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Study on Circulation Flow in Closed Loop Pulsating Heat Pipe

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Keywords：Pulsating Heat Pipe, Circulation Flow, Circulation Period, Thermal Resistance.

ABSTRACT

This research utilized 6 mm outer diameter and 3 mm inner diameter glass tubes to manufacture 9 turns Closed-Loop Pulsating Heat Pipe (CLPHP) with a total length of 1980mm. For achieving the loop circulation easily, a water cooling system kept at 35 ° C was used as the condenser. The experiment was conducted to evaluate the thermal resistance under different fluid filling ratios (20%, 30%, 40%, 50%, 60%, 70% and 80%), and at a series change of heat inputs (40W, 80W, 120W, 160W, 200W). Through a digital video camera, the visualization experiment was carried out to observe the circulation flow period in the PHP. A styrofoam ball was designed to put into the tube for a better observation and a correct estimation of fluid flow direction. Circulation times and circulation period were observed and calculated. The results showed that PHP reached fully circulation under the filling ratio of 60%, 70%, and 80%, at an input power of 200W. The circulation can be categorized into clockwise circulation, counterclockwise circulation and transition circulation status. The CLPHP thermal resistance was observed to be the least in circulation flow situation.

INTRODUCTION

Heat pipes are usually applied to the thermal control of the electronic equipment in recent year. The technology of Pulsating Heat Pipe (PHP) which is circulates the working fluid within the meandering capillary tube. It is called meandering capillary tube heat pipe, or self-excited oscillation (pulsation) heat pipe or Akachi pipe named after Hisateru Akachi (Akachi et al., 1996), and they are being researched for many year (Zhang and Faghri, 2008). The schematic of a CLPHP is shown in Fig. 1. CLPHP is the meandering tube, the ends of which are joined to form a continuous loop. When one end of the capillary tube is heated (the evaporator), the working fluids evaporate and increase the pressure of vapor, thus causing the bubbles in the evaporator zone to grow. This pushes the liquid towards the low-temperature end (the condenser). Cooling of the condenser results in a reduction of vapor pressure and condensation of bubbles in that section of the heat pipe. The growth and collapse of bubbles in the evaporator and condenser sections, respectively, results in an oscillating motion within the tube. Heat is transferred through latent heat in the vapor and through sensible heat transported by the liquid slugs (Reay and Kew, 2006). As long as heating and cooling system exists, motion of the liquid and vapor are spontaneous.

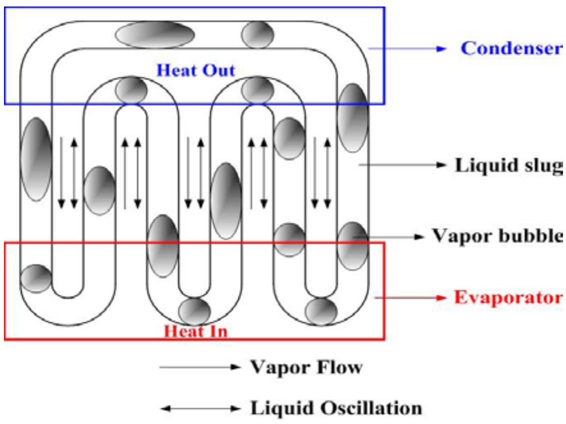

Fig. 1. The schematic of a CLPHP

Research and development on pulsating or oscillating heat pipes can be categorized as either experimental or theoretical. Experimental studies have been focused on either visualizing the flow pattern in PHPs or characterizing the heat transport capability of PHPs. Theoretical examination attempts were made to analytically and numerically model the

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fluid dynamics and/or heat transfer associated with oscillating two-phase flow (Faghri, 2012). Nazaria et al. (2018) studied the effects of working fluids on the thermal performance of different pulsating heat pipes, thermophysical parameters relating to working fluids, such as boiling point, latent heat of vaporization, surface tension, thermal conductivity and dynamic viscosity, were presented based on experimental and numerical studies done in recent years.

Zhang et al. (2021) reported that the fluids with high thermal conductivity, low dynamic viscosity and low surface tension (such as nano-fluid, deionised water, etc.) are more conductive to starting characteristics of PHP. Applying nanostructures in the base fluid can significantly reduce the thermal resistance of heat pipes compared with utilizing pure as operating fluid (Kang et al., 2006; Lin et al., 2008; Kang et al., 2009; Kang et al., 2017; Nazaria et al., 2019).

