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Measurement of internal pressure and thermal performance in a closed-loop oscillating heat-pipe with check valves (CLOHP/CV)

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The internal pressure and the thermal performance as characteristic parameters in a closed-loop oscillating heat-pipe with check valves (CLOHP/CV) under the normal operating condition have been investigated experimentally. The test CLOHP/CV was made of a copper capillary tube with various inner diameters. The inclination angle and the working temperature have been varied in the experiments. The working fluids of distilled water, ethanol and R123 were used with a filling ratio 50% of the total internal tube volume; the number of meandering turns was 40 and the number of check valves was 2. The lengths of the evaporator, adiabatic and condenser sections are all the same. The evaporator section was heated by electric strip heaters. The heat was removed from the condenser section by forced convective flow of ambient air blowing through the sections. The adiabatic section was well insulated by foam insulation. The thermal performance of the CLOHP/CV was evaluated by calculating the rate of heat transferred from the condenser to ambient air. It was found that the thermal performance of the CLOHP/CV has been improved by increasing the working temperature, the inclination angle and the inner diameter. The best performance of all the test CLOHP/CVs occurred for the case of R123 as working fluid, 2.03 mm inner diameter, 90° inclination angle and the working temperature of 200°C, where the maximum internal pressure was 7.53 MPa and the minimum thermal resistance was 0.048°C/W.

Keywords: Closed-loop oscillating heat-pipe with check valves, Heat transfer, Thermal performance, Thermal resistance, Inclination angle

1 Introduction

Now-a-days, there is rapid development of practical engineering solutions of a multitude of heating problems. For the heat removal generated in micro-devices special solutions are required.

The pulsating heat-pipe (PHP) or the oscillating heat-pipe (OHP) is one type of heat transfer devices that is relatively a young member in the heat-pipe family. In 1990s, Akachi[1,2] invented a new type of heat-pipe made of a capillary tube. They are now classified into 3 groups: (a) closed-end oscillating heat-pipe (CEOHP); a capillary tube is bent to meandering turns and closed at both ends; (b) closed-loop oscillating heat-pipe (CLOHP) a capillary tube is connected at both ends to form close-loop; (c) closed-loop oscillating heat-pipe with check valves (CLOHP/CV). Both check valves are inserted in a closed-loop and installed in the center of heat-pipe to control the flow direction of working fluid so that the flow should be only in one direction[3,4] (Fig. 1). Each loop may have one or more check valves. The CLOHP/CV is a new type of heat transfer device among the three which gives a high performance and several advantages. The CLOHP/CV is a very effective heat transfer device. Heat is transported from the evaporator to the condenser by the oscillation of a working fluid moving in the axial direction inside the tube. In this type of system, the

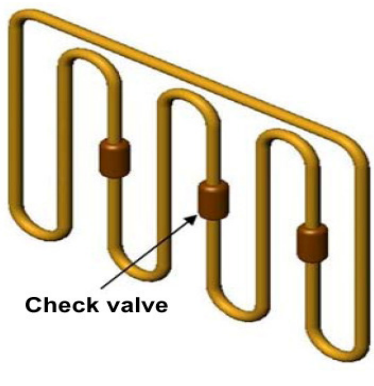

Fig. 1 — Closed-loop oscillating heat-pipe with check valve (CLOHP/CV)

selection of the inner diameter of the pipe is important. It must be small enough to form; liquid slugs and vapour plugs in it. Some research has been performed on the operational behaviour, including various experimental studies[5-7] for CLOHPs. However, the CLOHP/CV has been studied less frequently, though it can now be considered as a standard cooling device.

The parameters which affect the internal pressure and the thermal performance, have been investigated. The closed-loop oscillating heat-pipe with check valves, under normal operating condition, is capable of controlling the flow direction of the working fluid. Previous research established a correlation that predicted the heat transfer performance at vertical orientation (when the evaporator section is below the condenser).

The CLOHP/CV is commonly favoured in cooling electronic devices, humidity control in air conditioning system, etc. Despite these common applications, limited experimental studies are available on the operation of a closed-loop oscillating heat-pipe with check valves (CLOHP/CV). The detailed data on the effects of working fluid, working temperatures and internal pressure, pipe diameter and heat transfer of a closed-loop oscillating heat-pipe with check valves CLOHP/CV are insufficient. Therefore, this study focuses on determining the actual performance of CLOHP/CV.

2 Experimental Details

The experimental set-up with the test rig is shown in Fig. 2 and photographic view experimental set-up is shown in Fig. 3. The system consists of a test CLOHP/CV, a heater power supply with temperature controller, a cooling air fan with a motor speed controller, a temperature recorder and a personal computer. The CLOHP/CV was made of a copper capillary tube. The evaporator, adiabatic and condenser sections were adjusted to the equal length. The evaporator section was heated by electric plate heaters. The heaters placed on the outer surface of the tube walls were connected to the *ac* power supply with the temperature controller (Linking PID LT400 series with ±2°C accuracy). The evaporator temperature was varied with the temperature controller. The heat was removed from the condenser section by forced convective heat transfer to ambient air that was blown through the section. The air flow velocity was controlled by the *ac* motor controller at 0.6 m/s and the temperature of the air conditioner was kept at 25°C. The adiabatic section was insulated well by using foam insulation (Aero flex). The thermocouples (OMEGA type K with uncertainty of 0.58°C) were used to measure the temperature of the evaporator, adiabatic and condenser sections of the CLOHP/CV. The ambient air temperature was

