Effect of Inclination Angle on the Heat Transfer Performance of a Closed Loop Oscillating Heat Pipe with Check Valve (CLOHP/CV) and Fins on Tube Wall

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Abstract

This research aims to study the effect of inclination angle on the heat transfer performance of a Closed-Loop Oscillating Heat-Pipe with Check Valve (CLOHP/CV) with fins on the tube wall. The heat pipe was made from a copper pipe, and the capillary tube had a 5.0 mm inside diameter. There were 24 meandering turns with two check valves. The lengths of the evaporator section and condenser section were 200 mm and the adiabatic section was 100 mm. The working fluid used was water with a filling ratio of 50% of the total volume of the tube. The temperatures for the evaporator section were 60, 70 and 80°C. Inclination angles were 0, 20, 40, 45, 60, 80 and 90 degrees from the horizontal axis were established. It was found that when the variable temperature increased from 60, 70 to 80 °C heat flux and thermal efficiency increased. In addition, when the inclination angle increased from 0, 20, 40, 45, 60, 80 and 90 degrees heat flux and thermal efficiency increased. Therefore, this research concluded, from the experiment that the heat pipe was a CLOHP/CV. The maximum specific heat flux equaled 1,926.97 W/m^2 and the maximum thermal effectiveness equaled 0.44, the operating temperature was 80 °C and an angle of inclination to the horizontal axis was 90°

Keywords: Oscillating heat pipe, Check valve, Inclination angles, Heat transfer, Fin

Introduction

The heat pipe is a type of heat transfer equipment that has received much attention. It is a passive device with high performance and thermal conductivity of about 10-100 tons. It can operate even if the difference of temperature between the heat source and the heat sink is small. An oscillating heat pipe (OHP) is one type of heat pipe. It is made from a capillary tube and can be divided into 3 types: closed end oscillating heat pipe (CEOHP): closed-loop oscillating heat pipe (CLOHP) and closed-loop oscillating heat pipe with check valves (CLOHP/CV) fig. 1 An OHP has three sections: evaporator, adiabatic and condenser sections[1-2] Rittidech et al.[3] presented the CLOHP/CV as the best overall. For the past many years, the CLOHP/CV has been used in a variety of engineering heat transfer applications, such as the cooling of electronic equipment, retaining heat from gasses leaving an engine cooling system, breaking down snow and medical applications, Meena et al.[4] This study aims to design, construct and test waste heat recovery by closed-loop oscillating heat pipe with check valve from pottery kilns for energy thrift. It has been found that a CLOHO/CV has an application as an air-preheater for reduced relative-humidity in drying systems. Wannapakhe et al.[5] studied saving the energy from a hot air dryer with a closed-loop oscillating heat pipe (CLOHP/CV) It was found that the hot air dryer with CLOHP/CV can save thermal energy more than a normal hot air dryer. Moreover, if determining savings of electrical energy, the hot air dryer with CLOHP/CV can save more energy than a normal hot air dryer by an average of 28.13%. Heat transfer enhancement techniques have been widely applied to heat exchanger equipment. In the design of heat exchangers heat transfer efficiency must take into account size, shape and proper

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use. Currently, developing heat exchangers focuses on two methods: an Active method and a Passive method. Most researchers are often interested in the Passive method because it does not require external power to stimulate the increase of surface area inside or outside the pipe. For several years, many researchers have devoted research to thermal performance.[6-9]. Wannapakhe et al.[10] investigated the effect of aspect ratios (evaporator length to inner diameter of capillary tube), inclination angles, and concentrations of silver nanofluid on the heat transfer rate of a closed-loop oscillating heat pipe with check valves (CLOHP/CV). It was found that the heat transfer rate of the CLOHP/CV using silver nanofluid as a working fluid was better than that of the heat transfer rate when pure water is used because the silver nanofluid increases the heat flux by more than 10%. Nuntaphan et al.[11] presents the performance of a wire-on-tube heat exchanger of which the wire is an oscillating heat pipe. The experiments for this heat exchanger were performed in a wind tunnel by exchanging heat between hot water flowing inside the heat exchanger tubes and air stream flowing across the external surface. R123, methanol and acetone were selected as working fluids for the oscillating heat pipe. The results of the models agreed very well with the experimental data with fins often employed to effectively improve the overall performance of the heat pipe[12-14]. Some general research has reported on the effects of inclination angle on heat transfer performance of closed-loop oscillating heat-pipe with check valve (CLOHP/CV) and with fins at tube wall. In response to the lack of detailed data, this study focuses on determining the actual thermal performance of such a system through experimental investigations.