In order to study the operation characteristics directly, the flow characteristics of working fluid in PHP are studied by visualization. Tong et al. (2001) performed the flow visualization for the closed loop PHP. It was observed that during the start-up process the working fluid oscillates with large amplitude. The working fluid circulates for the steady oscillation state.

Charoensawan et al. (2003, 2003) performed a wide range of experimental studies providing vital information on the parameter dependence of their performance. The influence characterization has been done for the variation of internal diameter, number of turns, working fluid and inclination angle. Their results strongly indicate the gravity and number of turn effects on the thermal performance.

The above literature surveys show that most of the previous works focus on the thermal performance evaluation and simple flow visualization. In the present study, a series of visualization experiments were carried out to investigate thermal characteristic of circulation flow in a CLPHP and is organized as follows. Firstly, illustration of the experimental setup is shown. Secondly, description of the effect of filling ratio and heat input power based on the present experimental findings, including flow patterns and bulk circulation flow phenomenon. Finally, the major conclusions are summarized.

EXPERIMENT

PHP Set-up

Fig. 2 illustrates the experimental setup, consisting of the CLPHP assembly, the power supply unit, thermostatic water bath, and acquisition device. For flow visualization, the PHP assembly was made of heat resistant glass capillary tube with an outside diameter of 6.0 mm and an internal diameter of 3.0 mm. The CLPHP has ten capillary tubes which are identified as 1,2,3,4,5,6,7,8,9,10 from left to right. CLPHP loop is divided into evaporator, adiabatic and condensation composing of three sections. Working fluid is pure water. The heating device of the CLPHP is an electric heating wire with winding in the evaporator section. A constant temperature is kept in the condenser section by cooling water circulating in thermostatic water bath. The capillary resistances in the tube increase with the decrease of the inner diameter, which has a great influence on the working ability of PHP. The working fluids can form the vapor plug and the liquid slug in the tube under surface tension when the inner diameter of PHP is appropriate. The best range for the tube diameter can be obtained from Eq. (1) (Dobson et al., 1999).

$$0.7\sqrt{\sigma/(\rho_{liq}-\rho_{vap})g} \le D \le 1.8\sqrt{\sigma/(\rho_{liq}-\rho_{vap})g} \quad (1)$$

(σ: surface tension; ρ_{liq}: density of working liquid; ρ_{vap}: density of vapor; g: acceleration of gravity; D: diameter of tube). In order to observe the period of circulation flow easily, a styrofoam ball (diameter 2.5mm; weight 0.5mg) was used in the tube. Details of the experiment are shown in Table 1.