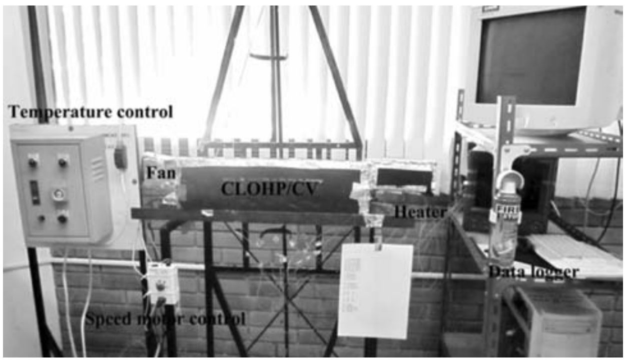

Fig. 3 — Photographic view experimental set-up

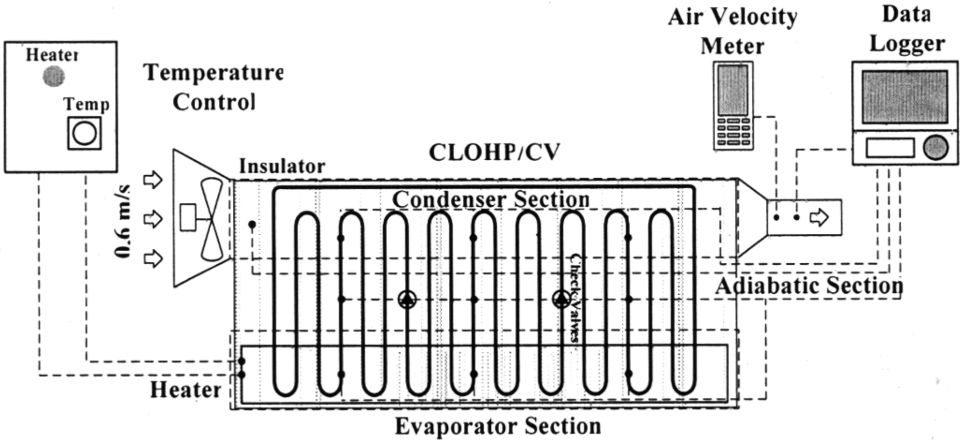

Fig. 2 — Details of experimental set-up

measured at the inlet and outlet of air flow duct. The transient record of the internal pressure was measured and then converted to the average pressure. All the temperature data were recorded by the data logger (Yokogawa DX200 with ±0.1°C accuracy) and then transferred to a PC every 1 hour. The air velocity was monitored with the humidity and anemometer measurement equipment (A testo 445 with ± 0.05% accuracy) of pitot tube probe type. First, the CLOHP/CV was evacuated by a high performance vacuum pump (Makashi, 501/min) and then filled with required amount of working fluid. The test CLOHP/CV was set into a test rig that could be tilted to vertical orientation. The evaporator temperature was set to the desired value through controlling the *ac* electric power supplied to the strip heaters. Simultaneously, ambient air at a 25°C temperature was blown at 0.6 m/s velocity through the condenser section. After a quasi steady state was reached, all temperatures were recorded. Then the experimental parameters were varied according to the required conditions. The thermal performance of the CLOHP/CV was evaluated by calculating the heat transfer to the ambient air at the condenser part given by the following Eq. (1).

$$Q = \dot{m}C_p(T_{\text{out}} - T_{\text{in}}) \qquad \ldots(1)$$

The error of calculation by Eq. (1) was found as:

$$dQ = \left[\left(\frac{\partial Q}{\partial m}d\dot{m}\right)^2 + \left(\frac{\partial Q}{\partial T_{\text{out}}}dT_{\text{out}}\right)^2 + \left(\frac{\partial Q}{\partial T_{\text{in}}}dT_{\text{in}}\right)^2\right]^{1/2}$$

where Q is the heat transfer of the CLOHP/CV, C_p is the specific heat of dry air and T_{out} and T_{in} are the temperatures of dry air at the exit and the inlet of the air flow duct, $\dot{m}$ is the mass flow rate of dry air calculated by the following Eq. (2):

$$\dot{m} = \rho v A \qquad \ldots(2)$$

where ρ the dry air density, v is the dry air velocity and A is the cross-sectional area of the air flow duct. In this experiment, the CLOHP/CV thermal resistance R is defined as the temperature difference between the condenser section and the evaporator section divided by the heat transfer as equation:

$$R = \frac{T_e - T_c}{Q} \qquad \ldots(3)$$

where T_e and T_c are the wall temperatures of the evaporator section and the condenser section, respectively. The measurement error of the recording instruments and the heat conduction rate through the copper capillary tube by calculating the rate of heat transferred to the ambient air at the condenser part were also considered. The complete experimental parameters are summarized in Table 1. After completing all the operational experiments of the CLOHP/CV, the effect of the various experimental parameters on the thermal performance was investigated. The thermal performance is presented in the form of the thermal resistance.

