [W].
R_{th} Thermal resistance [°C W^{-1}].
T Temperature [°C].

Greek symbols

ρ Density [kg m^{-3}].

Subscripts

e (Evaporator)
c (Condenser)
in Heat sink inlet (related to cooling water).
out Heat sink outlet (related to cooling water).

Abbreviations

FR Filling ratio
FP Flat plate
HP Heat pipe
PHP Pulsating heat pipe
CLPHP Closed loop pulsating heat pipe

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1 Introduction

Heat pipes (HPs) are one of the most effective tools dissipating heat over the surfaces. They provide high heat transfer rate in a purely passive way. There are various types of heat pipes; however, the pulsating ones (PHPs) being firstly introduced by Akachi [1] in 1990 attract great attention of the researchers. The merits of the PHPs can be specified as easy construction, low cost, applicability for long distances and successful thermal management [2, 3]. Because of these superiorities, they are often used to control the temperature of electronic components, satellites, energy recovery systems, etc. [2, 4]. Also, regarding with the PHPs, the number of influential parameters is high. The relevant parameters may be grouped as operational (filling ratio, fluid type, orientation, etc.) and geometrical ones (turn number, flow passage diameter, etc.). Due to both the practical-oriented importance and existing of many influential parameters, this new research topic draws heavy attention from researchers.

Depending on their experimental observations, Charoensawan et al. [5] presented some important information about the relation between the parameters (working fluid, turn number, channel diameter, orientation) and thermal performance for a constant filling ratio (50%). They underlined the importance of the gravity on the operation of a PHP, and they stated that the adverse effect of the horizontal orientation could be prevented by increasing number of turn. Rittidech et al. [6] focused on the influence of tube diameter, fluid type and evaporator length on the thermal characteristics of an open loop PHP. The filling ratio was fixed at 50%. It was concluded that increasing evaporator length adversely affected the thermal performance, and the contribution of internal diameter could be either positive or negative depending on the fluid type. Xu and Zhang [7] examined the startup characteristics and thermal oscillations (for steady case) of a PHP. The PHP was a capillary tube type with internal diameter of 2 mm. FC-72 was selected as fluid. They pointed that depending on the distribution of liquid slugs and vapor plugs, two different types of thermal oscillations appeared. Khandekar et al. [8] presented experimental reports related to quasi-steady state types in a single loop glass PHP. Steady-state types were divided into four groups, and each of which represented by different flow patterns, and thus, presented different thermal performance. The best one was characterized with one-directional continuous flow type, while the switching behavior (bidirectional reversals) was observed in the poorest one. Narasimha et al. [9] examined the transient and steady characteristics of a closed loop single turn PHP for an experimental range covering various types of fluids, heat loads and evacuation degrees (the filling ratio was 60%). According to their findings, acetone was the best fluid, and atmospheric conditions were more suitable for proper operation. Also, more fluctuating flow behavior was observed in the usage of ethanol. Chien et al. [10] dealt with uniform and non-uniform channel distributions (as cross section) with the experimental range covering filling ratio between 40 and 70% and angular positions of 0°, 30°, 60° and 90°. The fluid was distilled water. They underlined the importance of filling ratio, and pointed out that the operation of the modified PHP in the horizontal orientation was only possible for specific values of the filling ratio (≥ 50%). In an experimental manner, Qu and Wang [11] examined the influence of diameter, working fluid, evaporator length and filling ratio under various heat loads in capillary type closed loop pulsating heat pipe (CLPHP). They pointed out that the performance level strongly depended on different combinations of applied conditions. Depending on the parameter selection, the optimum performance was obtained either at the filling ratio of 40% or 50%. Mameli et al. [12] studied with a multi-turn capillary CLPHP filled with FC-72 to investigate the orientation and filling ratio effects. They emphasized the influence of gravity on the performance, and pointed out that 50% was the optimum filling ratio as a result of overall evaluation. Spinato et al. [13] conducted experimental efforts to research the thermal performance of a single turn flat plate closed loop PHP (FP-CLPHP) charged with R245fa for the filling ratio range of 10–90%. The strong relation between the thermal characteristics and the flow patterns were revealed, and the operational maps were exploited in the analyses. The effective role of the evaporation of thin liquid film was underlined, and also, they stated that increasing filling ratio raised the required heat load for unidirectional flow in the vertical position. Sedighi et al. [14] added an extra branch to the evaporator zone of a single turn PHP in order to enhance the pumping action, and thus, the flow circulation. The range of the filling ratio and inclination angle covered 40–70% and 0–90°, respectively. The optimum filling ratio was obtained as 60%. Also, it was stated that the addition of the branch decreased the dependency on the filling ratio variation. Sun et al. [15] conducted experiments related to startup behavior of a flat plate CLPHP through flow images. HFE-7100 was the working fluid, and the filling ratio ranged between 31 and 72%. They declared that the filling ratio clearly affected the heating power value at which the initial activation of the PHP occurs. Furthermore, in high filling ratios (greater than 40%), bubble nucleation had a critical role on the startup performance. Srikrishna et al. [16] studied with an aluminum alloy FP-CLPHP filled either water or methanol. Test range covers the filling ratio between 30 and 70% and the inclination angles between 7.5–90°. The lowest thermal resistance was obtained for methanol with the filling ratio of 40%; and near the horizontal position (7.5–10°), it was declared that the PHP cannot successfully operate (dry out problem). It should be stated that in the scope of the study, any visualization study was not performed. Betancur et al. [17] experimentally dealt with the effect of roughness on heat transfer performance of flat plate type PHP. They investigated the thermal performance variation for different filling ratios (10–75%) and orientations (0° and 90°) with the working fluid of distilled water. Three different flow regimes were defined as stable, unstable and conduction. The heat pipe having different roughness in the evaporator and condenser sections was better than the one having uniformly roughed surfaces except 75% filling ratio. Also, it was understood that the filling ratio had a clear effect on the flow behavior.

As clearly seen by the above literature survey, pulsating heat pipes are new and promising tools for applications regarding with electronics cooling, while their performance can present different trends/behaviors depending on various combination of many influential parameters. Obviously, filling ratio and inclination angle are among the most important parameters. In a recent review article, Bastakoti et al. [18]

underlined the importance of filling ratio and stated that optimum filling ratios should be investigated under different conditions. Also, two phase flow occurs in heat pipes, and it should be emphasized that two phase flow in mini/micro channels need detailed analysis including interpretation of flow patterns. Hence, this subject requires new researches covering different test conditions. It should be pointed out that flow visualization is a quite essential method for supplementary (or even exact) interpretation and analysis of the results. In this regard, main objective of the present paper is to investigate thermal performance of a multi-turn FP-CLPHP for a wide range of filling ratio at two critical angular orientations through flow visualization support. To the best of the authors' knowledge, this is the first investigation covering methanol charged flat plate type CLPHP under a quite wide filling ratio range and a high speed visualization support (simultaneous flow visualization and flow pattern analysis). Herein, depending on the test parameters, thermal resistance behavior, evaporator temperatures and startup characteristics are analyzed, and the relevant discussion is supported via flow images taken by a high speed camera.