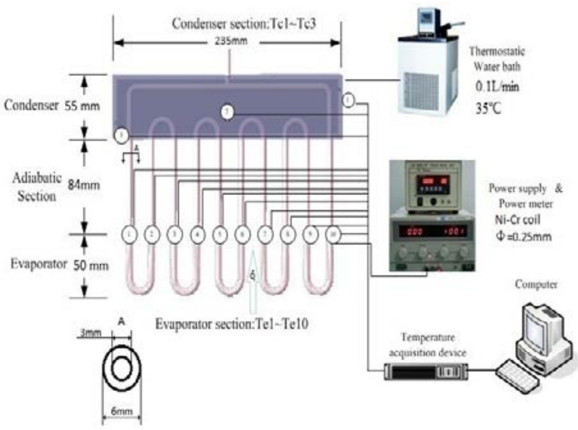

Fig. 2. Schematic of experimental set-up

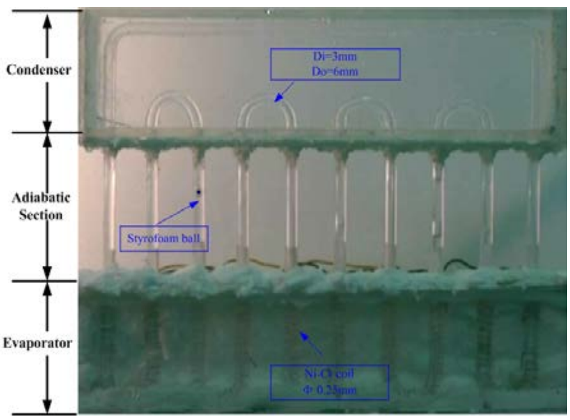

Fig. 3. Photograph of CLPHP loop

Table 1 Details of the experiment

Specifications of CLPHP	1. Material：Glass 2. Total length：1980 mm 3. Outer diameter：6 mm 4. Internal diameter：3 mm 5. Total volume：16.15 ml
Specifications of Condenser	1. Flow velocity: 0.1L/min 2.Condenser Vol.: 0.341L
Thermocouple (T-type)	1. Material：Cr-Ni wire 2. Electric resistance：22.2 Ω/m
Input Power (Q)	40W, 80W, 120W, 160W 200W
Filling Ratio (FR)	20%, 30%, 40%, 50% 60%, 70%, 80%
Working Fluids	DI Water
Angle	Vertical orientation

Experimental procedure

(1) Put T-type thermocouples fixed in suitable position, i.e. ten thermocouples in the evaporator and three thermocouples in the condenser, respectively, which are connected with the temperature scanner from Te1~ Te10, and Tc1~ Tc3 as shown in Fig. 2. Tc1is the cooling water inlet temperature and Tc3 is the cooling water outlet temperature. Photograph of the CLPHP loop is shown in Fig. 3.

(2) Evaporator insulating and heat wire twining are connected with the power supply. It will cover with heat insulation material in the adiabatic section, which can prevent heat from being lost and influence in the experimental result.

(3) Evacuate the loop to 0.01 Pa, fill with the necessary working fluid and seal.

(4) Allow the water coolant flow into condenser, setting the temperature of thermostat bath at 35±0.1°C.

(5) Set up the digital video camera, to record the working situation of the working fluid inside the tube.

(6) Turn on the temperature scanner and power supply, adjust the heating power to 40 W, and then begin to observe and note down the temperature at each point through the computer.

(7) When the steady state is achieved, adjust the input power to 80 W (plus 40 W). Again, when the study state is achieved and the input power is adjusted to 120 W. Repeat this step until 200 W or CLPHP gets dry out.

(8) Fill in the working fluid with different filled ratio. Steps 4–7 are repeated.

The overall thermal resistance for the system is defined as

$$R = (Te_{ave} - Tc_{ave})/Q \quad (2)$$

(R: Overall thermal resistance; Te_{ave} : Average temperature of evaporator; (Te1~ Te10); Tc_{ave} : Average temperature of cooling water; (Tc1~ Tc10); Q : Input power)

The uncertainty of the thermal resistance (U_R)is performed as given by

$$\frac{U_R}{R} = \frac{1}{2}\left[\left(\frac{U_Q}{Q}\right)^2 + \left(\frac{U_{\Delta T}}{\Delta T}\right)^2\right] \quad (3)$$

where U_Q and $U_{\Delta T}$ are uncertainties of the input power and the average temperature difference of evaporator and cooling water, respectively. The uncertainty of presented experiment was calculated as 1.8-5.7%.

RESULTS AND DISCUSSIONS

Effect of the filling ratio and input power

Transient and steady state experiments are conducted with working fluids water. The experiments are carried out at different heat loads, filling and ratio. The wall temperatures of evaporator and condenser are recorded. The filling ratio is defined as the total liquid volume divided by the total inside volume. Results show that between 20% and 80% filling ratio, the device functions in a true pulsating mode in this study. As there is a continuous pressure pulsation during the flow in the CLPHP, there will be fluctuations in both the evaporator and condenser temperatures even at steady state. Fig. 4-7 show the variation of average temperature of evaporator and condenser with time at different heat inputs when filling ratio is 20%, 60%, 70%, and 80% respectively. It is clear that the temperature fluctuations are more in the evaporator due to more intermittent motion of the working fluid. It also shows from these figures that the variation of condenser temperature is less at lower heat input compared to higher heat input. This is because of the slow and intermittent motion of the working fluid at lower heat input. As the movement of the working fluid is slow at lower heat input due to lower energy levels, the hot fluid takes more time to reach the condenser from the evaporator. Thus the rise in the temperature of the cooling fluid is less which results in lower values of condenser temperature at lower heat input. The thermal resistance of the CLPHP, in all cases, was evaluated based on the steady state average evaporator temperature and the corresponding average condenser temperature. Since the evaporator was vacuum insulated, the thermal power was directly calculated from the source electrical power. Fig. 8 shows the variation of overall thermal resistance of the CLPHP with increasing heat input power at different filling ratios. From the figure it is clear that the thermal resistance decreases with increase in heat input at all filling ratios considered. Table 2 shows the corresponding thermal resistance at different heat input power and filling ratios. More the bubbles (lower filling ratio), more is the degree of freedom but simultaneously there is less liquid mass for sensible heat transfer. Less the bubbles (higher filling ratio) cause less perturbations and the bubble pumping action is reduced thereby lowering the performance. From the table, the filling ratio of 70% exhibits the lower values of thermal resistance compared to other filling ratios.