3 Operation Behaviour of CLOHP/CV

The heat transfer Q of the CLOHP/CV is compared between the data of normal CLOHP/CV operation and those without heat-pipe operation. After calculating the heat transfer of the CLOHP/CV (Q), the data were compared with the measurement error of Q (dQ) and the heat conduction rate through the copper capillary tube wall (Q_{cond}). If dQ is less than 5% and Q is more than Q_{cond}, it was found that the heat conduction through the pipe walls of the heat-pipe was rather small as shown in Fig. 4, the heat transfer of the CLOHP/CV was not higher than 5 times that of the heat conduction rate of the copper capillary tube wall by calculating the rate of heat transferred to the ambient air at the condenser part and thus the CLOHP/CV actually worked as a heat transport device. This chart shows the heat transfer of the CLOHP/CV using R123 as working fluid. The maximum heat transfer was achieved at the working temperature of 200°C and the inclination angle of 90°. The effect of the inner diameter, working fluid, working temperature and inclination angle on the

Table 1 — Experimental parameters

Parameters	Details
The controlled parameters:	
- Number of turns	40 turns
- Number of check valves	2
- Filling ratio (FR)	50% of total internal tube volume
- Air inlet velocity	0.6 m/s
The variable parameters:	
- Inclination angle	90°, 80°, 60°, 40° and 20°
- Tube inner diameter (D_i)	1.77 and 2.03 mm
- Evaporator length (L_e)	50, 100 and 150 mm
- Working fluids	distilled water, ethanol and R123
- Working temperature (T_e)	100, 150 and 200°C

performance will be presented later. Previous studies[8-11] have shown that CLOHPs operated as a heat transfer device only when the working fluid was able to flow (oscillating and/or circulating flow) in the capillary tube because the fundamental mechanism of the oscillating heat-pipe's heat transfer results from the working fluid of oscillating incorporates with phase change of working fluids. The operation can be done if/and there is a coexistence of liquid plugs and vapour bubbles throughout the length of tube. When oscillating heat-pipe is operated, there is evaporation in the side which contacts the high temperature resulting in higher vapour pressure and vapour bubble size. The change in size of the bubble causes the driven force, pushing the liquid slug to the condenser, which has the lower temperature. In addition, the condensation at the condenser will make the increase in pressure different between both sides. It should be noted that oscillating heat-pipe is made from a single tube, therefore, the movement of the liquid slug and vapour bubble in a particular turn will cause the other turns to move, too. When the liquid is pushed by the vapour into the condenser section, liquid and vapour in the next turn will also be pushed into the evaporator section. The liquid and vapour which are pushed back to the evaporator will have higher pressure resulting in restoring force. The cooperation between driven and restoring force generates the oscillating flow along the tube axis. This feature can be seen from the oscillatory variation of adiabatic temperatures in adjacent tubes. Similar results can be observed in the operation of the CLOHP/CV in this research as shown in Fig. 5. If the CLOHP/CV is able to transfer heat (Q = 830±5% W and Q_{cond} = 172 W) as shown in Fig. 5(a), the adiabatic temperatures of adjacent tubes (T1 and T2) always alternate so that T1 is sometimes higher than T2 and vice versa. This indicates that the flow of working fluid does not occur in one fixed flow direction. When the CLOHP/CV is unable to operate, T1 and T2 are nearly equal and constant as shown in Fig. 5(b). It was clearly seen that a CLOHP/CV worked under normal operating condition.

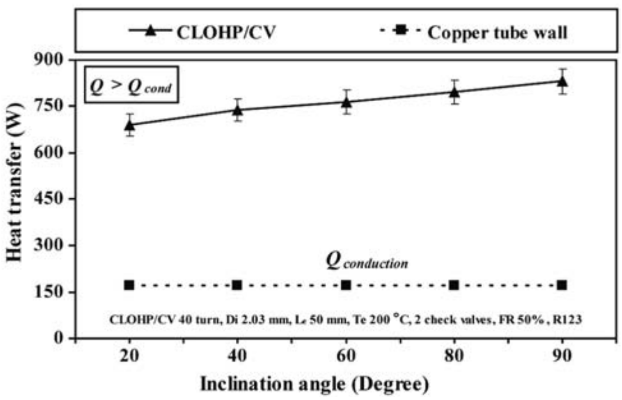

Fig. 4 — Relationship between the heat transfer and the inclination angle of CLOHP/CV's operation criteria

4 Results and Discussion

After completing all experiments on the operation of the CLOHP/CV, the effect of the various experimental parameters on the internal pressure and the thermal performance of has been investigated.

4.1 Inclination angle

Figure 6 shows relationship between the inclination angle and the internal pressure for different working fluids. The experimental result shows a significant effect of the inclination angle on the internal pressure for the case of the working temperature of 200°C and the inner diameters of 2.03 mm and 1.77 mm. It is found that at high working temperature the inclination angle affects the internal pressure. In a vertical position, 90° the driving force of the working fluid that is the pressure between the evaporator and the condenser section becomes the largest. Then, the bubbles easily move towards the condenser section at

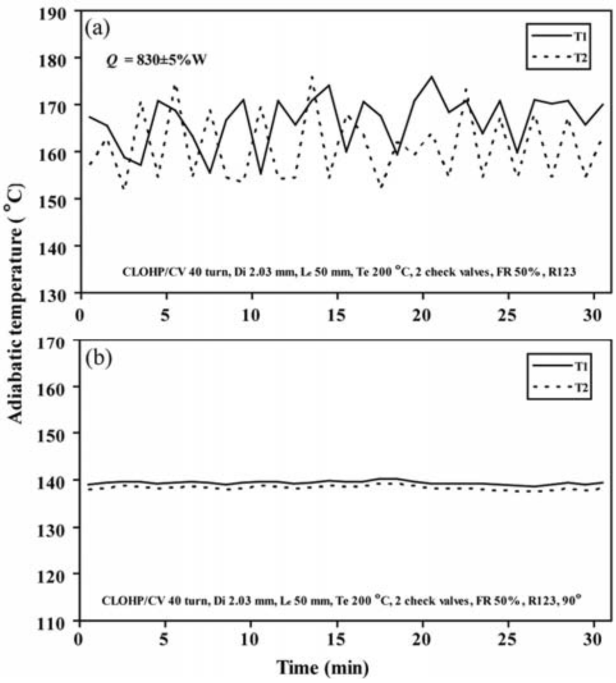

Fig. 5 — Adiabatic temperature in adjacent tube of CLOHP/CV (a) can operate and (b) can not operate