Theoretical consideration

The Oscillating Heat Pipe (OHP), by Akachi et al[10], was invented as a new type of heat-pipe made from a capillary tube that has been applied to cool small electronic devices. This new type of heat-pipe is called an oscillating heat-pipe (OHP), and has the same basic operational principle as the oscillating movement of the fluid and phase change phenomena. The first type is a closed-end oscillating heat pipe (CEOHP). In this type, a capillary tube is bent into many meandering turns and closed at both ends. The second type is a closed loop oscillating heat-pipe (CLOHP), in which the capillary tube is connected at both ends to form close-loop. The third type is a closed-loop oscillating heat-pipe with check valves (CLOHP/CV). This type is a closed-loop oscillating heat-pipe, in which both ends of the capillary tube are connected to form a closed-loop. The loop has one or more check valves[11], see Fig 1.

(a)
(b)
(c)

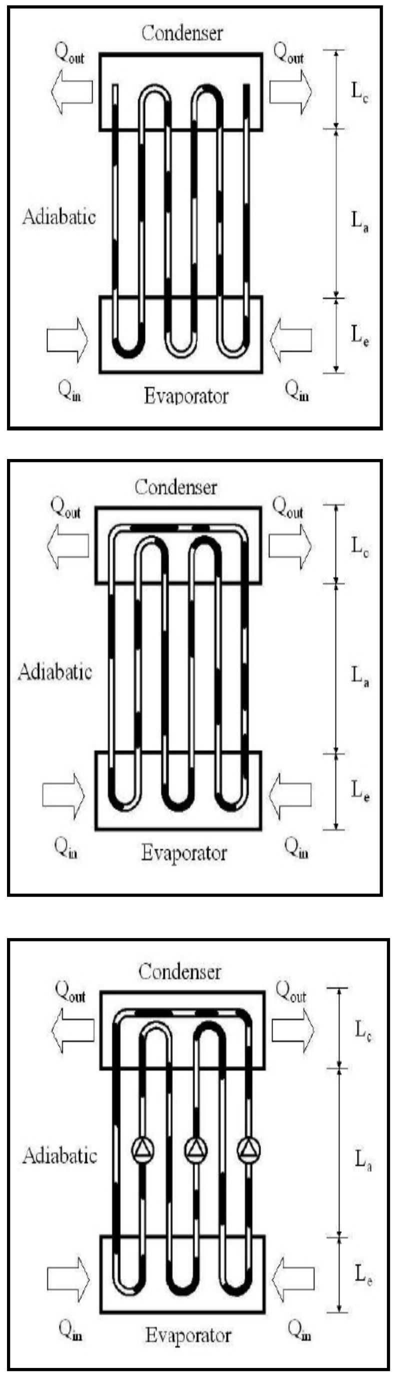


Figure 1 Type of Oscillating Heat Pipes: (a) CEOHP, (b) CLOHP, (c) CLOHP/CV

Heat transfer characteristics the CLOHP/CV

Heat transfer characteristics of the Oscillating heat pipe with Check Valve (CLOHP/CV). Determination of heat transfer to the condenser section uses the calorific method calculation by measuring the temperature of the heating fluid at the inlet and outlet of the condenser. The values are calculated using the following equation.

$$Q = \dot{m} C_p \left(T_{out} - T_{in}\right) \tag{1}$$

Where Q is the heat transfer rate (W), $\dot{m}$ is the mass flow rate (kg/s), C_p is the specific heat (J/kg-°C), T_{in} is the inlet temperature (°C) and T_{out} is the outlet temperature (°C).