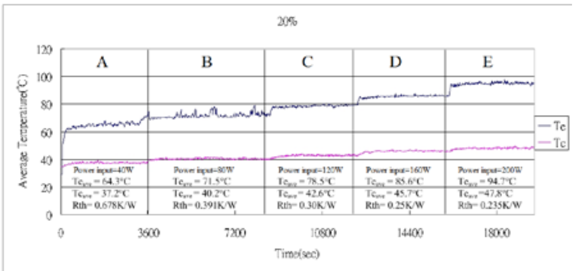

Fig. 4. Variation of Te and Tc for filling ratio 20%

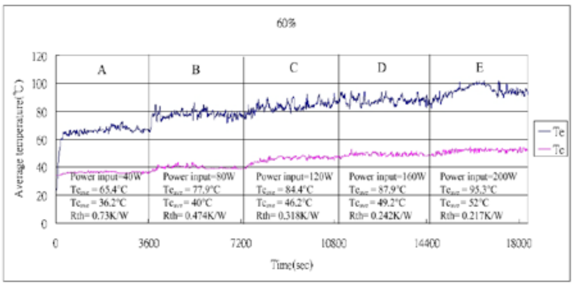

Fig. 5. Variation of Te and Tc for filling ratio 60%

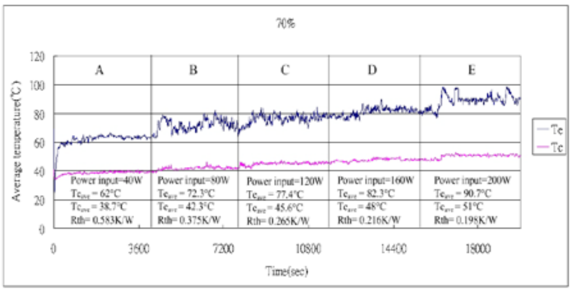

Fig. 6. Variation of Te and Tc for filling ratio 70%

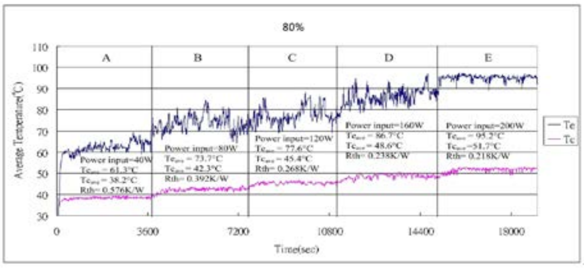

Fig. 7. Variation of Te and Tc for filling ratio 80%

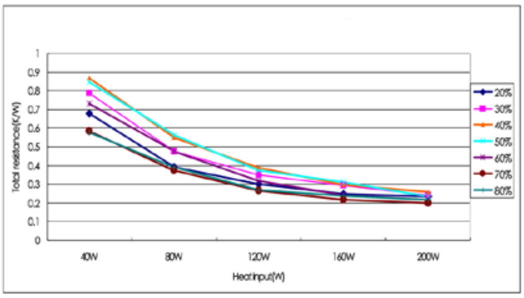

Fig. 8. Variation of thermal resistance with heat input power at different filling ratios