a very high speed. Oscillation of the vapour bubbles between the evaporator and condenser was sufficiently strong. Thus, a high amount of heat could easily be transferred in this vertical setting. When the inclination angle decreases from 90° to 20°, the internal pressure also decreases. The maximum internal pressure, which was measured at the inclination angle of 90° was 7.53, 4.00 and 1.7 MPa for R123, ethanol and distilled water, respectively. As the inclination angle decreases the internal pressure becomes lower than that at 90°, and thus the driving force for the working fluid that is the pressure difference between the evaporator and condenser section weakened. Furthermore, due to the effect of gravitational force, the frequency of oscillation of the vapour bubbles and liquid slugs became comparatively low. Thus, the heat transfer decreases. Figure 7 shows the inclination angle versus the internal pressure for different working temperature which recommends that the working temperature increases from 100 to 200°C and the inclination angle increases from 20° to 90°, the internal pressure increases. The working temperature directly affects the internal pressure because of working fluids received more heat that is the cause of their properties to be changed with respect to their density, surface tension, viscosity and latent heat of vapourization. Concerning these four properties, the latent heat of vapourization is the major property that has the greatest effect on the motion of the liquid slugs and vapour bubbles in a tube, as well as directly affects the internal pressure increase of the CLOHP/CV. As a result, at the inclination angle of 90°, working temperature of 200°C, the inner diameters of 2.03 mm and R123 as working fluid beget the internal pressure was 7.53 MPa.

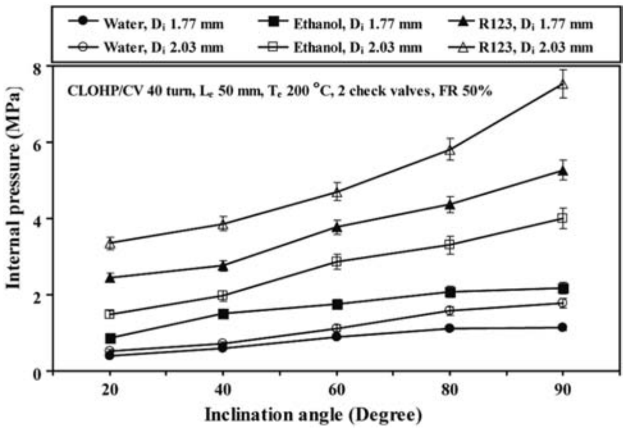

Fig. 6 — Relationship between the inclination angles and the internal pressure

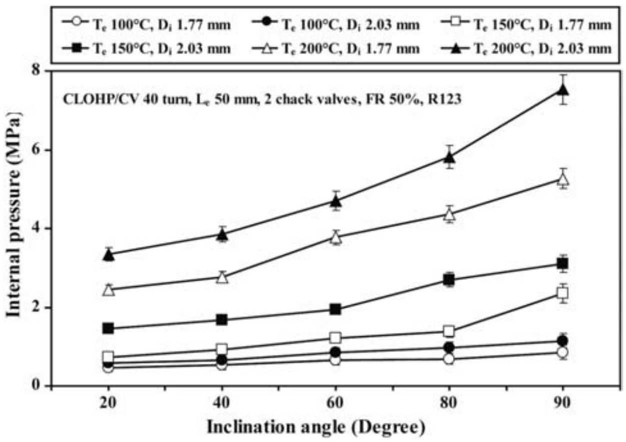

Fig. 7 — Working temperature difference on the internal pressure

Figure 8 shows relationship between the inclination angle and the thermal resistance of the CLOHP/CV for three working fluids (distilled water, ethanol and R123) at the working temperature of 200°C. It was found that as the inclination angle increases from 20° to 90°, the thermal resistance decreases and the thermal performance is improved. This is because of the oscillation of vapour bubbles between the evaporator and the condenser section was sufficiently strong for large inclination angle. The CLOHP/CV with R123 as working fluid at the working temperature of 200°C worked at the highest performance for both inner diameter of 1.77 and 2.03 mm. The minimal thermal resistance was 0.147°C/W and 0.048°C/W for the inner diameter of 1.77 and 2.03 mm, respectively. Figure 9 shows the inclination angle and the thermal resistance for different working temperature.

