International Journal of the Physical Sciences Vol. 7(29), pp. 5097-5105, 26 August 2012
Available online at http://www.academicjournals.org/IJPS
DOI: 10.5897/IJPS12.344
ISSN 1992-1950 ©2012 Academic Journals

Full Length Research Paper

Internal flow patterns behavior of a top heat mode closed-loop oscillating heat pipe with check valves (THMCLOHP/CV)

S. Thongdaeng, S. Rittidech* and B. Bubphachot

Heat-Pipe and Thermal Tools Design Research Laboratory (HTDR), Division of Mechanical Engineering Faculty of Engineering, Mahasarakham University, Thailand

Accepted 25 June 2012

An experimental study of the internal flow patterns of a top heat mode closed-loop oscillating heat pipe with check valves (THMCLOHP/CV) was carried out. In this study, the heat pipe was made of a Pyrex tube with an inner diameter of 2.4 mm which was bent into 10 meandering turns and filled with ethanol, R141b and R123 at a filling ratio of 50% by total volume. The number of check valves was 2 sets. The length of evaporator, adiabatic and condenser sections was 50 mm. The pipe was operated at the top heat mode, and the heat applied at the evaporator section was controlled at 85, 105 and 125°C. The detailed flow patterns were recorded with a digital camera and a video camera. The experimental results showed that the operation of the THMCLOHP/CV included three main phenomena: Energy storage, movement of slug-train and restoration. At an evaporator section length of 50 mm, the maximum heat flux occurred with R123 as the working fluid at the evaporator temperature of 125°C. The total internal flow patterns occurred as slug flow/dispersed bubble flow/churn flow. In addition, the evaporator temperature increased from 85 to 105°C and 125°C with ethanol, R141b and R123 as working fluids. The average length of the vapor slug decreased and the average velocity of the vapor slug increased, respectively.

Key words: Flow patterns, closed-loop oscillating heat pipe, top heat mode

INTRODUCTION

A pulsating or oscillating heat pipe (OHP) first proposed by Akachi et al. (1996) projected a new type of heat-pipe made of a capillary tube that was applied to cool small electronic devices. Gi et al. (1999) studied OHPs applied to cooling central processing unit (CPU) chips. Miyazaki et al. (2000) presented a closed-loop oscillating heat pipe with check valves (CLOHP/CV). Pitpatpaiboon et al. (2004) investigated the heat flux of CLOHP/CV and found that it was a very effective heat transfer device. The advantages of CLOHP/CV includes the simplicity of construction, no wick structure, high thermal performance and capability of operation in any heat mode, such as a bottom heat mode (BHM), or horizontal heat mode (HHM). However, the BHM and HHM cannot be used in all applications because some devices are small and have limited area for a set-up. A set-up area is necessary for the top heat mode (THM). The CLOHP/CV operation in this heat mode is called the THM closed-loop oscillating heat pipe with check valves (THMCLOHP/CV).

Charoensawan and Terdtoon (2008) studied the thermal performance of a THMCLOHP. It was found that the best thermal performance depended on an evaporator temperature that was related to the number of turns. Rittidech et al. (2010) investigated the thermal performance of a THMCLOHP/CV. It was observed that the highest performance was obtained when the number of the check valves was 2 sets. The maximum heat flux occurred with a 2 mm inner diameter tube and R123. Khandakar et al. (2003) studied the operational regimes of CLOHP. The results of the study showed the effect of input heat flux and filling ratio on the thermal performance

*Corresponding author. E-mail: s.rittidech@hotmail.com. Tel: +66 43 754316. Fax: +66 43 754316.

of the device Xu et al (2005a) investigated the high speed flow visualization of a CLOHP. It was operated in BHM in order to understand the oscillation behavior and the translation of flow patterns definition in the CLOHP. Tong et al (2001) studied the closed-loop pulsating heat pipe. It was found that the main behavior consisted of a driving force and restoring force for fluid circulation and oscillations. Kim et al (2003) studied the flow visualization of oscillation characteristics of liquid and vapor flow in the oscillating capillary tube heat pipe. It was found that the oscillation of vapor bubbles was caused by nucleate boiling. Huo et al (2004) investigated boiling heat transfer in small diameter tubes. It was found that the experiment categorized six flow patterns: dispersed bubble, bubble, slug, churn, annular, and mist flow. Rittidech et al (2008) studied the effect of evaporator length and check valve ratios to the number of turns on the internal flow patterns of a CLOHP/CV. It was found that the internal flow patterns could be classified according to the Le and Rcv. Bhuwakietkumjohn and Rittidech (2010) found that the flow patterns occurred as annular flow/slug flow, slug flow/bubble flow and dispersed bubble flow/bubble flow, respectively. The main regime of each flow patterns can be determined from the flow patterns map using ethanol and a silver nano-ethanol mixture. Each of the two working fluids gave corresponding flow patterns.