2 Setup and test section used in the experiments

The schematic drawing of the setup used during the experiments is shown in Fig. 1. The setup may be explained by dividing three basic sections: (1) test section with heating unit, (2) circulation line and (3) visualization section.

Test section is the most important zone of the experimental setup; and its assembly, and relevant details for subsections are presented in Fig. 2a-c. Test section contains heat pipe (HP). The HP is a closed type (in terms of circulation), and the channels are carved over a flat copper plate through the milling technique. There are 16 parallel channels meaning 8 turns in the HP. Both the width and height of the passages are 2 mm. The technical details belong to the HP (copper plate part of HP) are presented in Fig. 2b and c. To create a closed volume and to make the flow visualization enable, a glass plate is put over the copper one; and they are compressed via a brass compression piece. Also, it should be stated that between glass and copper part, an O-ring is used to prevent any leakage. Actually, this assembly (copper part and glass cover combination) constitutes the HP. Classically, the present HP has three well-known sections as condenser, adiabatic and evaporator (see Fig. 2c). The evaporator is placed on a heating plate of which details can be seen from Fig. 2a. Heating plate acts as a heat source for evaporation, and this is achieved via two cartridge heaters placed into heating plate. Cartridge heaters are cabled to a power supply. On the other hand, condenser section is seated on a heat sink. The heat sink consists of flow passages engraved onto a polycarbonate plate, and a thin (2 mm thick) copper upper sheet (for effective heat transfer). Thin copper sheet gets in touch with bottom surface of condenser region of HP. Thus, heat transported from evaporator to condenser region of heat pipe is rejected from condenser region of HP to cooling water passing through the heat sink. It should be stated that three thermocouples are placed for each of the three region of HP. For evaporator and condenser regions these thermocouples are placed radially; while for adiabatic region they are placed axially. In Fig. 2b, grooves for thermocouple locations are seen (at the bottom surface) T-type thermocouples are used for temperature readings.

The other section is the circulation line providing the required cooling water to the heat sink placed beneath the condenser side of the HP (see Fig. 2a). As seen from Fig. 1, the main components in this line are the constant temperature bath, micro pump coupled with driver, manometer and flow controller. Via this line equipped with relevant devices,