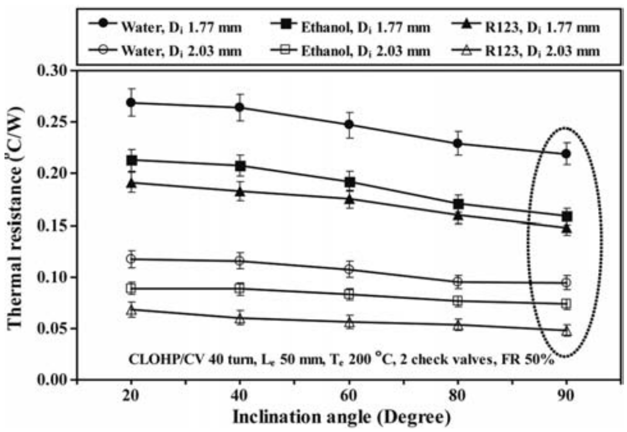

Fig. 8 — Relationship between the inclination angles and the thermal resistance

4.2 Evaporator length

Figure 10 shows the relationship between the evaporator length and the internal pressure for the cases of the CLOHP/CV with inner diameters of 2.03 and 1.77 mm, working temperature of 200°C and the inclination angle of 90°. The evaporator, adiabatic and condenser lengths were of the same length. The experimental results clearly show the effect of the evaporator length on the internal pressure. When the evaporator length decreases, the effective length between the condenser and the evaporator section also decreases. It is seen that as the increase of the evaporator length, the internal pressure decreases for every working fluid. The highest internal pressure was obtained for the shortest evaporator length of 50 mm and the inner diameter of 2.03 mm. They were 7.53, 4.00 and 1.78 MPa for R123, ethanol and distilled water as the working fluid, respectively. Under these conditions, the best heat transfer performance is attained.

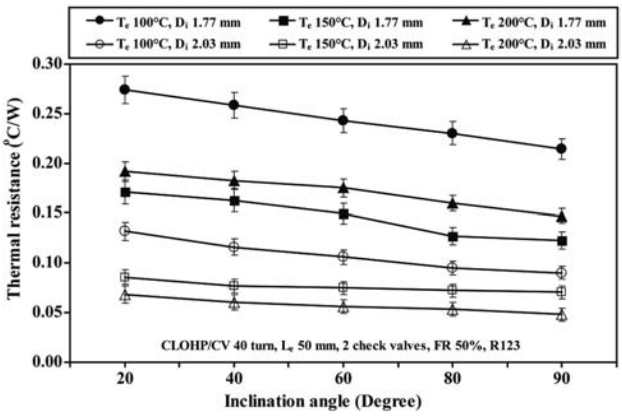

Fig. 9 — Working temperature difference on the thermal resistance

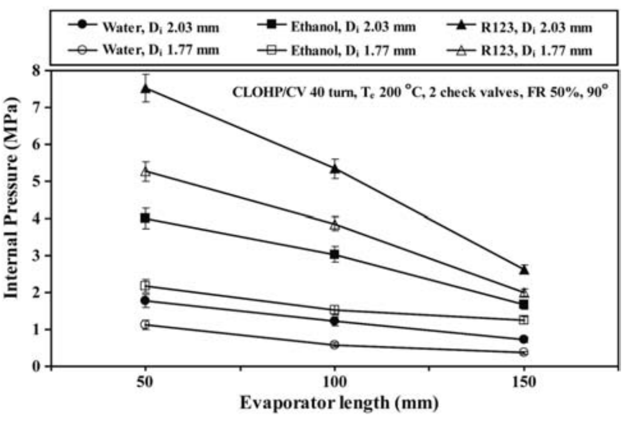

Fig. 10 — Relationship between the evaporator lengths and the internal pressure

Figure 11 shows the dependence of the thermal performance on the evaporator length for the CLOHP/CV with 40 turns and T_e of 200°C. When the evaporator length was long, the thermal resistance clearly increased. Since the evaporator, adiabatic and condenser lengths were of the same length, the evaporator length directly relates to the effective length of the fluid flow path between the evaporator and condenser sections, L_e. Thus, the thermal performance improves with the decrease in the evaporator length and the effective length. The maximum performance occurred at the shortest evaporator length of 50 mm. This may be because for shorter effective length, the frictional pressure drop of the fluid flow is reduced and thus the working fluid has more chance to flow from the evaporator to the condenser.

4.3 Inner diameter

Figure 12 shows the relationship between the inner diameter and the internal pressure of the CLOHP/CV