Flow patterns

It has been established that the zone of interest for a CLPHP operation is achieved when the FR is between about 20 to 80%. Below FR ≈ 20%, there are not enough distinct liquid plugs and the operation becomes 'unstable' resulting in large unacceptable variations in the average evaporator temperature. Above FR ≈ 80% there are not enough bubbles to provide the pumping action and so the performance drastically deteriorates. In this study, the circulation flow is not initiated with increasing heat input power when filling ratio is 20%, 30%, 40% and 50%. Circulation flow only happened when heat input power is reaching at 200W while filling ratio is 60%, 70%, and 80%. The schematic diagrams in Fig. 9-11 illustrate the observed phenomena in the CLPHP loop operated with increasing heat input power when filling ratio is 60%, 70%, and 80% respectively. It is observed that the amplitude of oscillations with slug flow is lower at lower heat input of 40 W compared to higher heat input of 80 W and 120 W. As the heat input is increased to 160W, the amplitude of oscillations can be reached to 2/3 lap of a complete turning of fluid. The fluid flow takes an arbitrary direction, a complete turning of fluid starts sometimes in the clockwise and sometimes counterclockwise direction until heat input is reaching at 200W. During the circulation flow period, it was observed that 33% were clockwise, 63% were counterclockwise direction for filling ratio 60% and 70%, while 25% clockwise and 75%

counterclockwise for filling ratio 80%. The randomness in the diction of circulation could be attributed to the uneven of the distribution of the slug and plugs as well as their initial position during start-up.

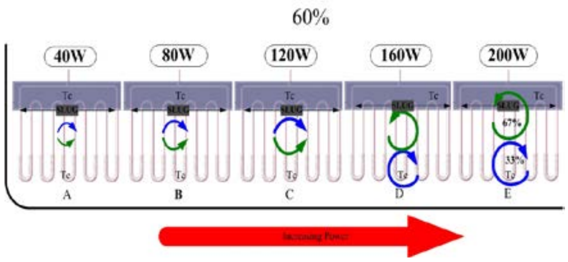

Fig.9. Observed flow patterns for FR= 60%

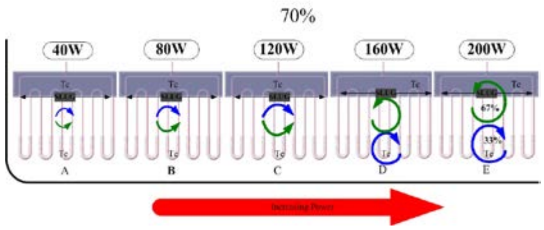

Fig.10. Observed flow patterns for FR= 70%

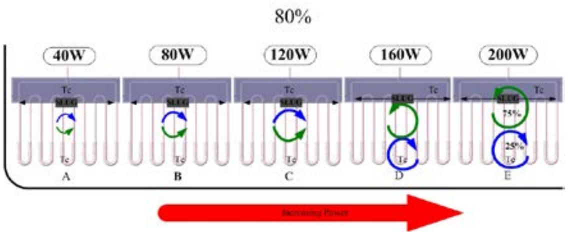

Fig.11. Observed flow patterns for FR= 80%

Bulk circulation flow phenomenon

From the observations of the styrofoam ball and fluid flow in each tube, the fluid motion involves bulk circulation flow in clockwise or counterclockwise direction and transition with local oscillation. Fig. 12 to Fig.14 show a series of pictures for clockwise direction period, transition period and counterclockwise direction period respectively when 200W heating power and 80% filling ratio is applied to the CLPHP, in which the ten tubes are identified as 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 from left to right. Fig. 12 illustrates the clockwise flow direction for a full cycle for the CLPHP. On the top of each subfigure, a solid or dashed arrow is drawn, with the solid line for the bulk circulation flow, the dashed line for the flow direction switch flow. When t = 0 sec, the Styrofoam ball is moving upwards and the CLPHP is operating in the bulk clockwise flow. The pictures show that the CLPHP is bulk circulation in clockwise direction when t = 1.66 sec, 2.33 sec, 5.33 sec, 6.42 sec and 8.41 sec.

For the bulk circulation flow, most of the time the flow direction in each adjacent tube is alternate and this is indicated by the arrow for each bend. When the circulation flow is reached, the fluid that exits the evaporator at a U-bend is immediately replaced by the incoming working fluid from the neighboring bend. In this mode, the heat transfer operation is connected and the thermal performance is enhanced. Therefore, thermal resistance of the CLPHP is decreased as shown in Table 2. It is also shown that not all of the tube changes the flow direction simultaneously. When t = 4.33 sec, both of the tubes 5 and 6 share the upward flow, while the tubes 7 and 8 share the downward flow. When t = 9.66 sec, both of the tubes 4 and 5 share the downward flow, while the tubes 6 and 7 share the upward flow and the tubes 8 and 9 share the downward flow. Local oscillations in the slug were observed as it is going to switch in the direction of circulation.