The mentioned literature survey shows that most of the previous work was on thermal performance evaluation and internal flow patterns in BHM and HHM. Therefore, the objective of the present work is to study the internal flow patterns behavior of a THMCLOHP/CV. The results of the investigation provided us a better understanding of the heat transport capability of CLOHP/CV for application.

EXPERIMENTAL PROCEDURE

The experimental set-up is shown in Figures 1a and b. The system was constructed using high quality glass capillary tubes with an inner diameter of 2.4 mm bent into 10 meandering turns. Ethanol, R141b and R123 were used as working fluids with a filling ratio of 50% by total volume. The number of check valves was 2 sets. The advantage of a check valve is that it controls the liquid slug flow in one direction. The check valve is a floating type valve that consists of a stainless ball and copper tube in which ball stopper and conical valves seat are provided at the ends, respectively. The ball can move freely between the ball stopper and the valves seat as shown Figure 2. The evaporator length was 50 mm. It operated on the THM and the heat applied to the evaporator section was controlled at 85, 105 and 125°C. The temperature of the cooling water from the condenser was kept constant at 20°C through a cold bath (EYELA CA-1112) with ±2°C accuracy and then pumped into the cooling jacket. The mass flow rate inside the cooling jacket was measured with a floating flow meter (Platon PTF2 ASS-C) with an uncertainty of 2.88%. The temperature was recorded by a data logger (Yokogawa DX 200) with ±1°C accuracy.

Thermocouples (OMEGA type K) with an uncertainty of ±0.58°C were employed to measure the temperature at the inlet and outlet of the condenser section to determine the heat transfer rate. Table 1 shows the details of experiment parameters, measurement uncertainty and device accuracy. A video camera (Sony CCD TR618E) was employed to continuously record the entire flow of the THMCLOHP/CV, and a digital camera (Nikon D90) was used to take photographs at specific times. A scale was attached to the apparatus to measure the length of vapor bubbles in the evaporator section and the velocity of vapor bubbles is determined by visual analysis of slow-motion video-replay using a Sony DSR 11 (100 fps). The experiment was conducted as follows.

The THMCLOHP/CV was set into the test rig. The temperature of the heater and cold baths was set at the required value and cold fluids were supplied to the jackets of the condenser section. When the evaporator temperature was increased until it reached under test conditions, the time was required to achieve steady state was about 30 min. After that a steady state was reached. The video camera was started and continuously recorded the flow patterns. The temperature and the flow rate of the cooling water were also recorded. The heat transfer rate can be calculated using Equation 1 as follows:

$$Q = mC_p(T_{o} - T_{i}) \quad (1)$$

where m is the mass flow rate of water in the condenser section (m = 0.0133 kg/s), C_p is the specific heat of water inlet in the condenser section (C_p = 4.183 kg/kJ °C), T_i and T_o are the temperatures at the inlet and outlet in the condenser section (°C). The heat flux was calculated using Equation 2 as follows:

$$q = \frac{Q}{A} \quad (2)$$

where Q is the heat transfer rate (W) and A is the outer surface area of the tube in the condenser section (A = 0.025 m²).