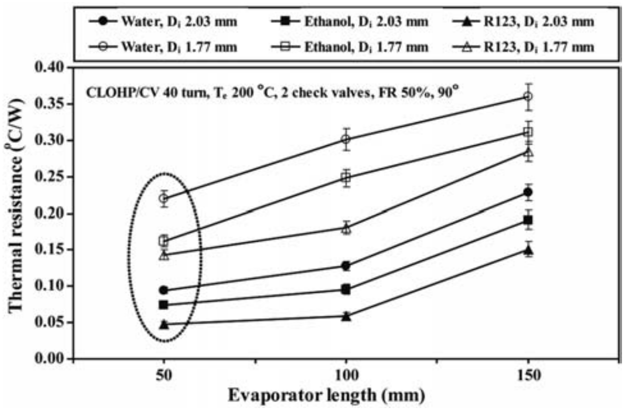

Fig. 11 — Relationship between the evaporator lengths and the thermal resistance

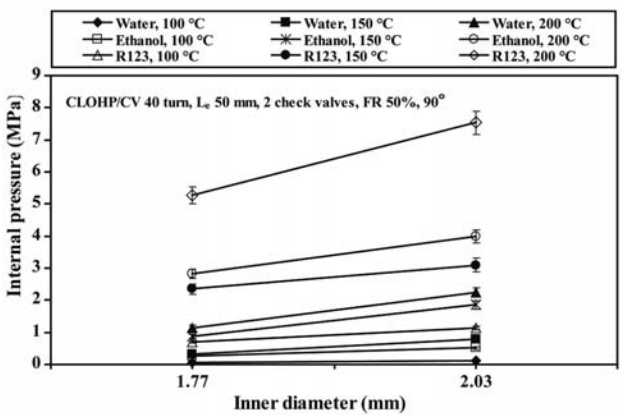

Fig. 12 — Relationship between the inner diameters and the internal pressure

for three working fluids (distilled water, ethanol and R123) and working temperature between 100 and 200°C. The result was found that the inner diameter increases from 1.77 to 2.03 mm, the internal pressure increases for both cases of the working temperatures of 100 and 150°C. In the case of the working temperature of 200°C, the internal pressure became higher, which affected the working fluid movement in the tube. It was difficult movement because of high surface tension and the internal pressure in the heat-pipe which are dropped if the internal diameter increases and then the working fluid boils and moves rapidly. Because of the working fluid properties, when the temperature rises, the density of working fluid drops and the surface tension and the shear force also drop, but the driving force increases. As a result, the heat transfer performance and thus the heat transfer would increase when the internal pressure increases. It can be concluded that the CLOHP/CV with R123 as the working fluid, working temperature at 200°C and inner diameter of 2.03 mm, gave the highest internal pressure, 7.53 MPa.

Figure 13 shows the effect of the tube inner diameter has an effect on the thermal performance of the CLOHP/CV with three kinds of working fluids (distilled water, ethanol and R123) at the working temperatures between 100 and 200°C. It is seen that increasing the inner diameter from 1.77 to 2.03 mm the thermal resistance decreases. The effect of operational orientation becomes relatively weak or insignificant with decreasing the inner diameter, because the surface tension much more dominates the fluid flow and vapour bubbles cannot move to the condenser section easily in the smaller tube. The heat transfer performance of the CLOHP/CV with an inner diameter of 2.03 mm has been investigated for all working fluids. The hypothesis proposed by Maezawa *et al*[2]. was used to estimate the optimum inner diameter of the CLOHP/CV, when it was thought that the vapour slug filled the cross-section area within the tube. It was, in reality, found the internal wall of the tube was covered by a liquid film. Therefore, the optimum inner diameter of the tube can be slightly larger than the value estimated in the reference[2]. In conclusion, for the case of the working temperature at 200°C and the inner diameter of 2.03 mm, the highest thermal performance was achieved for R123, which is better than that of distilled water and ethanol.

4.4 Working fluids

In the present paper, distilled water, ethanol and R123 were used as working fluids. Their properties are different, as namely their densities, surface tensions, viscosity and latent heats of vapourization. Concerning these four properties, the latent heat of vapourization is the dominant property that has a strong effect on the CLOHP/CV. Because a low latent heat will cause the liquid to evaporate more quickly at a given temperature and a higher vapour pressure; the liquid slug oscillating velocities will be increased and the heat transfer performance of the CLOHP/CV will be improved.

Figure 14 also shows the result of the internal pressure variation for three kinds of working fluids. The highest internal pressure, 7.53 MPa, is attained with a working fluid, R123 for the case of the inner diameter of 2.03 mm and the working temperature of 200°C, and thus the highest thermal performance is expected to be achieved for this working fluid. It is the medium transferring of the heat from the high temperature to the low temperature. When the

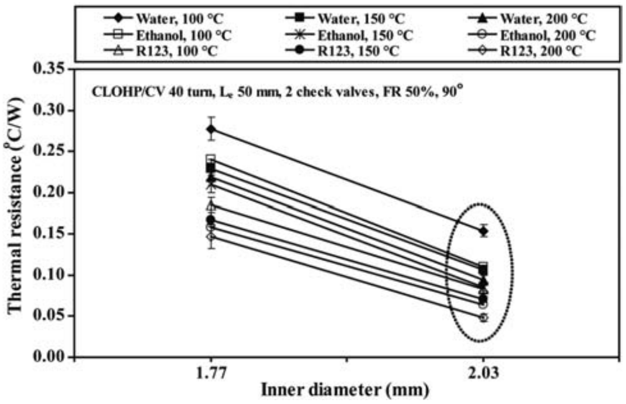

Fig. 13 — Relationship between the inner diameters and the thermal resistance

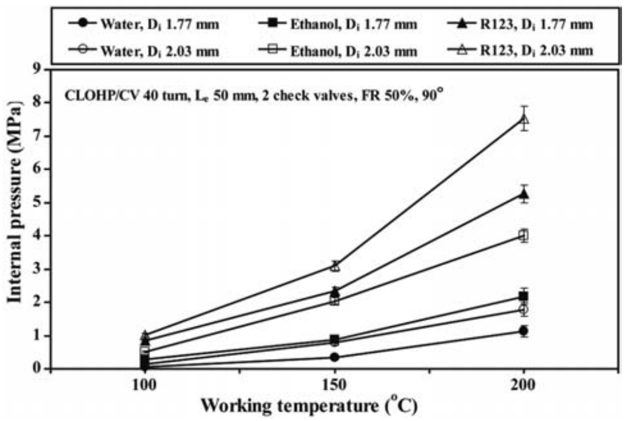

Fig. 14 — Relationship between the working temperature and the internal pressure

working fluids at the evaporator section receive the heat from heat source, they will evaporate and produce the vapour and move to the condenser section. When the vapour contacts the cool surface of the condenser, the latent heat of the vapor will be transferred to the inner surface of the condenser. Then, it will condense to be liquid and flow back to the evaporator section again, which has the highest thermal conductivity and the lowest latent heat of vapourization. Due to this excellent property, active motions of liquid slug and vapour bubbles are induced in the tube, which result in high heat transfer.

