VISUAL STUDY ON TWO-PHASE FLOW IN A HORIZONTAL CLOSED-LOOP OSCILLATING HEAT PIPE

by

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Original scientific paper
https://doi.org/10.2298/TSCI170514232C

Two-phase flow boiling of working fluid within a closed-loop oscillating heat pipe in the horizontal orientation was studied visually. The closed-loop oscillating heat pipe in the horizontal orientation was made of Pyrex glass tubes with an inside and outside diameter of 2 and 7 mm, respectively. The evaporator, adiabatic and condenser of the closed-loop oscillating heat pipe in the horizontal orientation were 50 mm in length. The internal flow phenomena was carefully investigated for various number of turns, evaporator temperatures and filling ratios of the two working fluids, i. e. distilled water and absolute ethanol. The closed-loop oscillating heat pipe in the horizontal orientation was installed on cooling and heating copper plates and the two-phase flow patterns were recorded by digital still and video cameras. The rate of heat transferred to the cooling water at the condenser was evaluated. The fluid motion characteristics may be separated into two main conditions: the oscillating slug flow and the standstill condition. The thermal performance improved when the number of turns reached the critical value of 10 turns at which the vapor fraction was small and the time fraction of oscillating flow was long. For both working fluids, the time fraction of oscillating flow was longest for 50% filling ratio, which led to the lowest thermal resistances. The wavy vapor-liquid interface which induced the vapor/liquid slug train formation was only found for water. Nucleate boiling followed by oscillating flow was discovered in the evaporator part only at the 50% and 80% filling ratios of water. At these filling ratios the thermal resistance of water tended to be lower than that of ethanol.

Key words: *closed-loop oscillating heat pipe, horizontal orientation mode, two-phase flow*

Introduction

The visualization studies were conducted to obtain the internal flow phenomena of a closed-loop oscillating heat pipe (CLOHP) and understanding its heat transfer mechanisms. A CLOHP is a special type of heat pipe with high thermal performance and was first introduced by Akachi *et al.* [1]. The internal flow was assumed to be a liquid slug and vapor plug arrangement over the total capillary tube length and the basic operational principle was the self-excited oscillating movement of the working fluid with the phase change phenomena. During the past two decades, several researchers have tried to prove these phenomena. The majority

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of the research was able to investigate the flow phenomena within CLOHP at only the bottom heating mode where the evaporator was lower than the condenser. Operation of a CLOHP in horizontal orientation, horizontal closed-loop oscillating heat pipe (HCLOHP) as shown in fig. 1, is problematic. It has been found [2-6] that in some cases horizontal operation was not possible at all. The working fluid stopped moving or only oscillated about a *mean position* with very small amplitude and high frequency (in fig. 6, however, the frequency is rather low, about 0.25 Hz). For increased heat input the dry-out phenomenon appeared in the evaporator. Then there were no more pressure and temperature oscillations, and the thermal resistance increased dramatically. However, some previous research revealed that the operation of a HCLOHP was possible if the number of meandering turns was more than a critical value [7, 8]. The minimum number of turns at which HCLOHP can operate as a heat transporting device was defined as the critical number of turns and it depends on the working fluid and the tube's inner diameter. This critical value tended to be lowered when the evaporator temperature increased and the tube's inner diameter increased [9]. After the operation of the HCLOHP was successfully started-up, its thermal performance improved by increasing the number of turns, input power, and internal diameter [10-12]. The adiabatic temperatures always oscillated and alternated in adjacent tubes [9]. For a given input heat power, the higher the thermal performance, the lower the evaporator temperature [13]. Furthermore, the flow phenomenon within a HCLOHP was observed and found that the flow pattern of working fluid was only the slug flow [8, 14]. If the number of turns were less than the critical value, the liquid slugs and the vapor plugs only vibrated about a mean position, namely, the standstill condition [8]. When the critical number of turns was reached, heat was transferred by the oscillation of liquid slugs and vapor bubbles. The oscillatory slug flow was able to be intermittently superimposed by the bulk circulation of fluid when the input heat load was sufficiently high and the filling ratio of working fluid was approximately between 40% and 70% [10]. From all the previously mentioned research, the effect of the previous number of turns on the internal two-phase flow phenomena was investigated by using only one working fluid with a defined filling ratio. On the other hand, the effects of filling ratio and heat load were studied by using only one HCLOHP with specified geometry and working fluid. Therefore, the objective of this work is to visually study the internal two-phase flow and thermal performance of a HCLOHP by varying the parameters, *i. e.*, number of turns, evaporator temperature, working fluid and filling ratio. The operating pressure and temperature variation is also investigated.