RESULTS AND DISCUSSION

Operational behavior of the THMCLOHP/CV

The initial charge of the working fluid inside the THMCLOHP/CV results in randomly distributed vapor plugs and liquid slugs (slug-train) (Xu et al 2005a) in the capillary tubes because the effect of surface tension force is stronger than the force of gravity as shown in Figure 3. The temperature in the evaporator section increases when heat is applied to the evaporator section at the top of the condenser section. Resulting volume expansion of the vapor plug moves it to the condenser section due to the pressure difference between the evaporator section and condenser section. When the vapor plug moves to the condenser section, it is at a lower temperature. As such, the vapor plug collapses due to condensation. Then, the slug-train which is adjacent to the vapor plug in the condenser section is pushed to the neighboring vapor plug and the liquid slug moves to the evaporator section for nucleation as shown in Figure 4a. In the case of BHM, working fluid moves to the evaporator section

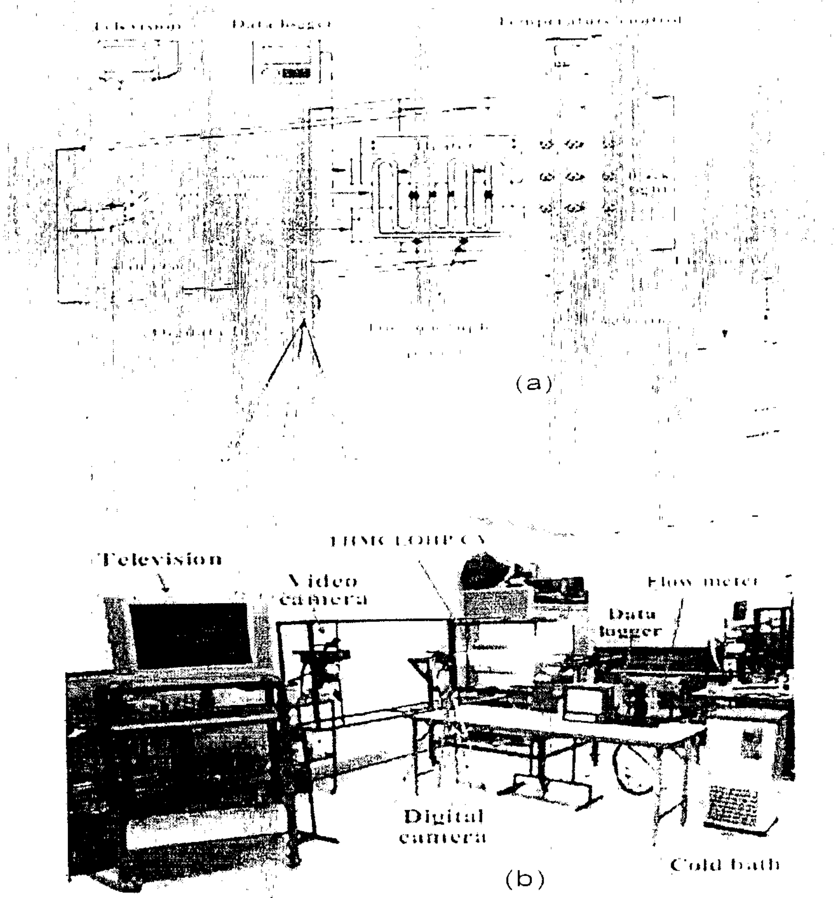

Figure 1. (a) Diagram of the experimental procedure (b) experimental set-up

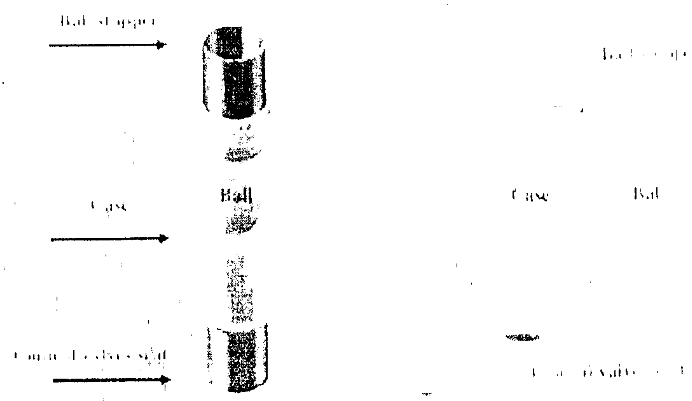

Figure 2. Check valves

Table 1. Measurement uncertainty and accuracy of devices.