Figure 15 shows the relation between the working temperature and the thermal resistance for three kinds of working fluids. If the heat input to the evaporator increases, both the evaporator temperature and the fluid temperature will increase gradually which cause the surface tension and the latent heat to decrease. Higher surface tension will allow using larger tube diameter and then the pressure in the tube drops. Larger tube diameter would allow to the improved performance, and causes the pressure to drop. But if the pressure drops largely, greater bubble pumping force is required and thus higher heat input is also required to maintain pulsating flow. Low latent heat will cause much more liquid evaporation at a given temperature. The liquid slug oscillation velocity will increase and thus the heat transfer performance of the CLOHPs will be improved[12]. More vapours are generated to cause faster vapour flow. R123 as the working fluid which has the highest internal pressure and affected to the highest thermal performance of the CLOHP/CV will cause the lowest thermal resistance was 0.048°C/W.

4.5 Working temperature

Figure 14 shows the relationship between the working temperature and the internal pressure for the CLOHP/CV with three working fluids; distilled water, ethanol and R123 and inner diameter of 1.77 and 2.03 mm. The result shows that as the working temperature increases from 100 to 200°C, the internal pressure increases. The working temperature directly affects the internal pressure and thus the temperature rise results in the increase of the heat transfer, accordingly. The CLOHP/CV, with R123 as working fluids, an inner diameter of 2.03 mm, an inclination angle of 90° and the working temperature of 200°C result in the highest internal pressure of 7.53 MPa. When the CLOHP/CV is heated in the evaporator section, the working fluid evaporates and it will increase the vapour pressure, thus causing the bubbles in the evaporator zone to be grow. This pushes the liquid towards the low-temperature in the condenser section. Cooling of the condenser results in a reduction of vapour pressure and condensation of bubbles in that section of the heat-pipe. The growth and collapse of bubbles in the evaporator and condenser sections result in an oscillating motion within the tube, respectively. Heat is transferred through latent heat in the vapour and through sensible heat is transported by the liquid slugs. At higher temperature, R123 has a lower boiling point and thus higher internal pressure than ethanol and distilled water as working fluid, high heat input causes high internal pressure in the evaporator section. Heat input in the evaporator is the energy source which provides the driving force in the direction of motion in the tube that causes fluid flow to the condenser section[13,14]. When heat is extracted in the condenser section, the working fluid returns to the evaporator section.

Figure 15 shows the relationship between the working temperature and the thermal resistance for the CLOHP/CV with three kinds of working fluids; distilled water, ethanol and R123, and the inner diameter of 1.77 and 2.03 mm. The result shows that as the working temperature increased from 100 to 200°C, the thermal resistance decreased. In the case of R123 as the working fluid, the working temperature of 200°C, the lowest thermal resistance was 0.147°C/W and 0.048°C/W for the inner diameter of 1.77 and 2.03 mm, respectively. The thermal resistance of the CLOHP/CV with R123 as the working fluid, the working temperature of 200°C and the inner diameter of 2.03 mm is lower than those with ethanol and distilled water as the working fluid. As the working temperature increased, the heat

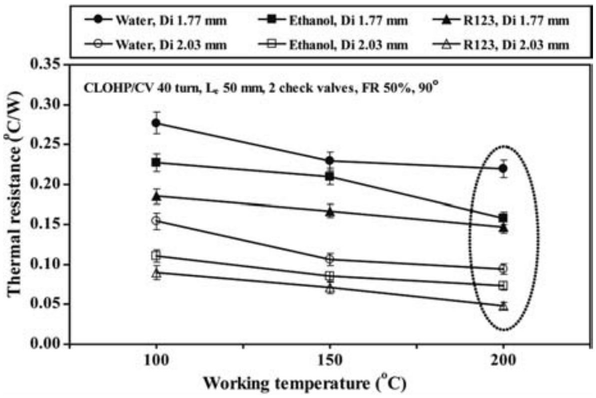

Fig. 15 — Relationship between the working temperature and the thermal resistance

transfer increased and the thermal resistance decreased. For R123, the thermal conductivity increases and the heat capacity increases. Moreover, with the increase of the temperature, the heat transfer increases because the buoyancy force decreases In conclusion, as the working temperature increases the thermal resistance decreases, and, accordingly the heat transfer increases.

4.6 Comparison of the performance of CLOHPs

Figure 16 shows a comparison of the heat transfer between the CLOHP/CV and the CLOHP without check valves (CLOHP, Charoensawan & Terdtoon[6]). The comparison results show the effect of the performance of the heat transfer between both the heat-pipe for the three working fluids (distilled water, ethanol and R123) and the inner diameters 2.0 mm in a vertical orientation, 90°. It was found that the heat transfer of the CLOHP/CV is more than the CLOHP because the CLOHP/CV provides a higher heat transfer by the addition of check valves which prevent bi-directional flow. Under normal oscillating heat-pipe operating conditions, the liquid slug and vapour plug are effectively located in the condenser and evaporator, respectively. The liquid forms U-shaped columns in individual turns of the oscillating heat-pipe and the oscillations form waves. Under these conditions, effective heat transfer is limited by the amplitude of the waves. When the amplitude of the heat transfer area is not included as part of the waves, an effective working fluid supply to the heat transfer area cannot be obtained and the heat transfer is not maintainable. This operating limit can be overcome by the implementation of check valves in the CLOHP. The check valves regulate the flow such that it becomes unidirectional and the heat transfer area is not restricted by the amplitude of the oscillating flow. However, the thermal performance is a complex combination, it is certainly difficult to prescribe or proscribe a certain working fluid unless all the boundary conditions are exactly known and individual effects have been explicitly isolated and quantified. The different heat-pipes (CLOHP/CV and CLOHP) are beneficial under different operating conditions. An optimum trade off of various thermo-physical properties has to be achieved depending on the imposed thermo-mechanical boundary conditions. R123 of the CLOHP/CV has the lowest latent heat of vaporization and the highest thermal conductivity as compared to distilled water and ethanol. So the CLOHP/CV has a higher heat transfer than the CLOHP.