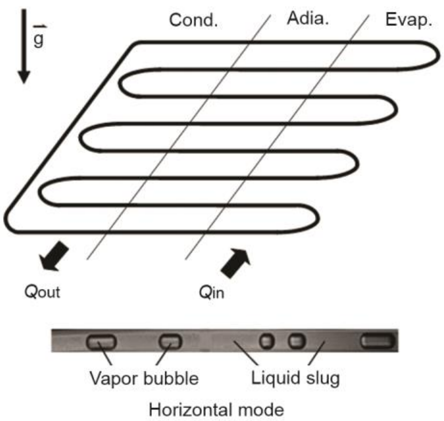

Figure 1. A horizontal closed-loop oscillating heat pipe

Experimental set-up and procedure

The details of experimental set-up are shown in fig. 2. The tested HCLOHP was made of Pyrex glass tube with an inside and outside diameter of 2 mm and 7 mm, respectively. The evaporator, adiabatic, and condenser were 50 mm in length. The condenser and evaporator sections were attached on the cooling and heating copper plates, respectively. The evaporator section was heated by electric heaters that were placed on the heating plate and connected to the AC power input source and temperature controller (SIGMA, SFN72). The condenser section was cooled by cold water that was circulating in a cooling bath and passed through the cooling plate at constant flow rate of 1 L per minute, and inlet temperature of 20 °C. The volume flow rate of coolant was measured by a floating rotameter (Uni-pure, z-3001 with ±0.3 L per minute accuracy). Two thermocouples each (OMEGA type K) were placed in the coolant to measure the temperatures at the inlet and exit of the cooling plate. The temperatures of the evaporator, adiabatic, and condenser sections were also measured by installing the thermocouples on the tubes of these sections. Two thermocouples each were placed on the evaporator and condenser parts and four thermocouples were placed on the adiabatic. The temperature recorder (Agilent, 34970A with ±1 °C accuracy) was used to continuously monitor all temperatures. The operating pressure of working fluid was measured by placing four pressure transmitters (Sensys with ±0.08 mA accuracy and –1 to 1 bar gauge pressure measurement range) inside the tubes in the adiabatic section and continuously monitored by the sensitive recorder (Wisco with ±0.02 mA). The video camera (Samsung, R10, 25 fps) was used to continuously record the fluid flow phenomena at all parts of HCLOHP and the digital still camera (Cannon, D500) was used to record at the specified times. The thermal performance of HCLOHP was evaluated by calculating the thermal resistance for a unit area of the total tube's inner surface of the evaporator section, R''. That is shown:

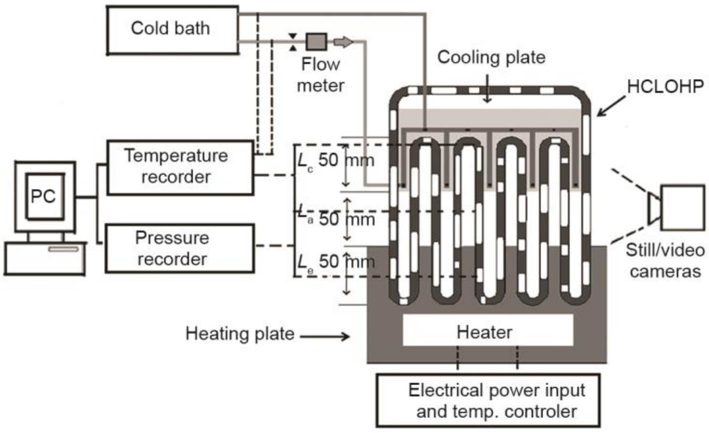

Figure 2. Details of experimental set-up

$$R'' = \frac{T_{\mathrm{e,aver}} - T_{\mathrm{c,aver}}}{q''} \tag{1}$$

where the radial heat flux of a HCLOHP, q'', can be calculated:

$$q'' = \frac{\dot{m}_{\mathrm{w}} c_{p,\mathrm{w}} (T_{\mathrm{w,out}} - T_{\mathrm{w,in}})}{2n\pi D_{\mathrm{i}} L_{\mathrm{e}}} \tag{2}$$

Because the HCLOHP were made entirely of glass tubes and were exposed to the ambient air in order to observe the two-phase flow in the entire tube, it was difficult to control the heat loss from the system. Therefore, the rate of heat transferred to cooling water at the condenser was rather low. However, the influences of various parameters on thermal performance were qualitative evaluated.

The complete experimental parameters are summarized:

– number of turns: 6, 8, and 10 turns,
– evaporator temperature: 80-130 °C with 10 °C increments,

– working fluid: distilled water and absolute ethanol, and
– filling ratio: 20%, 50%, and 80% of total internal tube volume.

Results and discussion

Effects of turns number and evaporator temperature

In order to understand the influences of number of turns and evaporator temperatures on the two-phase flow phenomenon in a HCLOHP, only the appropriate filling ratio of 50% was taken into consideration. As mentioned in previous research [15], it was found from an analytical model that the two-phase oscillating flow was caused by self-sustaining pressure oscillation which was caused by mutual excitation between the pressure and the void fraction. Thus, the void or vapor fraction and the pressure variation were experimentally analyzed.

Vapor fraction

In this paper, the vapor or void fraction of working fluid was defined as the ratio of the internal volume of tube, occupied by vapor bubbles and the total internal tube volume. It was obtained from still figures by planimetry. Although the filling ratio of working fluid was kept at a constant value, its vapor fraction can be changed by the effects of the number of turns and the evaporator temperature. Figure 3 shows the vapor fraction of working fluid within a HCLOHP with a 50% filling ratio of ethanol for the various number of turns and evaporator temperatures. At the evaporator temperature of 80 °C, the vapor fractions for all the number of turns are at a minimum and are the same at about 53% of total internal volume. Then the vapor fraction of each number of turns is increased with an increase in the evaporator temperature. The maximum vapor fraction is found at the highest evaporator temperature of 130 °C. In addition, the vapor fraction tends to be high when the number of turns is small, especially at 6 turns. This trend is distinctly observed when the evaporator temperature is high. When the evaporator temperature is at 130 °C, the vapor fraction of working fluid of the HCLOHP with 10 turns is 68% whereas they are 82% for 6 and 8 turns. This trend was also seen for all the HCLOHP filled with water as presented in fig. 4. This figure shows the vapor plug and liquid slug distribution of working fluid in a part of the glass tube of the HCLOHP with 6 turns for 50% filling ratio of water. It is seen that the higher the evaporator temperature, the volume of the vapor plug in the tube is larger. At 130 °C, the working fluid is almost in the form of being in the vapor phase.