Parameter	Uncertainty and accuracy
Thermocouples	Uncertainty of ± 0.58°C
Flow meter	Uncertainty of ±2.8%
Cold bath	Accuracy of ± 2°C
Temp control	Accuracy of ±2°C
Data logger	Accuracy of ±1°C

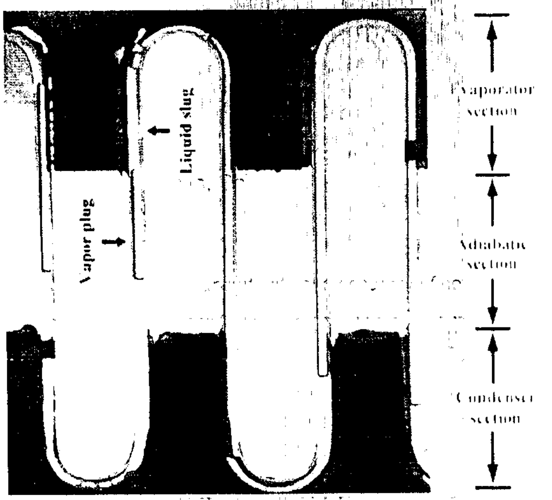

Figure 3. The THMCLOHP/CV configuration

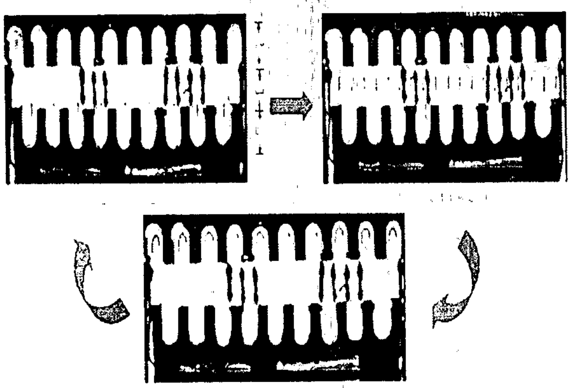

Figure 4. Flow directions of the THMCLOHP/CV in a full cycle

with respect to gravity. At the nucleation site, the dispersed bubbles form and coalesce to grow in size as the bubbles are continuously heated as shown in Figures 5a and b. The generation and growth of the dispersed bubbles occurred continuously when heat was applied to the evaporator section. This is due to the fact that the inner wall temperature of the tube was higher than the saturated temperature of the working fluid when the inner wall temperature, T_w was under the following conditions (Xu and Zhang, 2005b)

$$T_w > T_{sat} + \frac{2\sigma T_{sat}}{R \lambda \rho_v} \quad (3)$$

where T_w and T_{sat} are the wall and saturation temperature (°C) σ is surface tension (N/m), R is cavity radius (m), λ is latent heat of vaporization (kJ/kg) and ρ_v is density of vapor (kg/m^3)

As previously described the behavior occurs as a result of stored energy (Kim et al. 2003). The THMCLOHP/CV waits for some time to store enough energy, thus the movement can be activated by the driving force of the bulk flowing in the same direction as the check valves as shown in Figure 4b

For this process the vapor plug is condensate in the condenser section, and the reduced temperature causes a decrease in pressure resulting in the difference between the pressure in the evaporator section and condenser section. This phenomenon is the major mechanism that transfers the heat from the evaporator section to the condenser section which results in the lower pressure in the evaporator section. The vapor plugs cannot move to the next tube and return in an inverse flow direction. This mechanism takes place because of the restoring force as shown in Figure 4c. The process of storing energy and its relationship to new movement is shown in Figures 4a and b. The operation of THMCLOHP/CV occurs continuously in a cycle as described.

Flow patterns of the THMCLOHP/CV

The experimental results showed the representative internal flow patterns in the evaporator section of the THMCLOHP/CV. The detailed internal flow patterns were recorded by a video camera for two purposes: to analyze the vapor bubble length and velocity at a specified time and to compare the internal flow patterns at the same heat source temperature for all working fluids.

Figures 6 to 8 show the internal flow patterns of the THMCLOHP/CV using R123 as the working fluid with a Le of 50 mm, 2.4 mm and evaporator temperatures of 85, 105 and 125°C. It can be observed that when the evaporator temperature was increased the average velocity of the vapor bubbles increased from 0.3, 0.36 and 0.54 m/s respectively and the length of the vapor bubbles rapidly decreased from 0.14, 0.09 and 0.0825 m respectively.