Figure 17 shows a comparison of the thermal resistance between the CLOHP/CV and the CLOHP without check valves (CLOHP, Charoensawan & Terdtoon[6]). The comparison results show the performance of the thermal resistance of the both heat-pipe. The CLOHPs with three kinds of working fluids; distilled water, ethanol and R123, with a filling ratio 50% of the total volume, and the inner diameter 2.0 mm in a vertical orientation, 90°. The thermophysical properties of the working fluid coupled with the geometry of the device have profound implications on the thermal performance of the device and the check valves will support the working fluid within the heat-pipe to flow in the same direction and thus not cause any collisions between vapour plug and liquid slug that moves back and forth in the heat-pipe, thus affecting thermal performance. It can be seen that the highest performance at the

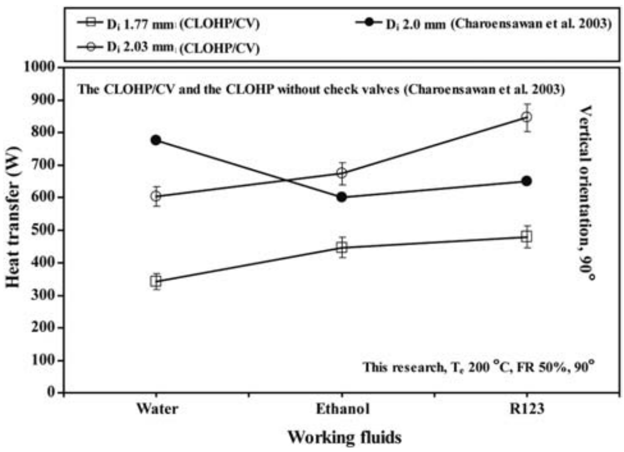

Fig. 16 — Comparison of the heat transfer

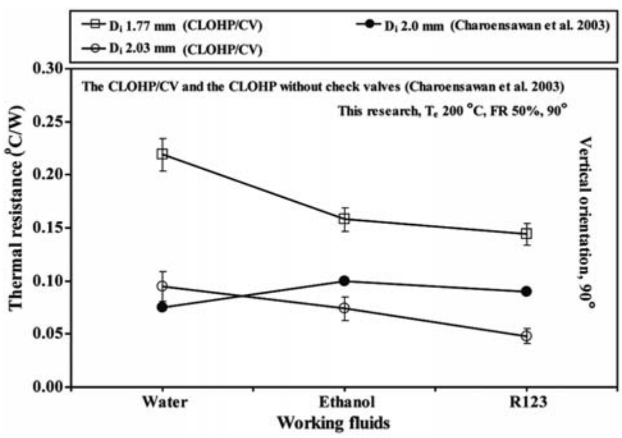

Fig. 17 — Effect of working fluids on the thermal resistance

maximum inner diameter of 2.0 mm. This trend was also seen for all the CLOHP/CV. This may be because the smaller inner diameter leads to increased frictional pressure drop and then flow resistance. The comparison results found that the thermal resistance of the CLOHP/CV with R123 as the working fluid is lower than those with as the other CLOHP.

5 Conclusions

An experimental study was performed on a closed-loop oscillating heat-pipe with check valve (CLOHP/CV) to investigate the effects of the inclination angle, the evaporator length, the inner diameter, the working fluid and the working temperature on the internal pressure and the thermal performance. The major results are summarized as follows:

- The optimum inclination angle for obtaining the highest internal pressure and the thermal performance was 90°.
- The maximum internal pressure and thermal performance occurred at the short evaporator length of 50 mm. For longer evaporator section, the thermal resistance clearly increased.
- Both the CLOHP/CVs with 1.77 mm or 2.03 mm inner diameters were operated successfully at all three working temperatures, showing excellent performances. The CLOHP/CV consisting of 2.03 mm ID tube had the highest internal pressure of 7.53 MPa and the lowest thermal resistance of 0.048°C/W.
- The working fluid has major effects on the thermal performance. The highest internal pressure and the thermal performance appeared for a CLOHP/CV with R123 as the working fluid.
- The internal pressure and thermal performance of a CLOHP/CV are improved by increasing the working temperature, and the lowest thermal resistance was recorded at 200°C.
- The performance of the CLOHP/CV is more than the CLOHP but the different CLOHPs are beneficial under the different operating conditions. An optimum trade off of various thermo-physical properties has to be achieved depending on the imposed thermo-mechanical boundary conditions.

Nomenclature

A	area (m^2)
C_p	specific heat at constant temperature (J/kg°C)
D	tube inner diameter (m)
FR	Filling ratio (%)
L	length (m)
m	mass flow (kg/s)
Q	heat transfer (W)
R	thermal resistance (°C/W)
T	temperature (°C)
V	dry air velocity (m/s)

Greek symbols

ρ	density (kg/m^3)

Subscripts

c	condenser section
e	evaporator section
i	inner
in	inlet
out	outlet

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