The mass flow rate is given by equation.

$$\dot{m} = \rho VA \tag{2}$$

Where Q is the density (kg/m^3), is the velocity (m/s), A is the area (m^2).The heat transfer rate determined from the equation.

$$q = \frac{Q}{A_c} = \frac{Q}{\pi D_o L_c N} \tag{3}$$

Where q is the heat flux (W/m^2), D_o is the Outside diameter of the tube (mm), L_c is the length of condenser section (mm), N is the number rods of heat pipe condenser section.

Fins efficiency

q Performance of the fin is the ratio between the heat transfer surface cooling fins, and is obtained from the following equation.

$$\eta_{fin} = \frac{Q_{fin}}{Q_{\max}} \tag{4}$$

The heat transfer rate of fin efficiency is given by the following equation.

$$Q_{\max} = A_{fin}\left(T_{out} - T_{in}\right) \tag{5}$$

And the heat transfer rate of the fins is given by the following equation.

$$Q_{fin} = n\eta_{fin} h\left(T_b - T_a\right) \tag{6}$$

Fin surface area exposed to the fluid is obtained from

$$A_{fin} = \left[2\pi\left(r_0^2 - r_i^2\right) + 2\pi r_o t\right] \tag{7}$$

When η_{fin} is the fins efficiency, Q_{fin} is the heat transfer Rate at fin surface (W), $Q_{\max}$ is the heat transfer rate at the maximum surface fins (W), A_{fin} is the fin surface area exposed to fluid.(m^2), h is the Coefficient of heat transfer.(W/m^2-K), T_b and T_a is the temperature of the pipe surface and ambient temperature, respectively. (°C), r_i is the internal radial of fins (mm), r_o is the external radius of fin (mm), t is the thickness of fin (mm), and n is the number of fin By Karl, A., Gardner, analyzed the performance of a circular copper fin, then analyzed in the form of graphs for ease of use. As shown in Fig 2.

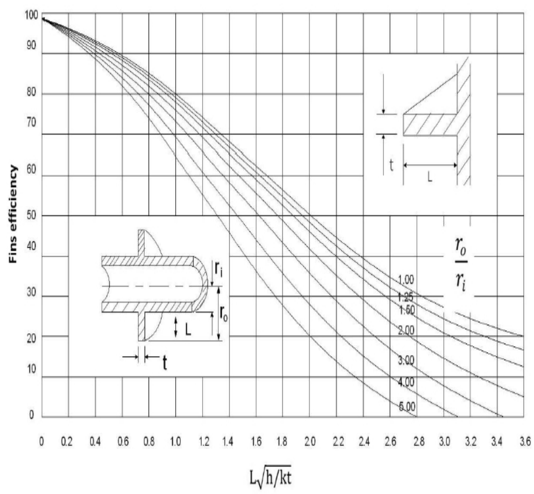


Figure 2 Performance graphs of circular copper fin Karl A. Gardner.

The y axis is given by the following equation.

$$y = \frac{r_o}{r_i} \tag{8}$$

And the x axis is given by the following equation.

$$x = L\sqrt{\frac{h}{kt}} \tag{9}$$

When L is the length of the tube surface to the fin (mm), k is the thermal conductivity of the fin material (W/m^2-K).