The flow direction is alternating with a period of about 4 seconds during transition as shown in Fig. 13. The flow direction switch process of the styrofoam ball from the Figure is as follows: Firstly, when t = 9.67 sec, the ball is still moving upward. At t = 9.80 sec, the movements of the ball stops, reverses and flow begins in the opposite direction. Then similar flow switch process was performed shown at t = 11.29 sec, 11.65sec, 11.67sec, 12.37sec, 13.33sec, 13.76sec, until the bulk counterclockwise circulation flow is reached shown in Fig. 14. When the fluid is circulating in counterclockwise direction, the slugs also experience local oscillations.

Table 2. Overall thermal resistance (R) at different input power (Q) and filling ratios (FR)

Q \ FR	20%	30%	40%	50%	60%	70%	80%
40W	0.678	0.785	0.868	0.845	0.730	0.583	0.576
80W	0.391	0.474	0.55	0.563	0.474	0.375	0.392
120W	0.300	0.350	0.389	0.375	0.318	0.265	0.268
160W	0.250	0.294	0.297	0.310	0.242	0.216	0.238
200W	0.235	0.243	0.258	0.236	0.217	0.198	0.218

(°C /W)

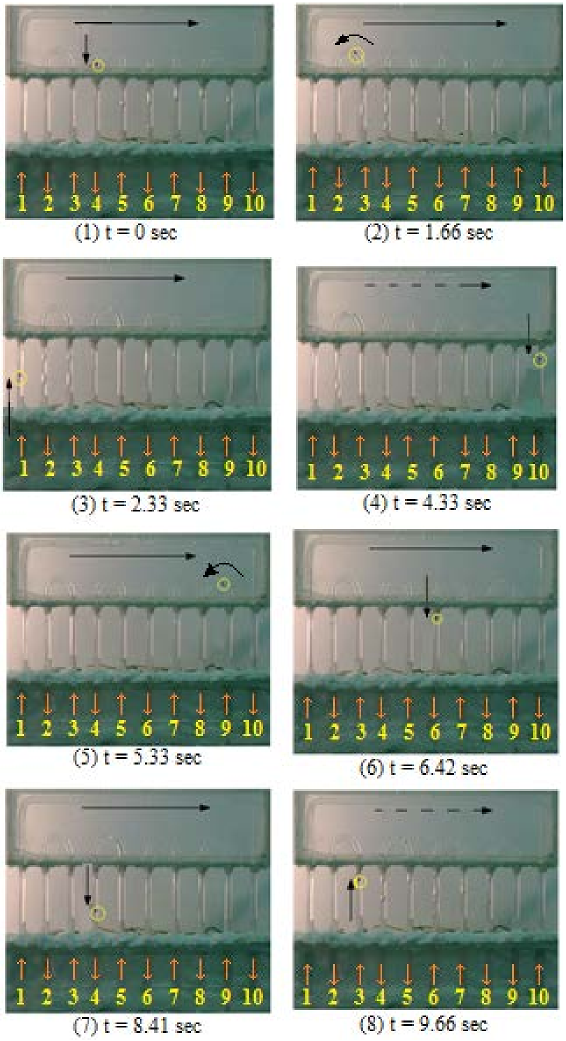

Fig.12. Clockwise direction period in circulation flow (200W, FR=80%)