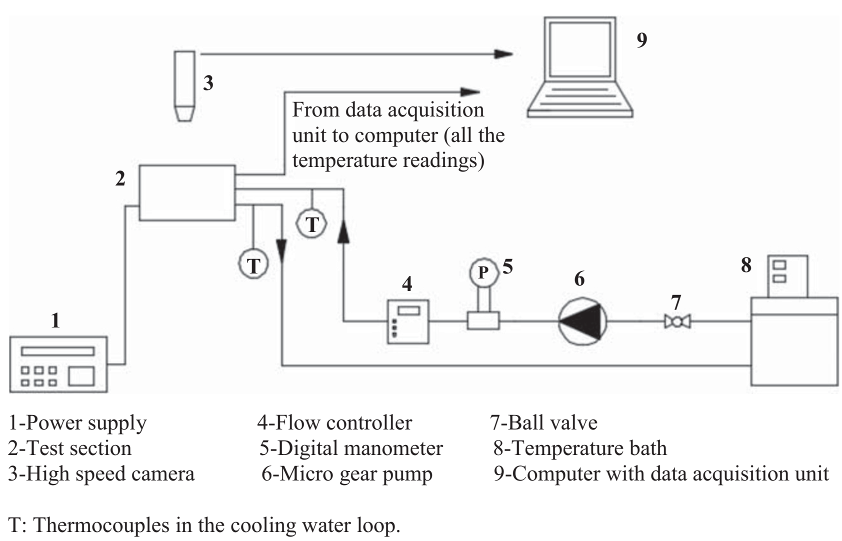

Fig. 1 Schematic drawing of the setup used in experiments

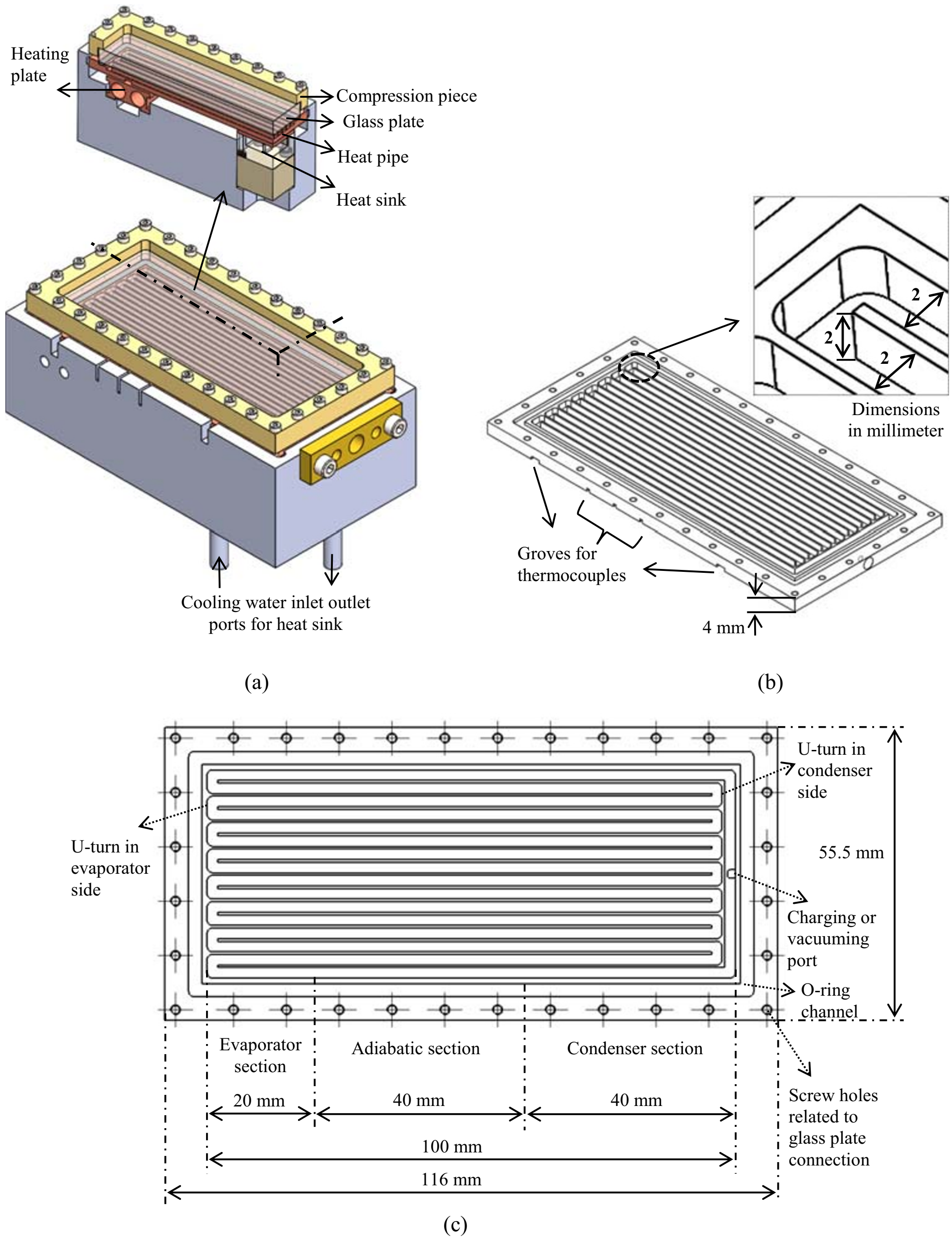

Fig. 2 Details of the test section: Assembly and sectional view (a), PHP channel details (b) and PHP dimensions (c)

temperature and volumetric flow rate of the cooling water are set to the desired values of 20 °C and 20 ml min^{-1}, respectively. Also, for calculation of the heat rejected from the condenser section, two T-type thermocouples are used just before and after the heat sink.

The last section is the visualization one containing a high speed camera and a computer (for software of the camera). The visualization part is very important for the analysis of this kind of complex-natured flow behaviors; and the flow images provide opportunity for deeper discussion of the results. Also, it ought to be stated that all the temperature readings are collected via a data acquisition unit.

In a test process, the following steps are applied:

- Before every experiment, vacuuming process is applied via a vacuum pump.
- Circulation line is activated (water circulation).
- Desired amount of methanol is filled into the HP.
- The angular position is adjusted.
- Power supply is activated and set to the starting level of 7 W. Until reaching the evaporator temperature of nearly 110 °C, heat load increases gradually (7 W intervals).
- Under any heat load, when the quasi steady state is achieved, the temperature readings are recorded via the data logger.
- Synchronously with temperature measurement, flow patterns are recorded through camera.

- Then, another parameter (filling ratio or inclination angle) is set, and the above-mentioned steps are repeated.

3 Calculation procedure

As generally accepted, one of the basic performance indicators of a PHP is the total thermal resistance [19] meaning the ratio of temperature difference (between the evaporator and condenser regions) and heating power. The relevant equation is presented below:

$$R_{th} = \frac{(T_e - T_c)}{Q} \tag{1}$$

In the above equation, the arithmetic mean values of the local temperatures in the evaporator and condenser regions are denoted as T_e and T_c, respectively. Especially, the evaporator temperature is another important performance evaluation criterion, and it should be considered together with the thermal resistance. Also; Q denotes arithmetic mean of the heat load supplied in the evaporator region (Q_i) and rejected heat from the condenser region (Q_o).

$$Q = \frac{(Q_i + Q_o)}{2} \tag{2}$$

The above method is a common procedure in the relevant literature [10, 13, 20]. In this way, heat losses are also considered in calculation of total thermal resistance. Herein, the heat rejection from condenser zone is obtained via the below equation.

$$Q_o = \dot{m} c_p (T_{out} - T_{in}) \tag{3}$$

The above equation is related to the cooling water entering to and exiting from the heat sink. Therefore, T_{out} and T_{in} denote the temperatures of the cooling water just after and before the heat sink (placed beneath the condenser section). On the other hand, c_p is the specific heat, and $\dot{m}$ is mass flow rate of cooling water.

In the present study, an uncertainty approach [21] is performed, and the uncertainty interval for thermal resistance is obtained as 3.2% – 5.2%.

4 Results and discussion

In the following sections, the detailed underlying physical mechanism related to thermal performance behavior is discussed based on clear flow images taken by a high speed camera. The experimental database includes a quite large filling ratio interval (10–85%) and two critical angular orientations (0° and 90°).

4.1 Influence of the filling ratio and general assessment covering heat input effect

In the literature regarding with pulsating heat pipes (PHPs); filling ratio representing the ratio of the working fluid volume over the PHP total internal volume is one of the most critical parameters. Its influence or impact level may be different depending on the various combinations of the geometrical and/or operational parameters. However, for the original combinations (such as PHP type/geometry−working fluid−orientation), performing a complete scanning over nearly all the possible filling ratio range contributes to the available knowledge in the literature. In this regard, in Figs. 3a to d, thermal performance characteristics of a FP-CLPHP filled by methanol are presented for a wide range of filling ratio. It should be stated that any performance evaluation depending only on thermal resistance variation may lead to incomplete discussion. Therefore, different tools are also considered for a deeper analysis. In this context, thermal resistance and mean evaporator temperature are examined together. Additionally, clear flow images are used as a supplementary technique.

As seen in Fig. 3a, as a general trend, increasing heat input induces significant reduction in thermal resistance; which is valid for all the filling ratios. As it is also pointed out by Wan et al. [22] and Liu et al. [23], the thermal driving force originated from the increasing vapor plug pressure in the evaporator increases with increasing heat load. As a result, oscillation and circulating characteristics of the flow improve, and thus thermal performance enhanced [24]. Differently from the above-mentioned studies [22–24] in which opaque flow passages used; in the present study, the relevant physical phenomena are analyzed by flow nature (flow patterns and transitions). In this context, Figs. 4a and b are presented. In the relevant figures, flow images belonging to the conditions of 40% filling ratio and 90° inclination angle are shown for heat inputs of 21 W and 49 W, respectively.