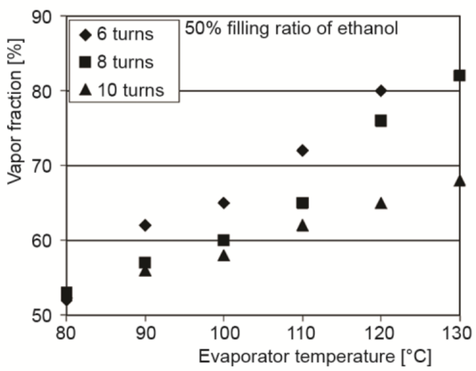

Figure 3. Effects of turns number and evaporator temperature on vapor fraction

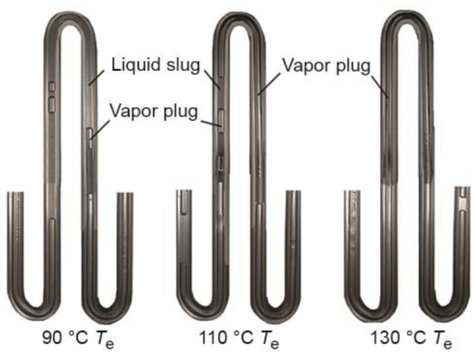

Figure 4. Visualization of vapor fraction at the various evaporator temperatures

Working fluid motion

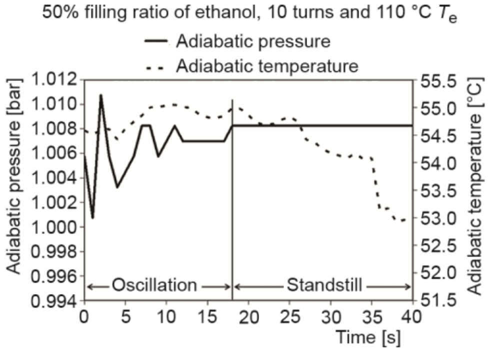

Figure 5. Relationship of fluid motions and variations of adiabatic pressure and temperature

It was observed along the time that the fluid motion characteristics can be related to the operating or adiabatic pressure and temperature as shown in fig. 5. This figure shows the operating pressure and temperature variations of the HCLOHP with a 50% filling ratio of ethanol and 10 turns at the evaporator temperature of 110 °C for a time interval of 40 seconds. At first, the self-oscillatory flow of vapor plugs and liquid slugs with irregular amplitudes and frequencies was observed until 18 seconds. It is seen that the absolute pressure at the adiabatic part clearly fluctuates whereas the adiabatic temperature hardly changes. Thereafter, the liquid slugs and vapor plugs stopped moving or only oscillated about a mean position and this was called the standstill condition [8]. It can be found at the remaining time of 22 seconds. The adiabatic pressure is completely constant but the adiabatic temperature still changes and gradually decreases. After these 40 seconds, the oscillation appeared again. Therefore, the fluid motion characteristic may be separated into two main conditions viz., the oscillating slug flow which enhances the operation of HCLOHP and the standstill condition, which corresponds to the previous results [8, 10]. Moreover, the local variation of adiabatic pressure corresponds more to the motion characteristics of working fluid than the variation of adiabatic temperature.

When the working fluid moves into the evaporator, heat is transferred to a liquid film around the vapor bubble and the vapor pressure increases so the pressure of the vapor plug is high when compared with that of the liquid slug. On the other hand, the low pressure of the vapor plug occurs at the condenser since a heat is removed from the vapor plug and liquid slug. When the oscillating flow happens *i. e.*, the vapor plug and liquid slug train alternately moves toward the evaporator and condenser, the pressure transmitter is able to detect the fluctuation of vapor pressure in the adiabatic section. When the working fluid stops moving, the pressure transmitter can not detect the pressure variation of the vapor plug and liquid slug so the adiabatic pressure is absolutely constant.

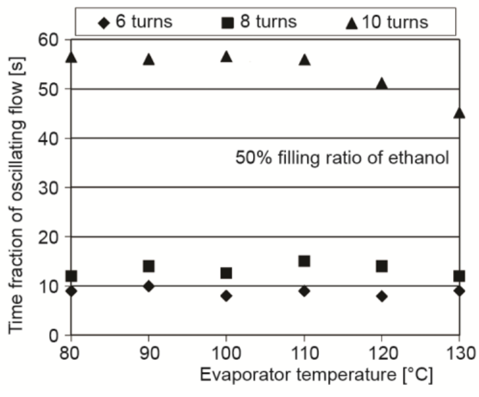

Figure 6. Effects of turns number and evaporator temperature on time fraction of oscillation