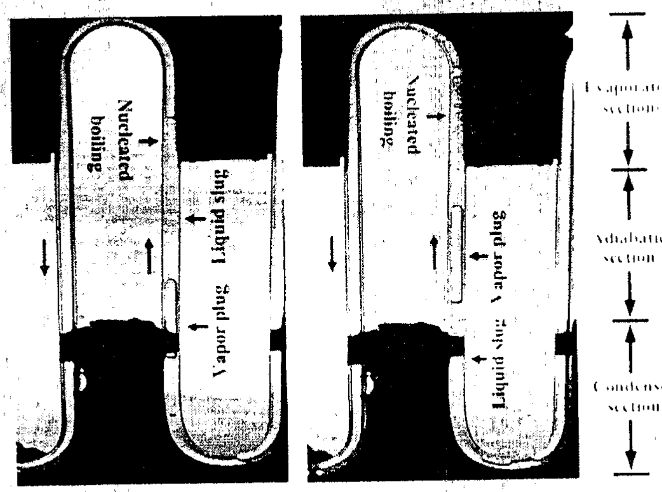

Figure 5. (a), The nucleated boiling (b) the nucleated boiling and coalescence phenomenon

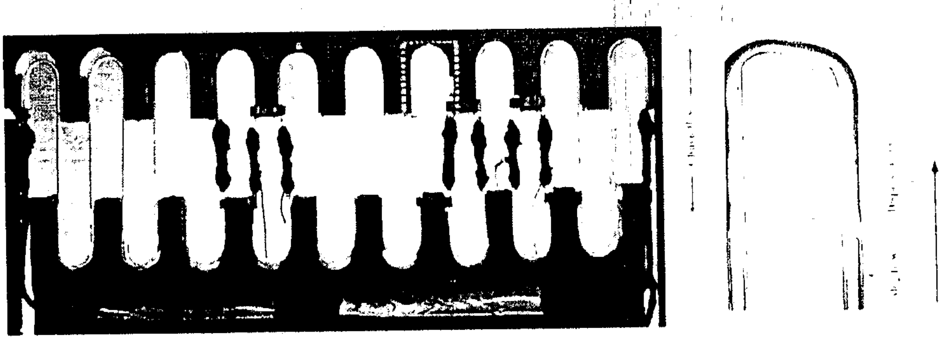

Figure 6. Internal flow patterns of the THMCLOHP/CV using a R123 at Le of 50 mm -90° of angle 2.4 mm ID the evaporator temperature of 85°C

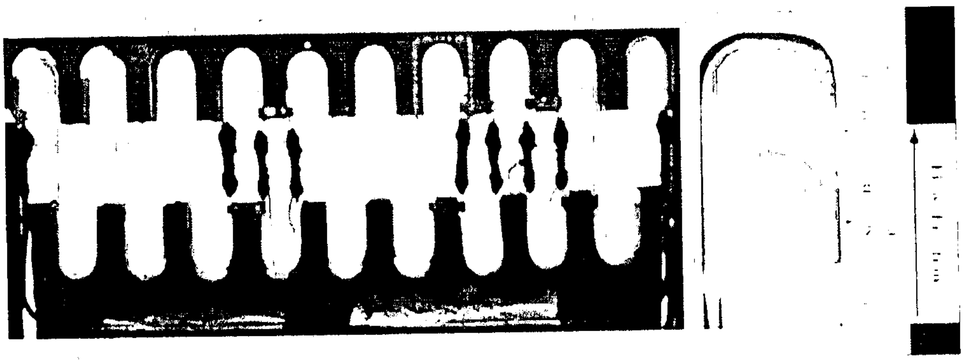

Figure 7. Internal flow patterns of the THMCLOHP/CV using a R123 at Le of 50 mm -90° of angle 2.4 mm ID the evaporator temperature of 105°C