It is important that Fig. 3a and Fig. 4a are evaluated together. As seen in Fig. 3a, the FP-CLPHP with the filling ratio of 40% starts operation at 21 W; which can be understood from the sudden decrease in the thermal resistance values (from 14 W to 21 W). Then up to 49 W, thermal resistance continues to decrease. The phenomenological changes are responsible for the performance enhancement. First of all, the flow velocity covering the circulation speed and oscillation frequency increases. Herein, the oscillation frequency is related to the sudden switching motion of the flow components named as liquid slug and vapor plug. Also, number of vapor plugs increases, and dimension of singular vapor plugs shrinks. This

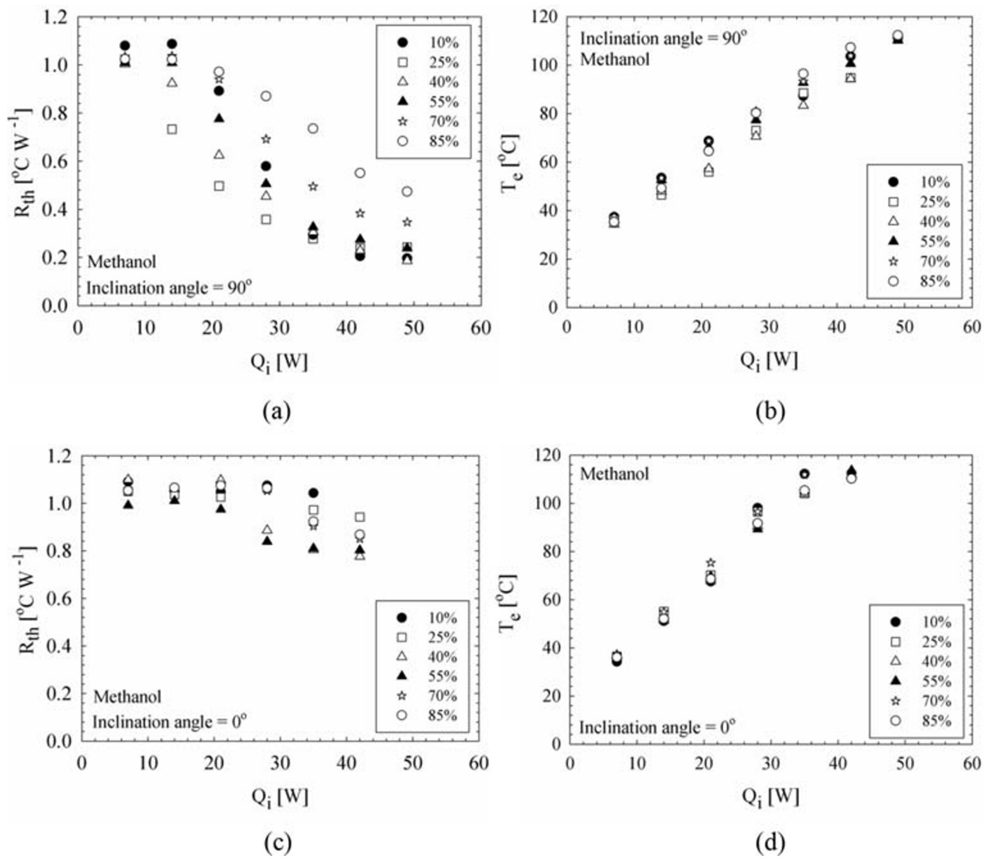

Fig. 3 Influence of filling ratio at different angular positions

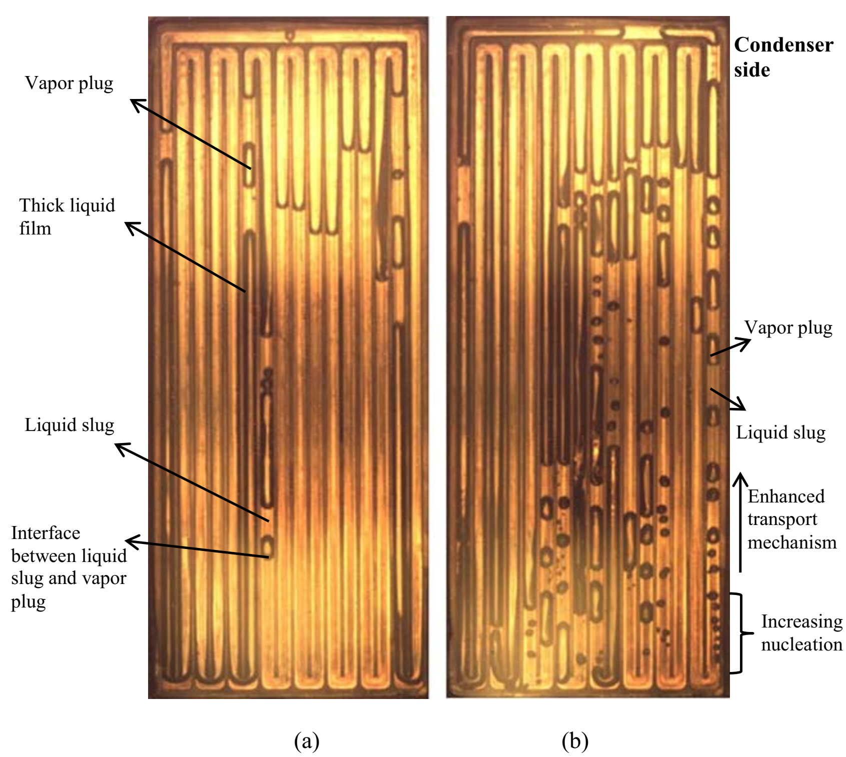

Fig. 4 Flow patterns and transitions at the conditions of 90°, 40%, 21 W (a) and 49 W (b)

means a basic change in heat transport mechanism. Bubble population increases, and thus nucleation takes a more effective role in thermal performance. Due to the increase of bulk temperature, for a longer time, the bubbles can maintain their individual motion without collapsing or coalescing. Therefore, in the evaporator section, heat can be easily absorbed and transported to the condenser region. The resultant fluctuation (regarding with bubble motion) also induces enhancement of convection. Also, the total liquid-vapor interface length throughout all the flow passages increases, which signifies enhancement of evaporation and condensation. Therefore, contribution of the phase-change based transport mechanism rises. Furthermore, when taking evaporation of the thin liquid film into consideration, it may be stated that role of convective boiling mechanism becomes significant. As a result, all the phenomenological variations based on the heat load increment are clearly discussed above.

Significant decrement occurring in the thermal resistance due to the increasing heating power is stated in the previous paragraphs. Even if this behavior reflects the general trend at vertical bottom heating mode, the filling ratio plays a key role in the results, and thus, obvious differences occur in thermal performance depending on the filling ratio values. However, it should be underlined that the correct assessment should be conducted by simultaneously taking the other performance indicators including start up characteristic and evaporator temperature into consideration. According to the Figs. 3a and b, filling ratios of 25% and 40% show significantly better performance against other conditions.