The effectiveness of the CLOHP/CV with fins. The effectiveness (ε) of CLOHP/CV can be defined as the ratio of the actual heat transfer rate (Q_{act}) for a CLOHP/CV to the maximum possible heat transfer rate $(Q_{\max})$ [18]. This can be represented by the following equation:

$$\varepsilon = \frac{Q_{act}}{Q_{\max}} \tag{10}$$

When

$$Q_{act} = \dot{m}_h C_{p,h}\left(T_{e,in} - T_{e,out}\right) = \dot{m}_c C_{p,c}(T_{c,out} - T_{c,in}) \tag{11}$$

As

$$\varepsilon_e = \dot{m}_h C_{p,h}(T_{e,in} - T_{e.out}) / \left(\dot{m} C_p\right)_{\min} (T_{e,in} - T_{c.in}) \tag{12}$$

$$\varepsilon_c = \dot{m}_c C_{p,c}(T_{c,out} - T_{c.in}) / \left(\dot{m} C_p\right)_{\min} (T_{e,in} - T_{c.in}) \tag{13}$$

From which it follow;

$$\varepsilon = Q_e / Q_{\max} = Q_c / Q_{\max} = Q_{ave} / Q_{\max} \tag{14}$$

Where the maximum possible heat transfer rate $(Q_{\max})$ can be represented by the following equation:

In case $C_c < C_h$

$$Q_{\max} = C_c\left(T_{e,in} - T_{c,in}\right) \tag{15a}$$

In case $C_c > C_h$

$$Q_{\max} = C_h\left(T_{e,in} - T_{c,in}\right) \tag{15b}$$

When $C_c = \dot{m}_c C_{p,c}$ and $C_h = \dot{m}_h C_{p,h}$

From equation 19a and 20b can be to write the general expression [19]:

$$Q_{\max} = C_{\min}\left(T_{hi} - T_{ci}\right)$$

$$Q_{ave} = (Q_e + Q_c)/2 \tag{16}$$

By definition the effectiveness, which is dimensionless, must be in the range

Experimental methods

The CLOHP/CV design

An important factor that has to be considered in building a CLOHP/CV is the tube diameter. The maximum inner diameter of the CLOHP/CV can be defined by the equation derived by Maezawa et al.[15]

$$d_{\max} \leq 2\sqrt{\frac{\sigma}{\rho_l g}} \tag{18}$$

Where *d*max [m] is the maximum inner diameter of the capillary tube, σ [N/m] is the surface tension of the fluid, ρl [kg/m^3] is the liquid density, and *g* [m/s^2] is the gravitational acceleration.