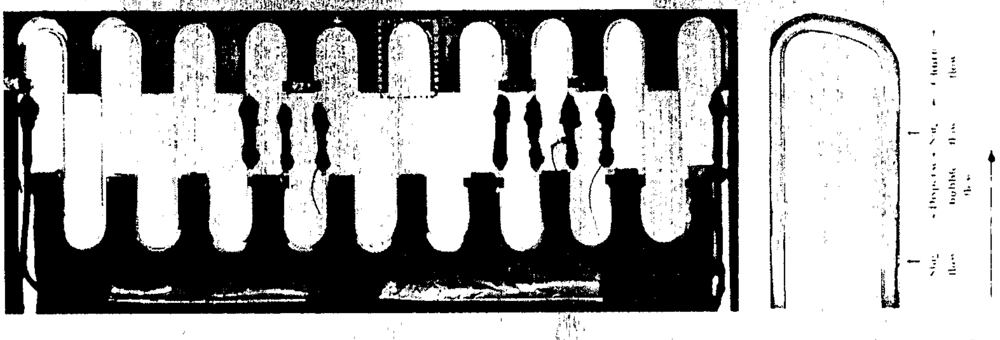

Figure 8. Internal flow patterns of the THMCLOHP/CV using a R123 at Le of 50 mm -90° of angle, 2.4 mm ID the evaporator temperature of 125°C

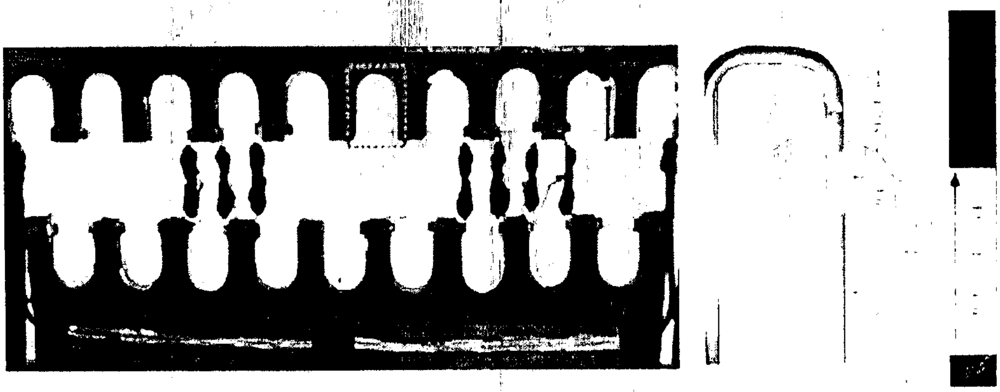

Figure 9. Internal flow patterns of the THMCLOHP/CV using a R141b at Le of 50 mm -90° of angle 2.4 mm ID the evaporator temperature of 85°C

This is because at high temperatures the vapor expands rapidly. This results in high pressure in the evaporator section and the vapor sustains the fast movement for a short time. As the volume of the vapor expands, and more vapor is generated at the high temperatures than at lower temperatures, the average velocity of the vapor increases to transfer heat from the evaporator section to the condenser section. The heat flux increases from 1.3352, 2.2254 and 3.338 kW/m^2, respectively (Example: $Q = \dot{m}C_p(T_{out} - T_{in})$ = 0.0133 × 4.183 × (28.5-27) = 83.45 W $q = Q/A$ = 83.45/0.025 = 3.338 kW/m^2). While the total internal flow patterns occur as slug flow/dispersed bubble flow/churn flow. Initially, the vapor plug pushes the liquid slug to the evaporator section, and the dispersed bubble nucleation site at the inner wall of the tubes dominates the lower part of the evaporator. The velocity increases and the vapor plug moves up the U-bend tube where the flow is oscillating due to the shedding of the liquid masses. As the liquid accumulates, the velocity of the liquid slug is lower than the vapor plug. The shape of vapor plug changes and the internal flow patterns transform into churn flow.

Figures 9 to 11 show the internal flow patterns of the THMCLOHP/CV using R141b as the working fluid with a Le of 50 mm, 2.4 mm inner diameter and evaporator temperatures of 85, 105 and 125°C. It can be observed that as the evaporator temperature increases the average velocity of the vapor increases from 0.293, 0.33 and 0.48 m/s, respectively and the length of vapor bubbles rapidly decreases from 0.14425, 0.1025 and 0.09625 m, respectively. We see that at high temperatures the vapor grows rapidly and as result there is high pressure in the evaporator section and the vapor sustains fast movement for a short time. As the volume of the vapor expands, more vapor is generated at high temperatures than at lower temperatures resulting in the average velocity of the vapor increasing to transfer heat from the evaporator section to the condenser section. The heat flux increases from 1, 11, 2 and 2.67 kW/m^2 respectively.