As a first step, startup performance should be evaluated. As seen in Fig. 3a, the earliest and sudden decrement in thermal resistance is observed at filling ratio of 25%. The relevant heating power is 14 W. This means the shortest time for starting of the operation, or the fastest response time. However, the startup score of the filling ratio of 40% is quite close to the filling ratio of 25%. Also, there is a small difference between the evaporator temperatures. The evaporator temperature in the case of 25% is nearly 1.5 °C smaller than the counterpart of the 40%. There are two possible reasons of this small difference. The first one can stem from the first motion ability due to the lesser amount of fluid which brings movement flexibility. The generated pressure force (thermal based) pushes the relatively small liquid bulks and/or liquid slugs to the condenser side in an easier way. In the literature [13, 25], the adverse effects of the liquid excess is stated and they have being associated to restriction of the motion or pumping action. In this regard, reverse interpretation (regarding with low fluid content) of such a statement supports the above-mentioned probable reason. The second probable but may be weaker reason can be related to randomness of the initial distribution of the fluid. The existence of some inconsistent results for the conditions of low filling ratios and early steps of heating process (lower heat loads) are also reported by Han et al. [26].

After evaluation of startup performance, a general discussion is presented on the basis of simultaneous analysis of the overall thermal resistance behavior and evaporator temperature. In this context, firstly, Fig. 3a and b characterizing the vertical bottom heating mode is analyzed. As seen in Fig. 3a, in the low and medium heat inputs (≤ 28 W), the filling ratio of 25% presents the lowest thermal resistance, while in the higher heating powers, the filling ratio of 40% catches it and performs lower values. Also, from Fig. 3b, it can be clearly seen that the filling ratio of 40% presents lower evaporator temperatures along the effective heat input range. The temperature difference between the filling ratios of 40% and 25% reaches up to nearly 5.2 °C in favor of the former one. In other words, the filling ratio of 40% presents lower evaporator temperature. Herein, the evaporator temperature has a critical importance for real applications, because it symbolizing surface temperature of a thermal system. Therefore, it can be concluded that the filling ratio range of 25–40% presents better results, and as an overall evaluation, the optimum performance is obtained for the filling ratio of 40% in the present experimental conditions. To analyze the difference between the 25% and 40% filling ratios in detail, and to discuss the underlying physical mechanism, it is better to investigate the flow images. In this regard, to perform a comparison with Fig. 4b, at the same operating conditions, the flow image taken for the filling ratio of 25% is presented in Fig. 5 (90°, 49 W, 25%). As seen in Fig. 5, the flow patterns are somewhat similar, but there are some basic differences influencing heat transfer mechanism. Due to the lesser amount of working fluid, number of separate vapor plugs and liquid slugs is less. The most important factor related to lesser amount is that most of the flow passages are

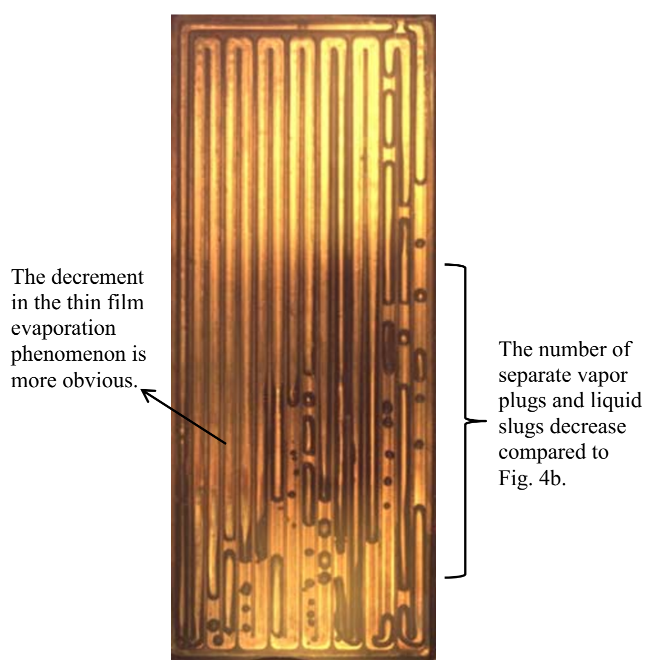

Fig. 5 Flow image taken at the conditions of 90°, 49 W and 25%

covered with vapor phase, which means bigger dryout problem. The existence of larger surfaces experiencing larger vapor regions leads to shortcomings in heat transfer process, and overall temperature of the system increases due to axial conduction in the heat pipe material. Also, the inadequacy of the liquid phase inhibits the formation of annular or quasi-annular type flow patterns, and thus thin liquid film contacting the hot channel surfaces. The contribution of liquid film evaporation in the heat transfer mechanism significantly reduces. As also emphasized by Spinato et al. [13], evaporation of thin film is the most influential physical fact positively affecting the heat transfer coefficient.

As a general trend, at vertical position (see Fig. 3a), thermal resistances increase with increasing filling ratio for a given heat input value. As an exception, the lowest filling ratio (10%) disobeys this generalization. Therefore, it can be concluded that the worst thermal performances are obtained for the lowest and topmost filling ratio values (10% and 85%). In terms of highest filling ratio (85%), the reason is related to the excess of liquid inventory restricting the flow motion in the PHP [13, 25]. Liquid single phase is dominant, perturbations caused by vapor bubbles are insufficient and basically the gravitational forces cannot be overcome [27]. In addition to these facts, it is observed that the heat pipe behaves as if it was a pool boiling system. The nucleation actively occurs in the evaporation section; however, due to the excess of liquid phase, the generated evaporation force does not overcome the liquid column above it. Consequently, the flow is inhibited or does not effectively occur. Furthermore, due to the single phase heat transfer, thin film evaporation is not the dominant heat transfer mechanism. Therefore, heat transport ability loses its effectiveness. The details are presented via Fig. 6a. Quite the contrary to the highest filling ratio (85%), for the lowest filling ratio (10%), there is liquid inadequacy in the FP-CLPHP. In pulsating heat pipes, the main source of pulsating/circulating flow is the occurrence and collapse of the bubbles in an asynchronous manner inside different turns/channels. Thermally based transient pressure forces applied by the growing bubbles lead to motion of the liquid slugs. Bubbles occur as the result of evaporation of the liquid bulks. Below a critical fluid content, adequate vapor pressures cannot generate. In addition, most of the heat transfer surfaces are covered via vapor phase which leads to poorer heat transfer. Also, inadequacy of the working fluid content causes effectiveness-losses in thin film evaporation phenomenon. Therefore, in spite of quite better thermal performance of the filling ratio of 25%, the filling ratio of 10% presents quite poor startup and thermal performance due to the above-mentioned physical facts/mechanisms. Actually, this proves existence of a critical filling ratio value for PHPs depending on operational conditions. The filling ratio of 10% corresponds to a filling ratio value lower than minimum (critical) required value. On the other hand, due to the vertical orientation, even for the lowest filling ratio (10%), the available liquid content can easily collect in the evaporator region; this partly inhibits any abrupt temperature jumps or increments in the thermal resistance. However, most of the flow passages even most part of the evaporator region are covered with vapor phase, which is one of the most terrible scenarios in terms of thermal transport. The system operates like a thermosiphon array with only