Because the adiabatic pressure variation and the flow visualization of working fluid were simultaneously analyzed along the recording time of 10 minutes. A duration of the oscillating flow happening can be evaluated in units of seconds in one minute of the recording time. The remaining time fraction in one minute, which was occupied by the standstill condition, was also found at the same time. Figure 6 shows the effects of the number of turns and the evaporator temperature on the time fraction of the oscillating flow of HCLOHP with a 50% filling ratio of ethanol. With an increase in the evaporator temperature from 80 °C to 130 °C, the time fractions of the oscillating flow of HCLOHP with 6 and 8 turns are nearly constant about 10 and 13 seconds, respectively. However for 10 turns, the time fraction of oscillation tends to be slightly reduced from 56 seconds to 45 seconds. For all the evaporator temperatures, a maximum of the duration of oscillating flow always occurs at 10 turns.

Thermal performance

Figure 7 shows the effects of the evaporator temperature and the number of turns on the thermal performance of HCLOHP with a 50% filling ratio. When the evaporator temperature increases, the thermal resistance of HCLOHP, filled with ethanol, as shown in fig. 7(a), clearly increases for all of the number of turns. With an increase in the number of turns, the thermal resistance is sharply reduced, especially at 10 turns, while for 6 and 8 turns their thermal resistances are high and slightly different. The minimum thermal resistance of 0.018 m^2K/W occurs at the evaporator temperature of 80 °C and 10 turns. For using water, this trend is also exhibited as presented in fig. 7(b). However, for the number of 10 turns, the thermal resistances for all the evaporator temperatures are almost the same and their values are approximately 0.017 m^2K/W.

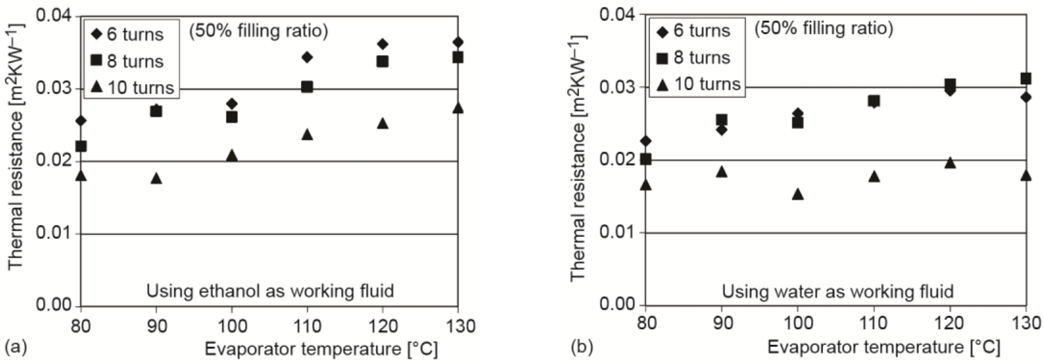

Figure 7. Effects of turns number and evaporator temperature on thermal resistance; (a) using ethanol as working fluid, (b) using water as working fluid

Because the vapor fraction was large at the number of 6 and 8 turns, the many long vapor plugs always presented in the evaporator part and the amount of working fluid in the liquid phase was small in this section. Therefore, the driving vapor pressure forces for both meandering turns were hardly generated. Since the gravity force was absent in the horizontal mode, the motion of plugs and slugs should be done by the pressure forces [5, 16]. These previous results agreed with this work, since the driving pressure forces are restricted, the time portion of oscillating flow is short at the number of 6 and 8 turns. Moreover the higher the evaporator temperature, the larger the vapor fraction and the shorter the time portion of oscillation, so the low thermal performance occurs. However, the thermal performance of HCLOHP improves for the number of 10 turns. This is about the critical number of turns (*i. e.* minimum number) at which a HCLOHP can work as a heat transferring device [7-9]. When the number of turns reached a critical value, the unbalanced pressures in the tubes between the evaporator and condenser parts were enough to initiate the self-excited oscillating flow. Their result is supported by this visual study *i. e.*, at the critical number of 10 turns, the vapor fraction is relatively small, and the time fraction of oscillating flow is the longest.