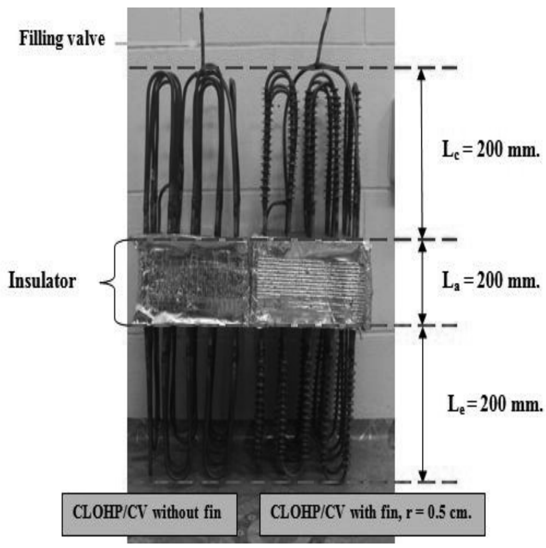


Figure 3 CLOHP/CV using in experiment

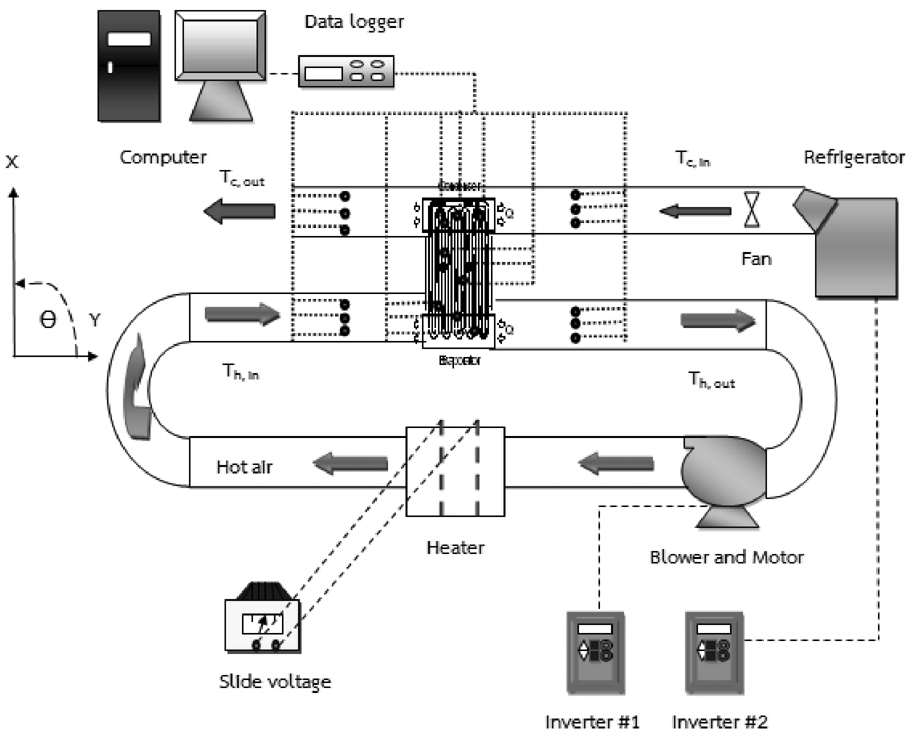
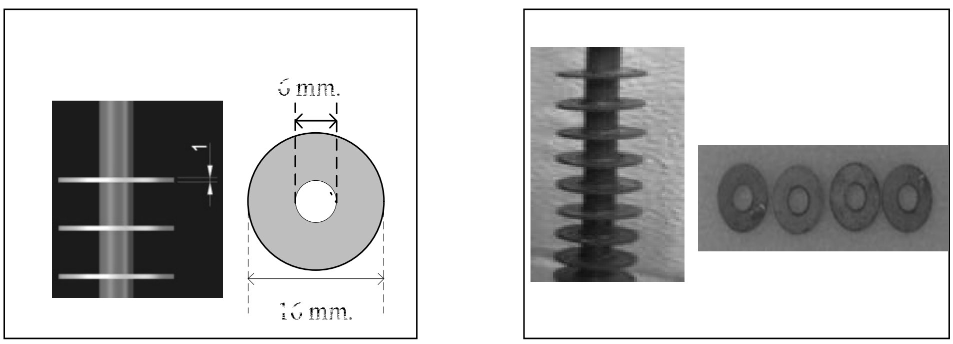


Figure 4 Schematic diagram of the experimental setup.



(a) Schematic (b) Photography

Figure 5 Specification of fin

Table 1 – Specification of the Oscillating heat pipe with check valve (CLOHP/CV).

	Parameters	Specification
Capillary tube	Inlet diameter (mm)	5.0
	Material	Copper
	Number of turn	24
	Thickness (mm)	1.0
	Radius of turn (mm)	40
	Alignment	Inline
	Length total (mm)	500
	Length of condenser (mm)	200
	Length of evaporator (mm)	200
	Length of adiabatic (mm)	100
Fin	Fin type	Annular
	Material	Copper
	Fin pitch (mm)	10
	Diameter (mm)	16
	Thickness (mm)	1.0
	Alignment	Inline

Table 2 Experimental condition.

Parameters	**Condition**
Inlet temperature evaporator section (^{o}C)	60, 70, 80
Inlet temperature of air (^{o}C)	25
Working fluid	Water
Velocity of air (m/s)	0.5
Inclination Angle (degree)	0, 20, 40, 45, 60, 80, 90
Filling ratio	50 % by volume of total pipe