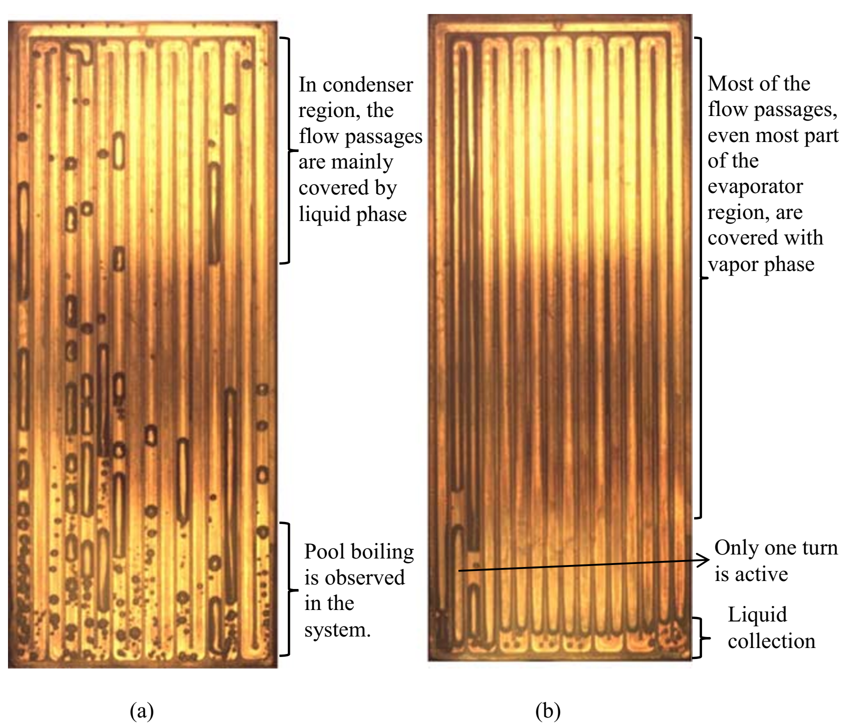

Fig. 6 Flow images for the conditions of 90°, 49 W, 85% (a) and 10% (b)

a few channels are active. Details are presented through an example image in Fig. 6b.

Another important point should be emphasized is the thermal resistance behavior of the lowest filling ratio condition (10%) for the higher heating powers. In the thermal resistance curve (see Fig. 3a), in higher heat loads, the curve of the filling ratio of 10% shows a significant decaying trend. However, from the flow visualization results, it can be clearly seen that this does not reflect a perfect working condition. Then, there should be another physical reason behind this behavior. The reason is related to the much more increment of the condenser temperature due to the axial and lateral conduction inside the heat pipe material. The inadequacy of the heat carrying fluid and thus the lack of effective heat transfer mechanisms lead to increase the temperature of whole heat pipe sections. Therefore, the temperature difference between the evaporator and condenser regions decreases, which causes deceptive trend in the thermal resistance curve. Hence, as perseveringly emphasized in the previous paragraphs, the thermal resistance should not be the only performance indicator. The other factors (evaporator temperature and flow patterns/visualization) should be simultaneously evaluated.

The results with detailed discussion for vertical position are presented in the above paragraphs. When the system is placed horizontally, completely different results are obtained. They are presented in Figs. 3c and d for thermal resistance and evaporator temperatures, respectively. In horizontal position, the heat pipe does not operate for any filling ratio, and the effect of filling ratio significantly decreases. The horizontal trend of the thermal resistance curve means failure of the heat pipe. In the medium and high heat loads, relatively lower thermal resistance values (and accompanying evaporator temperatures) are obtained for the filling ratios of 40% and 55%. The reason can be attributed to the start-stop motions [10]. The start-stop motions characterize discontinuous pulsations, more clearly, after pulsation motions a wait period (stationary period) occurs. Sometimes, in this kind of operation mode, only some channels are active. On the other hand, in terms of both the thermal resistance and evaporator temperature, the worst one is the filling ratio of 10%. In the vertical position, the available liquid content can collect in the evaporator section; however, when the system is placed horizontally, the fluid already being small amount distributes randomly throughout the channel. Therefore, early dryout occurs, and a dramatic increment takes place in the evaporator temperature in early stages. In the horizontal position, the filling ratio of 85% shows better thermal performance against the lowest filling ratio. The reason can be attributed to the better thermal conductivity of liquid phase than the vapor phase. In the next section, more detailed graphics are presented for the effect of orientation.

4.2 Influence of orientation

In order to show the effect of orientation (inclination angle) in a clearer manner, the separate graphs regarding with each filling ratio value are presented in Figs. 7a to l. Nearly for every filling ratio, the system can operate in vertical (bottom heating, 90°) position, while the system cannot properly operate at horizontal position. Similar results are reported in the open literature [5, 28]. The possible reasons are attributed to the lack of pressure perturbations and/or some other forcing mechanisms (such as unbalanced capillary force and non-uniform rapid bubble growth). To clearly show the flow distributions or mechanisms for horizontal case, Fig. 8 is presented at the filling ratio of 25% and heating power of 42 W. As also seen from Fig. 8, collections of liquid and vapor phases separately at different regions; and lack of separate vapor plugs and liquids slug mean there is no flow motion. If there is no flow motion and active bubble nucleation or ebullition processes, intake heat at the evaporator regions cannot be absorbed, and/or transported towards condenser region. In such a case, quite poor thermal performance is obtained. In the horizontal position, for the startup and sustainable operation, pulsating type heat pipes with uniform channels need a minimum channel number providing the required perturbations [5, 10, 13]. Also, in some studies [10, 24], it is shown that designing non-uniform channel configuration (unbalancing capillary force effect) can boost the system operation in the horizontal position. It may tolerate lack of the gravity support and the problems caused by insufficient turn number. On the other hand, in the vertical position (evaporator is below); the PHP with eight turns can operate, mainly, as a result of the gravitational force support.

In horizontal cases, from Fig. 7, it is seen that especially in the medium filling ratio range (40% – 55%), after the heating power of 21 W, some fall is appeared in the thermal resistance values. As explained in the previous section, this behavior can be attributed to the periodic start-stop motions or intermittent large amplitude pulsations. In this case, some separate vapor plugs and liquid slugs can form, and they perform instantaneously periodic movements in the channels (such as large amplitude pulsation motions with waiting periods).