Effects of working fluid and filling ratio

In order to understand the influences of working fluid and filling ratio on the two-phase flow phenomena in a HCLOHP, the flow pattern, working fluid motion and thermal performance of the transparent HCLOHP with 10 turns were considered.

Flow pattern

There were the differences of vapor bubble shapes between using water and ethanol as the working fluids because of the influence of their surface tensions. The surface tension of water is about three times of that of ethanol. The shape of the vapor bubbles of water is shown in fig. 8(a). There are the different contact angles between the bubble head (in flow direction) and the bubble tail (against flow direction), as shown in fig. 8. For a long vapor bubble in the evaporator part, as shown in fig. 9, the liquid film between vapor bubble and wall is thick in some evaporator parts and can grow to bridge the tube cross-section and form a liquid slug, namely, the wavy interface. However, there are the symmetrical shapes of the vapor bubbles head and tail for ethanol, as shown in the upper figure of fig. 8(b). Moreover, the wavy interface of liquid film was hardly found in ethanol as presented in the lower figure.

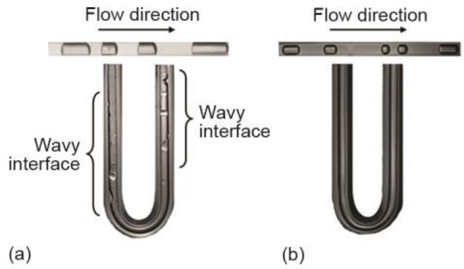

Figure 8. Differences of vapor bubble shapes; (a) water, (b) ethanol

Figure 9 shows the flow patterns of working fluid in the glass tube of the HCLOHP with a 50% filling ratio and 10 turns at the 110 °C evaporator temperature. Figure 9(a) presents the flow pattern of water while that for ethanol is presented in the fig. 9(b). It was found that the majority of flow patterns were slug flows for both working fluids. The bubble flow was rarely met. However, many long vapor plugs were observed at the evaporator, adiabatic and condenser parts of the glass tube filled with ethanol. For water, the medium vapor plugs and the small vapor bubbles existed in the evaporator and adiabatic parts, while at the condenser part the long vapor plugs were mostly observed. Furthermore, for HCLOHP filled with water, the nucleate boiling was sometimes discovered in the evaporator part of glass tube at the 50% and 80% filling ratios. After a vapor bubble was formed at the nucleation cite of the inner surface of the glass tubes wall, a small vapor bubble suddenly grew and the bubble diameter became the same as the tube's inside diameter. Then the oscillating flow of working fluid happened. However, the nucleate boiling completely vanished for ethanol.

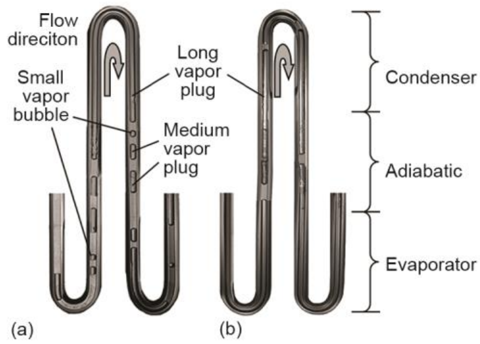

Figure 9. Flow patterns in HCLOHP with 50% filling ratio and 110 °C evaporator temperature; (a) water, (b) ethanol

Working fluid motion

The adiabatic pressure variation and the flow visualization of working fluid were simultaneously analyzed at the various working fluids and filling ratios. The time fraction of the oscillating flow was also investigated as presented in fig. 10. This figure shows the effects of the working fluid and the filling ratio on the time fraction of oscillation at the evaporator temperature range of 80-110 °C. For using ethanol as working fluid as shown in fig. 10(a), there is a maximum of the duration of oscillating flow of about 56 seconds at 50% filling ratio for all evaporator temperatures. For water, as seen from fig. 10(b), there is a similar behavior, *i. e.* maximum at 50%. However, the dependence on evaporator temperature is much less.