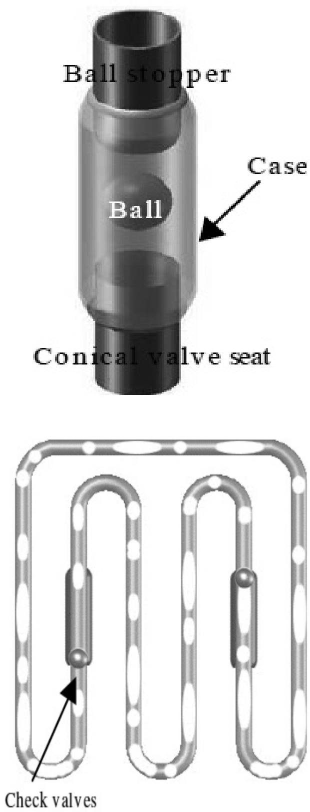


Figure 6 Check valve structure

Specifications of the oscillating heat pipe including a check valve (CLOHP/CV). The check valve is a floating-type valve that consists of a stainless steel ball and a copper tube in which a ball stopper and conical valve seat are provided at the ends of the top and bottom of the check valve case, respectively (Fig. 6). The ball can move freely between the ball stopper and the conical valve seat. The conical valve seat contacts the stainless-steel ball in order to prevent the working fluid flow reversal. The ball stopper allows the working fluid to travel to the condenser section for transferring heat. The CLOHP/CV operation principle relies on three driving forces: surface tension force, gravity force, and oscillating force. These forces are influenced by many parameters. This study selected water as the working fluid because of the latent heat of vaporization equal to 2455 kJ/kg and can be packed very high in copper pipe without corrosion reaction between water and copper pipes resulting in a long period of heat pipe life.

The experimental setup used in this study and the thermocouple locations is shown in fig.4. The specifications of oscillating heat pipe including a check valve (CLOHP/CV) are given in table 1. The test consists of three main sections: the CLOHP/CV section, the heating loop, the cooling section. For experimental purposes the device is completely insulated with glass wool. The amount of heat loss from the evaporator and condenser surface is negligible. The adiabatic section of the heat exchanger is completely insulated with polyethylene**.** In Figure .3. The experimental procedure in the CLOHP/CV section is repeated for different inclinations of the test section, i.e., (0°, 20°, 40°, 45°, 60°, 80° and 90°) to the horizontal. Measurements were made using thermocouples (K-type) with an uncertainty of $\pm0.1^{\circ}C$ at a total of 25 points. These are attached to thermocouples at a Data Logger (Agilent Technologies 34970A. The 34970A features 61/2 digits (22bits) of resolution, 0.004% basic DCV accuracy). The heating loop is in the region of the evaporator section of CLOHP/CV.. The air inlet and outlet temperature of the experimental setup are measured as the system reaches a steady state condition. The cooling loop is in the region of the condenser section of CLOHP/CV. This cooling is by refrigeration and the velocity is controlled at as 0.5 m/s by an inverter. The cooling air is allowed to flow through the condenser to cool the CLOHP/CV. Air inlet and outlet temperatures in the condenser zone are measured.