From Fig. 7, notable results are concluded for the lowest and highest filling ratios (10% and 85%). In the horizontal case, for the filling ratio of 10%, the system reaches the allowable maximum evaporator temperature (nearly 110 °C) at the lowest heating power compared to the other filling ratios. Also, variation of the thermal performance between the vertical and horizontal cases, in other words, dependence on orientation is much more. In the horizontal case, the maximum heat input value for the filling ratio of 10% is 35 W, while this value is 42 W for the other filling ratios. The reason is related to the inadequate content of the liquid phase and its distribution in the channel. In vertical case, in spite of inadequate content, the existing liquid phase collects in the bottom (that's in the evaporator of the heat pipe) due to the gravity effect. This phenomenon tolerates the early deterioration up to some degree. However, in the horizontal case, the liquid distributed randomly in throughout the channels, and already insufficient content cannot completely collect in the evaporator. This leads to obvious deterioration in thermal performance. On the other hand, for the filling ratio of 85%, completely different behavior occurs. The difference between the thermal performance characteristics between the vertical and horizontal conditions is relatively less compared to the other filling ratios. This is related to the higher content of fluid. Most of the internal volume is filled by working fluid. In the horizontal or vertical position, the distribution of the liquid phase does not considerably change. Although the vertical position present relatively better results, the difference depending on the orientation is quite small compared to the other filling ratio values. Consequently, in spite of the significant effect of filling ratio in vertical position, when the FP-CLPHP is placed horizontally, the effect of filling ratio on the thermal behavior significantly diminishes.

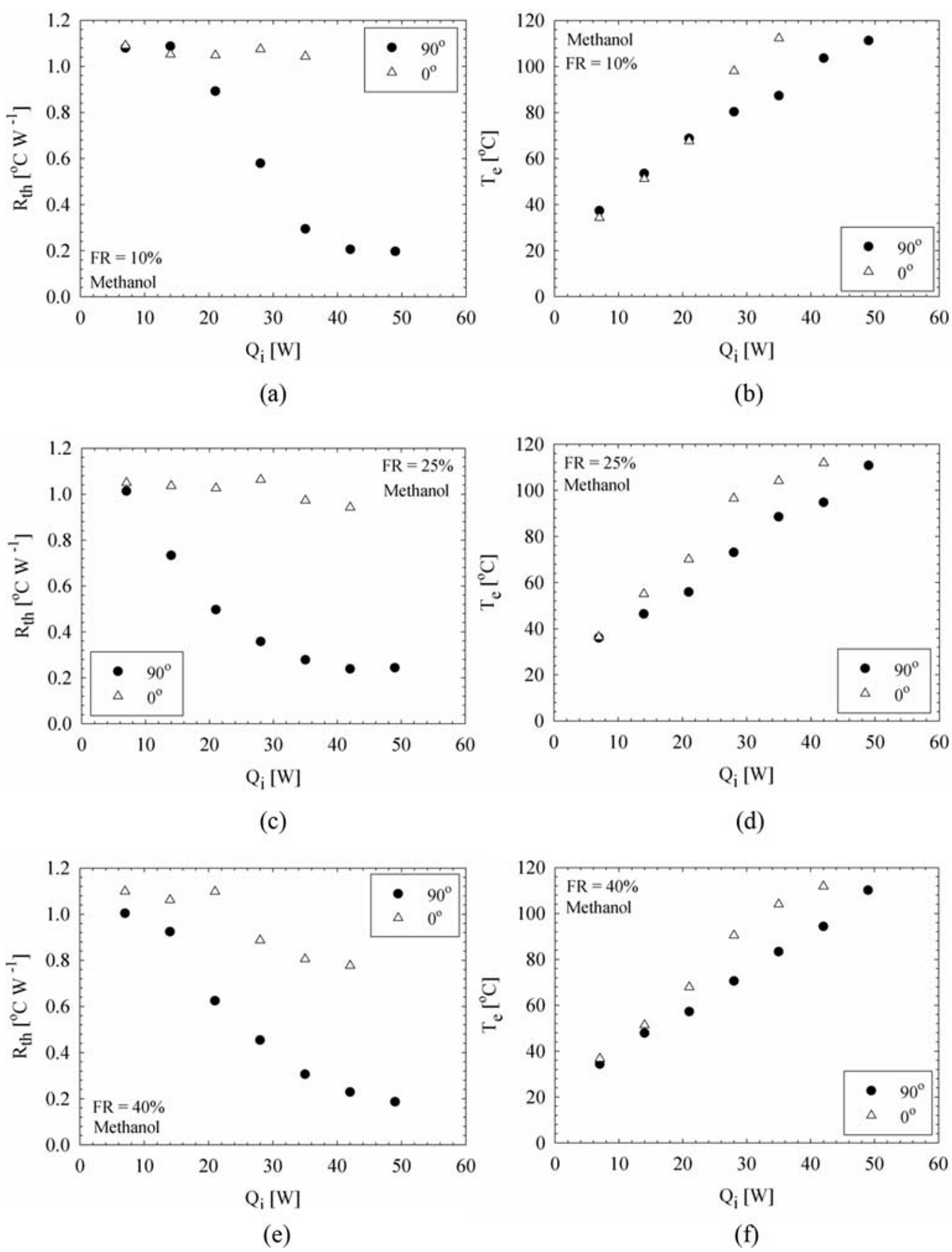

Fig. 7 Effect of inclination angle on the thermal characteristics for all filling ratios