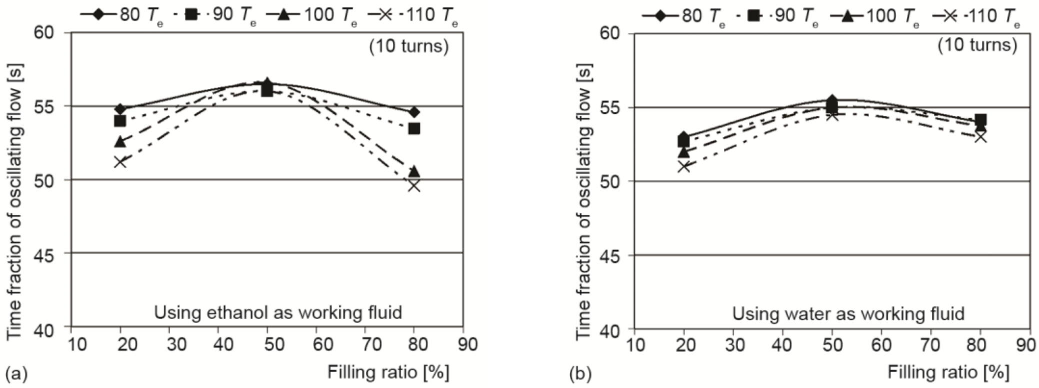

Figure 10. Effects of working fluid and filling ratio on time fraction of oscillation; (a) using ethanol as working fluid, (b) using water as working fluid

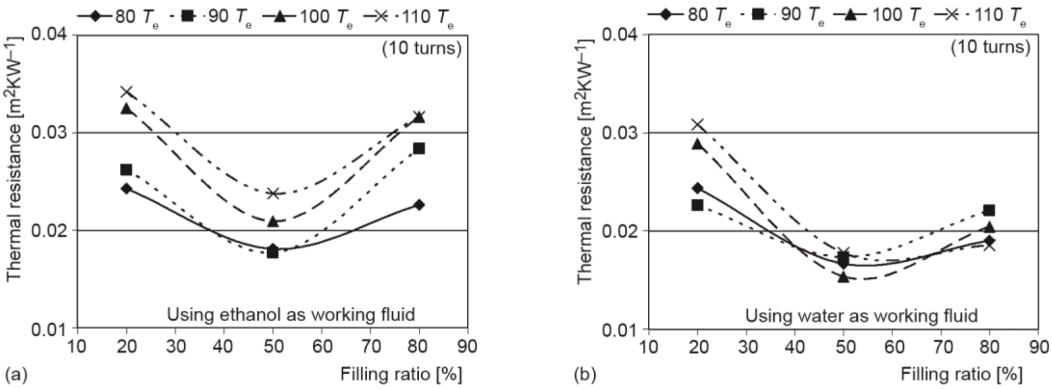

Figure 11. Effects of working fluid and filling ratio on thermal resistance; (a) using ethanol as working fluid, (b) using water as working fluid

Thermal performance

Figure 11 shows the influences of the working fluid and the filling ratio on the thermal resistance of HCLOHP at the evaporator temperature range of 80-110 °C. For using ethanol as working fluid, as presented in fig. 11(a), the minimum thermal resistance always occurs at the 50% filling ratio for all evaporator temperatures, while for the 20% and 80% filling ratios their thermal resistances are high and almost the same. For water, as seen from fig. 11(b), there is a similar trend. However, the thermal resistance is slightly increased when the filling ratio increases from 50% to 80% and the dependence on evaporator temperature is less at these filling ratios. At all the evaporator temperatures, the average thermal resistances are approximately 0.017 m^2K/W and 0.020 m^2K/W for the 50% and 80% filling ratios, respectively, while for the 20% filling ratio the thermal resistances are relatively high. Therefore, for both fluids with a 20% filling ratio, the thermal performances are almost the same, while for the 50% and 80% filling ratios the thermal performances of water tend to be higher than that of ethanol.