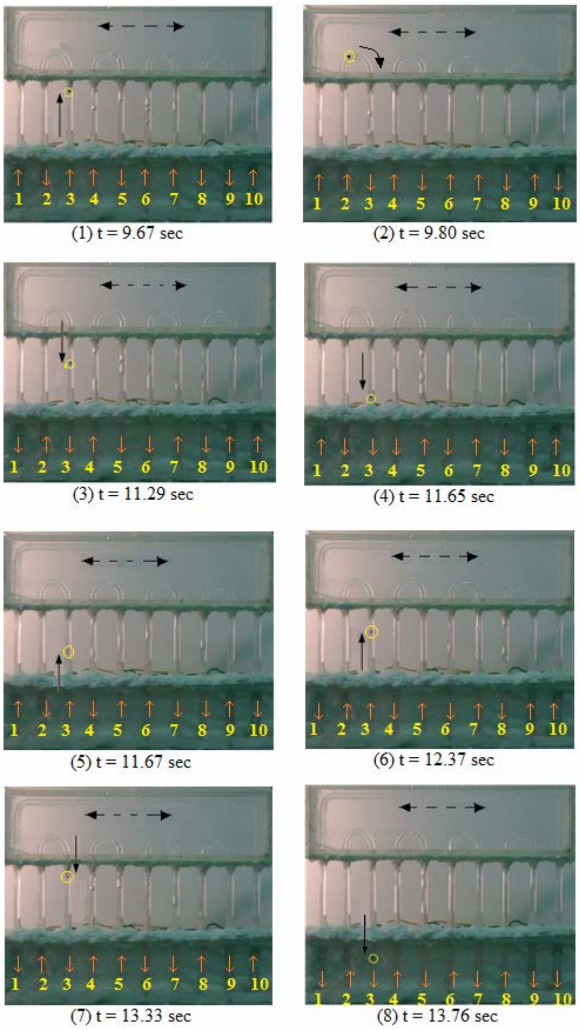

Fig.13. Transition period in circulation flow (200W, FR=80%)

CONCLUSION

Circulation flow of the CLPHP is achieved when heat input power is reaching at 200W while filling ratio is 60%, 70%, and 80%. In order to facilitate the observation of cycle status, a styrofoam ball was designed flowing in the tube. The fluid motion involves bulk circulation flow in clockwise or counterclockwise direction and transition with local oscillation. The bulk circulation flow is the major mechanism that transfers the heat from the evaporator to the condensation section. In this way, the heat transfer operation is continuous and the thermal performance is enhanced. The experiment shows that the lowest thermal resistance is 0.198 K/W under filling ratio of 70% at an input power of 200W.

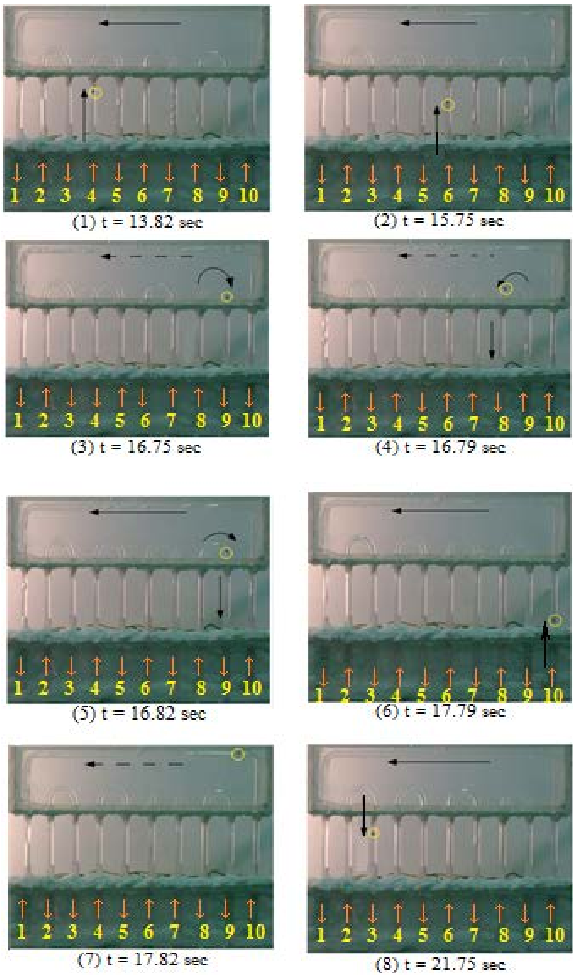

Fig.14. Counterclockwise period in circulation flow (200W, FR=80%)

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REFERENCES

Akachi, H., Polasek, F., and Stulc, P., “Pulsating Heat Pipes,”; Proc. of 5th International Heat Pipe Symposium, Melbourne, Australia, pp. 208–217 (1996).

Charoensawan, P., Khandekar, S., Schneider, M., Groll, M., “Closed loop pulsating heat pipes. Part A: Parametric experimental investigations,”; Applied Thermal Engineering, Vol. 23, Issue 16, pp. 2009–2020 (2003).

Charoensawan, P., Khandekar, S., Schneider, M., Groll, M., “Closed loop pulsating heat pipes. Part B: Visualization and semi-empirical modeling,”; Applied Thermal Engineering, Vol. 23, Issue 16, pp. 2021–2033 (2003).