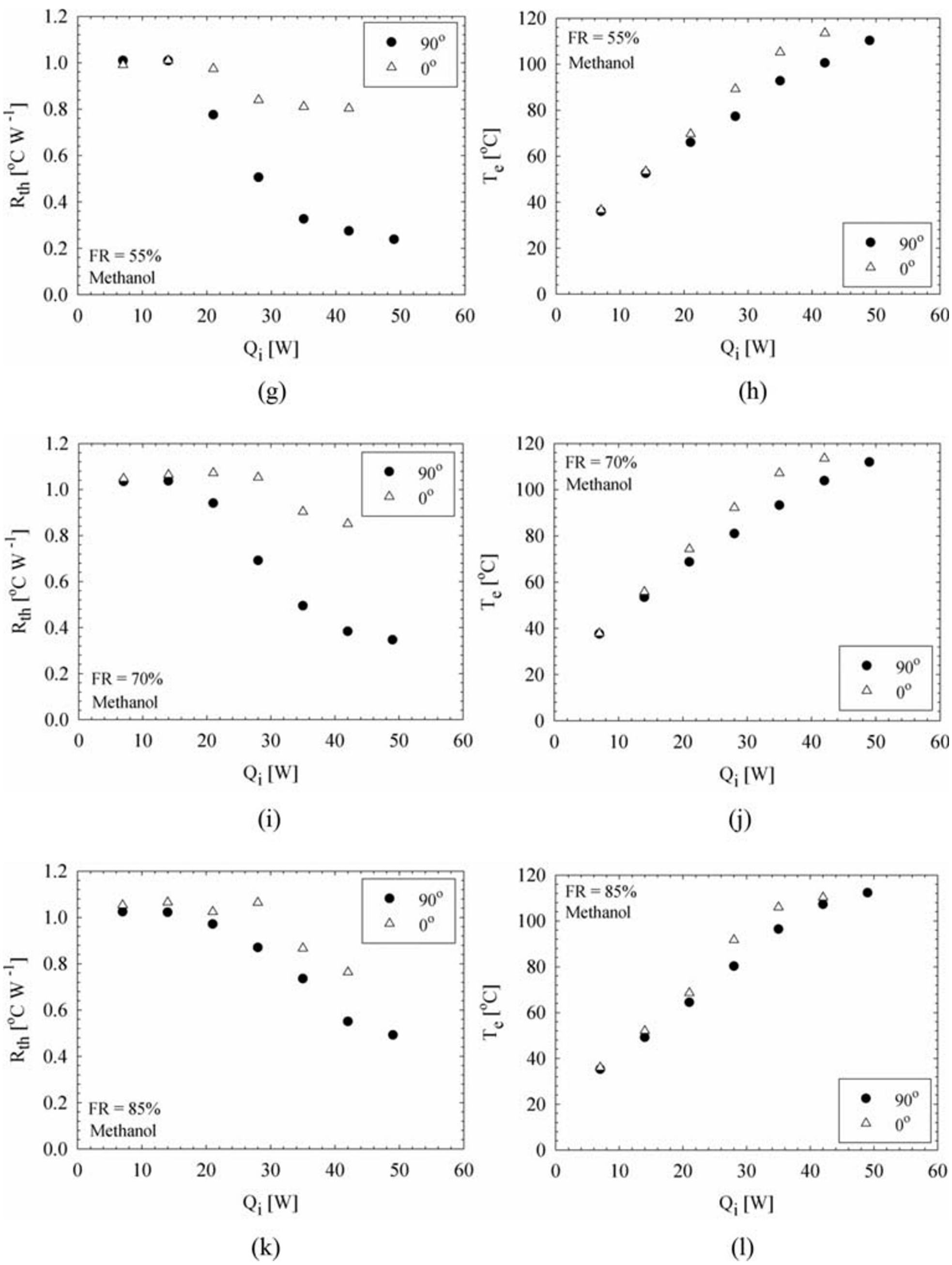

Fig. 7 continued.

5 Concluding remarks

At two critical angular orientations, extensive investigation of filling ratio effect on thermal performance of a FP-CLPHP is conducted. In this way, combined effect of the relevant parameters is presented. Also, underlying physical mechanism is analyzed in detail. Flow patterns, transitions and dominant flow mechanisms influencing heat transport ability are comprehensively discussed via visualization results. Summary of the results are presented below:

- At vertical bottom heating mode (90°), increasing heat input induces significant reduction in thermal resistance; which is valid for all the filling ratios. Via the visualization results general phenomenological variations based on the heat load increment can be addressed as follows: (1) flow velocity increases, (2) bubble population increases, and thus nucleation takes a more effective role in thermal performance, (3) the resultant fluctuation (regarding bubble motions) also induces enhancement of convection, (4) total liquid-vapor interface length increases (enhancement of evaporation and condensation).

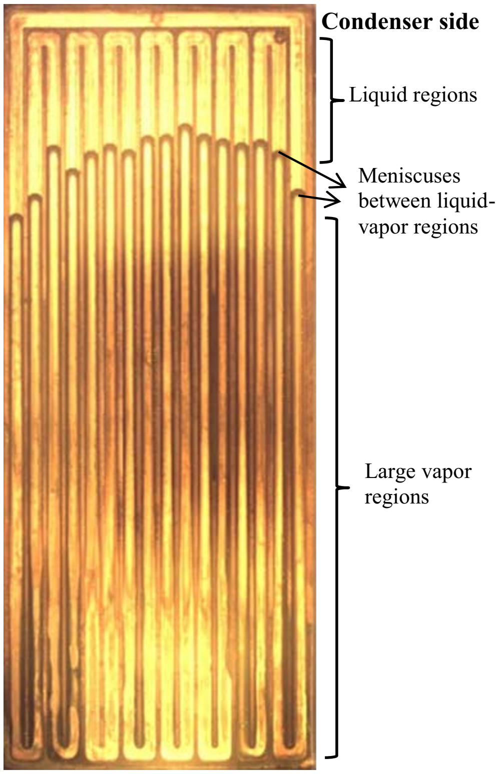

Fig. 8 Flow image at horizontal position for the conditions of 25% and 42 W

- At vertical bottom heating mode (90°), filling ratio plays a key role in the results, and thus, obvious differences occur in thermal performance depending on the filling ratio. Filling ratios of 25% and 40% show significantly better performance against the other conditions. However, as an overall evaluation (including flow patterns and evaporator temperature), the optimum performance is obtained for the filling ratio of 40% in the present experimental conditions.
- As a general trend, at vertical position, thermal resistance increases with increasing filling ratio for a given heat input value. As an exception, the lowest filling ratio (10%) significantly disobeys this generalization. The worst thermal performances are obtained for the lowest and topmost filling ratio values (10% and 85%). In terms of highest filling ratio (85%), the reason is related to the excess of liquid inventory restricting the flow motion. On the other hand, for the lowest filling ratio (10%), there is liquid inadequacy in the FP-CLPHP; in which case, pulsating/oscillating motion cannot effectively occur due to insufficient content.
- In horizontal position (0°), the heat pipe does not operate for any filling ratio. The possible reasons are attributed to the lack of pressure perturbations and/or some other forcing mechanisms due to less number of turns. In the medium and high heat loads, relatively lower thermal resistance values are obtained for the filling ratios of 40% and 55%. This behavior can be attributed to the periodic start-stop motions. In this case, some separate vapor plugs and liquid slugs can form, and they perform instantaneously periodic movements (covering dead periods) in channels.
- In horizontal position, the worst thermal performance is obtained for the filling ratio of 10%. For this condition, early dryout occurs, and a dramatic increment takes place in the evaporator temperature in early stages.
- In the horizontal case, for the filling ratio of 10%, the system reaches the allowable maximum evaporator temperature at the lowest heating power compared to the other filling ratios. Also, variation of thermal performance between the vertical and horizontal cases, in other words, dependence on orientation is much more. The reason is related to the inadequate content of the liquid phase and its distribution in the channel.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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