While the total internal flow patterns occurred as slug flow/dispersed bubble flow it did not affect the churn flow

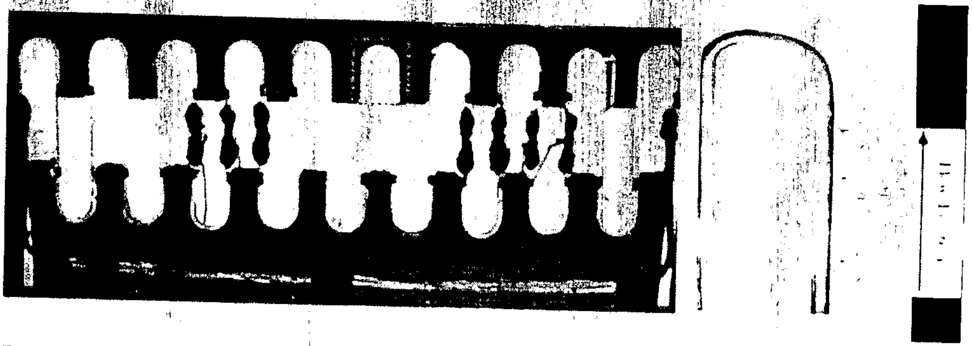

Figure 10. Internal flow patterns of the THMCLOHP/CV using a R141b at Le of 50 mm -90° of angle 2 4 mm ID the evaporator temperature of 105°C

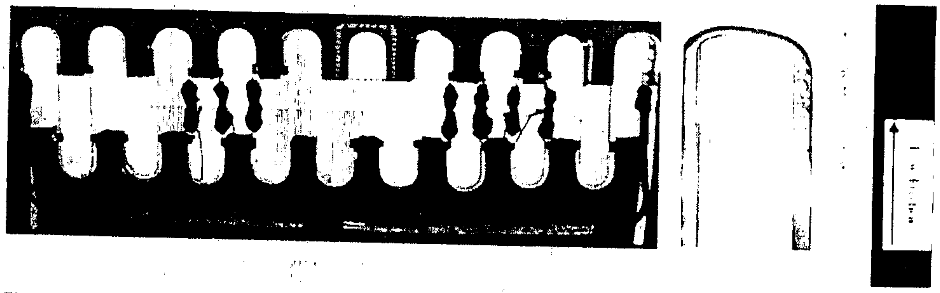

Figure 11. Internal flow patterns of the THMCLOHP/CV using a R141b at Le of 50 mm -90 of angle 2 4 mm ID the evaporator temperature of 125°C.

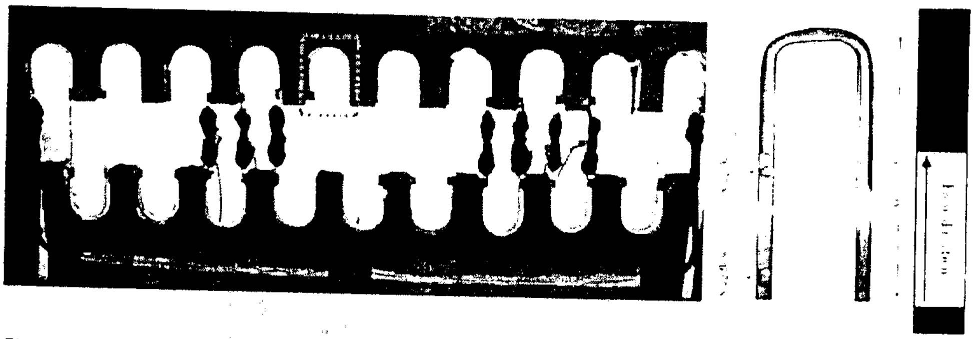

Figure 12. Internal flow patterns of the THMCLOHP/CV using an ethanol at Le of 50 mm -90° of angle 2 4 mm ID the evaporator temperature of 85°C

because the velocity of the vapor plug lowered the vapor slug of R123

Figures 12 to 14 show the internal flow patterns of the THMCLOHP/CV using ethanol as the working fluid with a Le of 50 mm 2 4 mm inner diameter and evaporator temperature of 85 105 and 125 C It can be observed that when the evaporator temperature was increased the average velocity of the vapor increased from 0 27 0 31