Dobson, R. T., and Harms, T. M. “Lumped parameter analysis of closed and open oscillatory heat pipes,”; Proceedings of the 11th International Heat Pipe Conference, Tokyo, Japan, pp. 137–142 (1999).

Faghri, A., “Review and Advances in Heat Pipe Science and Technology,”; Journal of heat transfer, Vol. 34, No. 12, pp.12300-1-18 (2012).

Kang, S. W., Wei, W. C., Tsai, S. H. and Yang, S. Y., “Experimental investigation of silver nano-fluid on heat pipe thermal performance,”; Applied Thermal Engineering, Vol. 26, Issues 17-18, pp. 2377–2382 (2006).

Kang, S. W., Wei, W. C., Tsai, S. H., and Huang, C. C., “Experimental investigation of nanofluids on sintered heat pipe thermal performance,”; Applied Thermal Engineering, Vol. 29, Issues 5-6, pp. 973–979 (2009).

Kang, S. W., Wang, Y. C., Liu, Y. C., and Lo, H. M., “Visualization and thermal resistance measurements for a magnetic nanofluid pulsating heat pipe,”; Applied Thermal Engineering, Vol. 126, pp. 1044–1050 (2017).

Lin, Y. H., Kang, S. W., and Chen, H. L., “Effect of silver nano-fluid on pulsating heat pipe thermal performance,”; Applied Thermal Engineering, Vol. 28, Issues 11-12, pp. 1312–1317 (2008).

Nazaria, M. A., Ahmadib, M. H., Ghasempoura, R., and Shafii, M. B., “How to improve the thermal performance of pulsating heat pipes: A review on working fluid,”; Renewable and Sustainable Energy Reviews, Vol. 91, pp. 630–638 (2018).

Nazaria, M. A., Ghasempoura, R., Ahmadib, M. H., “A review on using nanofluids in heat pipes,”; Journal of Thermal Analysis and Calorimetry, Vol. 137, pp.1847–1855 (2019).

Reay D. A. and Kew, P. A., *Heat Pipes. Theory, Design, and Application*, 5th Edition, Butter -Heinemann, (2006).

Tong, B. Y., Wong, T. N., and Ooi, K. T. “Closed-Loop Pulsating Heat Pipe,”; Applied Thermal Engineering, Vol. 21, Issue 18, pp. 1845-1862 (2001).

Zhang, D., He1, Z., Jiang, E., Shen, C., and Zhou, J., “A review on start-up characteristics of the pulsating heat pipe,”; Heat and Mass Transfer, Vol. 57, pp. 723–735 (2021).

Zhang, Y., and Faghri, A., “Advances and unsolved issues in pulsating heat pipes,”; Heat Transfer Engineering, Vol. 29, No. 1, pp. 20-44 (2008).

NOMENCLATURE

D	tube diameter, m
FR	filling ratio, %
g	gravity, m/s^2
Q	input power, W
R	overall thermal resistance, °C /W or K/W
T	temperature, °C or K
U	uncertainty, %
U_Q	uncertainty of the input power, %
$U_{\Delta T}$	uncertainty of the average temperature difference of evaporator and cooling water, %

Greek symbols

ρ	density, kg/m^3
σ	surface tension, N/m

Subscripts

1,2..	tube's no.
ave	average
c	condenser section
e	evaporator section
liq	liquid
vap	vapor
ΔT	temperature difference

閉環震盪式熱管之循環流研究

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摘 要

本研究利用外徑 6mm、內徑 3 mm 之玻璃管製作 9 個折彎數總長 1980mm 之閉環震盪式熱管，為了使震盪式熱管更容易達到循環狀態，以水冷系統為冷凝器並控制溫度在 35°C，在不同工作流體填充率(20%、30%、40%、50%、60%、70%及 80%)、及不同輸入功率(40W、80W、120W、160W、200W)下評估整體熱阻值。利用數位攝影機拍攝影片，分析記錄震盪式熱管內流體循環之週期，為了方便觀察流體的動向，本實驗加入保麗龍球來確認流體流動之方向，觀測流體作動情況並計算循環週期與次數。結果顯示熱管在填充率 60%、70%、80%，輸入功率 200W 時將呈現完全循環狀態。循環狀態可分為順轉、逆轉及過渡狀態，實驗顯示，閉環震盪式熱管之熱阻在循環流狀態下最小。