Because for both working fluids, the time fractions of the oscillating flow were relatively the longest at the 50% filling ratio, the thermal resistances were also lowest. This result agrees with the previous research [10], which was found that at this proper filling ratio, the oscillating slug flow was self-sustained for the horizontal operation. Since, at the 20% and 80% filling ratios, the oscillation time-fractions were shorter than that for 50%, their thermal performances were also lower. Because in the previous research [9], the thermal performance of a HCLOHP improves by decreasing the effective length, in this work the evaporator, adiabatic and condenser lengths of tested HCLOHP were assigned to attain the short effective length. Although the unsymmetrical shape of the vapor bubbles head and tail only occurred by using water as the working fluid, it was found that for the specified filling ratio, the influence of the short effective length overcame that for the unsymmetrical bubble shape on the frictional pressure drop and flow resistance. Thus for each filling ratio, the time fractions of the oscillating flow of both working fluids were almost the same. Although at a 20% filling ratio, the thermal resistances of both fluids were nearly equal, the thermal resistance of water tended to be lower than that for ethanol at the 50% and 80% filling ratios. This is because although the main flow pattern is the oscillating slug flow for all the working fluids and filling ratios and this agrees with the previous researches [8, 10, 14], the wavy vapor-liquid interface which induces the liquid slug formation is only found for water. When using ethanol, many long vapor plugs were clearly observed at the evaporator part, while for water the alternate arrangement of a medium and/or small vapor plug and a liquid slug happened and easily led to generate the driving pressure forces of the oscillating slug flow. Moreover, the nucleate boiling followed by the oscillating flow was discovered in the evaporator part at only the 50% and 80% filling ratios of water. This visual result can be used to support the previous quantitative work [9] in which it concluded that, HCLOHP with short effective length, a 2 mm inner diameter and using a 50% filling ratio of water had a higher thermal performance than that of ethanol.

Conclusions

The results for the HCLOHP can be summarized as follows.

- The local variation of adiabatic pressure is more corresponding to the motion characteristics of working fluid than the variation of adiabatic temperature.
- The fluid motion characteristic may be separated into two main conditions viz., the oscillating slug flow, which enhances the operation of a HCLOHP and the standstill condition.
- The vapor fractions were large and the time portions of the oscillating flow were short at the number of 6 and 8 turns and the high evaporator temperature led to the low thermal performance.

- The thermal performance improved when the number of turns reached the critical value of 10 turns, at which the vapor fraction was relatively small, and the time portion of the oscillating flow was the longest.
- For both working fluids the time portions of the oscillating flow were longest at the 50% filling ratio, which led to the lowest thermal resistances.
- The wavy vapor-liquid interface which induced the vapor/liquid slug train formation was only found for water. Moreover, the nucleate boiling followed by the oscillating flow was discovered in the evaporator part at only the 50% and 80% filling ratios of water. Therefore, at these filling ratios, the thermal resistance of water tended to be lower than that of ethanol.

Acknowledgment

This research work was done at Faculty of Engineering, Naresuan University, Thailand under the auspices of The Thailand Research Fund (under Contact No. MRG5180120).

Nomenclature

c_p – specific heat, [kJkg^{-1}K^{-1}]
D – tube diameter, [mm]
L – length, [mm]
$\dot{m}$ – mass flow rate, [kgs^{-1}]
n – number of turns
q'' – heat flux, [Wm^{-2}]
R'' – thermal resistance, [m^{2}KW^{-1}]
T – temperature, [°C]
Q_{out}, Q_{in} – volume flow rate, [L per minute]

Subscripts

a – adiabatic section
aver – average
c – condenser section
e – evaporator section
i – inside
in – inlet
out – outlet
w – cooling water

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Paper submitted: May 14, 2017
Paper revised: November 4, 2017
Paper accepted: November 9, 2017