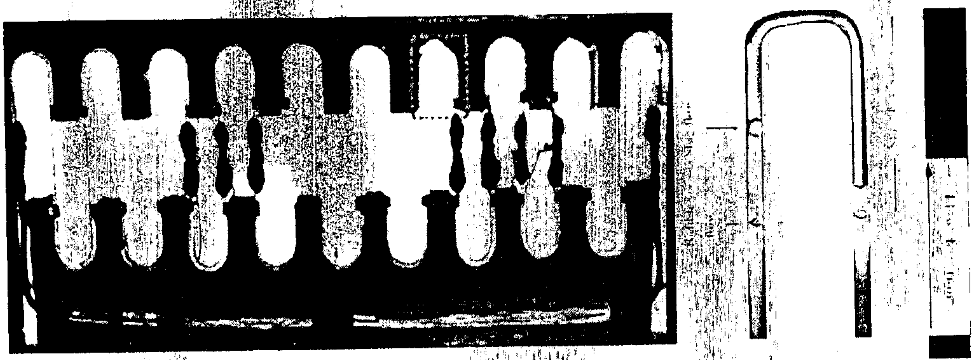

Figure 13. Internal flow patterns of the THMCLOHP/CV using an ethanol at Le of 50 mm -90° of angle 2.4 mm ID the evaporator temperature of 105°C

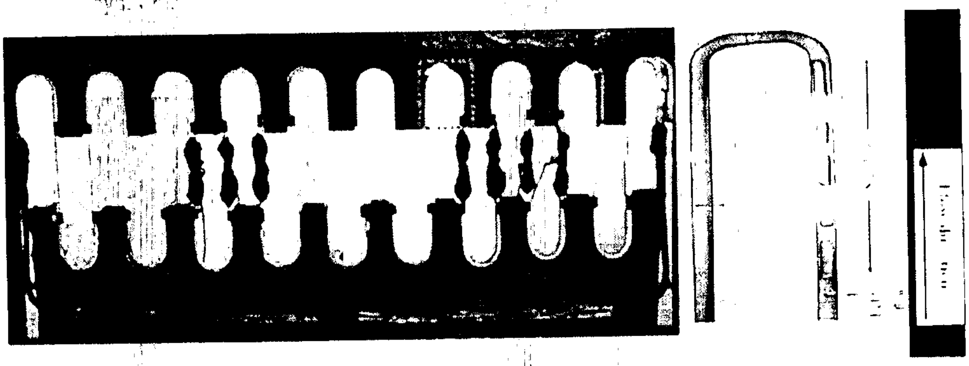

Figure 14. Internal flow patterns of the THMCLOHP/CV using an ethanol at Le of 50 mm -90° of angle 2.4 mm ID the evaporator temperature of 125°C

and 0.43 m/s, respectively and the length of vapor bubbles rapidly decreased from 0.15775, 0.10475 and 0.099225 m, respectively. This is because at high temperature the vapor grows rapidly. As a result, the high pressures in the evaporator section and the vapor sustain fast movement for a short time. The volume expands and more vapor is generated at high temperatures than at lower temperatures resulting in the average velocity of the vapor to increase to transfer heat from the evaporator section to condenser section. The heat flux increases from 0.89, 1.78 and 2 kW/m^2, respectively. The total internal flow patterns at the low heat source occurred at slug flow/annular flow because the heat source was close to the boiling point of ethanol, but the high heat source prompted slug flow/bubble flow because the heat source temperature was higher than the boiling point of ethanol.

In addition, the flow patterns of the THM are similar to those in BHM, as shown in the results of Rittidech et al. (2008) but the vapor bubbles length and velocity of THM is longer than BHM because of the effect of gravity. It is hard for working fluid to circulate and the liquid has less movement toward the evaporator section, resulting the rapid volume expansion.

Conclusions

The following facts summarize the essential aspects of this study.

(1) The operation of the THMCLOHP/CV includes three main phenomena that occur: storing the energy, movement of slug train and restoration.

(2) The heat flux occurred at the maximum of the THMCLOHP/CV using R123 as the working fluid with the evaporator temperature at 125°C. The total internal flow patterns occurred as slug flow/dispersed bubble flow/churn flow. In addition, the temperature of the evaporator section increased from 85, 105 and 125°C