Results and discussion

Effect of inclination angles on the heat transfer rate

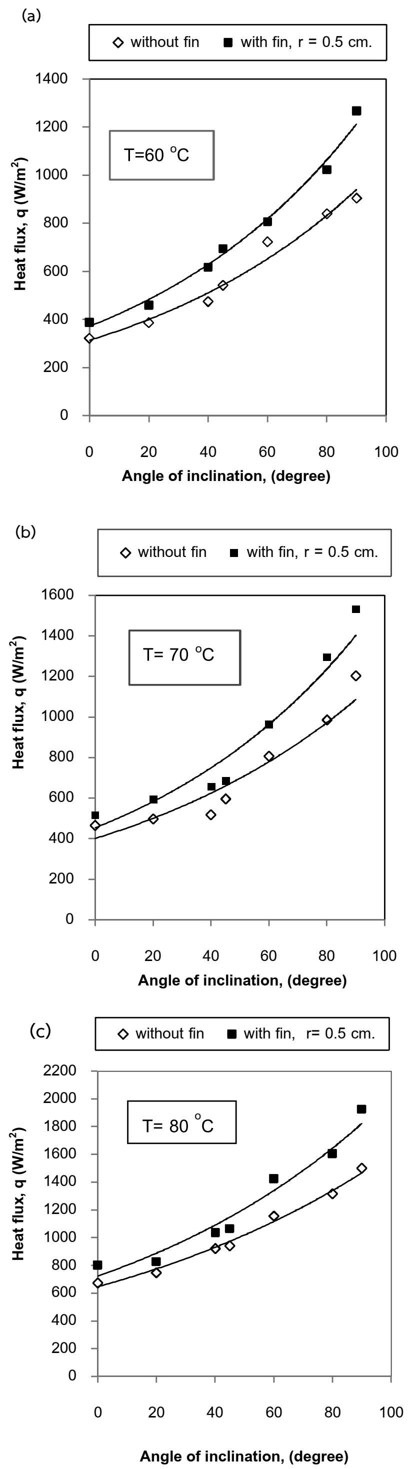


Figure 7 **(a-c)** Effect of inclination angles and presence or absence of fins on the heat transfer rate of the CLOHP/CV at evaporator operating temperatures of 60, 70 and 80°C respectively.

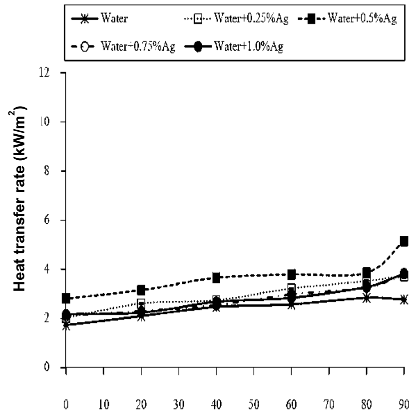


Figure 8 Effect of inclination angle of CLOHP/CV on the heat transfer rate at an aspect ratio of 50. S. Wannapakhe et al. (2009)[16].

Fig.7 (a-c) shows the effect of inclination angle and presence or absence of fins (radius of fin is **0.5 cm) on the heat transfer rate of the CLOHP/CV using water as the working fluid.** The operating temperatures were 60, 70 and 80°C with an air velocity at the condenser section of 0.5 m/s. It was found that when the inclination angle increased from 0, 20, 40, 45, 60, 80 to 90°, the heat transfer rate also increased. Thus, the inclination angle of the CLOHP/CV has an effect on the heat transfer rate because of a pressure difference brought about by the hydrostatic head of the liquid being positive, negative or zero. This depended on the fluid's density, acceleration from gravity, tube length and inclination angle of the CLOHP/CV to the horizontal axis. This result is similar to that of Wannapakhe et al. (2009) as shown in Figure 8. The pressure difference may be determined from the following equation:

$$\Delta P_g = \rho_l g L \sin\phi \tag{19}$$

In which ϕ is positive when the evaporator is lower than the condenser.

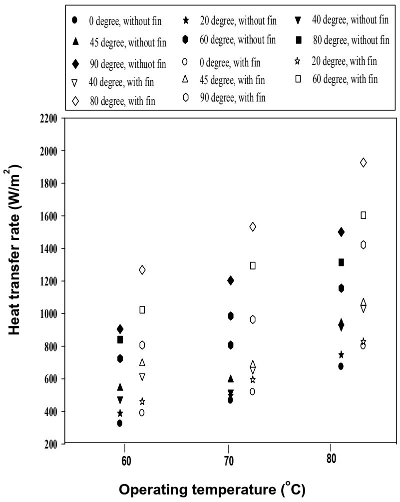


Figure 9 Effect of operating temperature and inclination angle on the heat transfer rate of CLOHP/CV.

The results of different working temperatures on the heat transfer rate of the CLOHP/CV are shown in Fig.9. The experimental results clearly present the effect of working temperatures on the heat transfer rate. Comparing the working temperatures found that the heat transfer rates for both CLOHP/CVs increased when the operating temperature increased from 60, 70 to 80°C. This was due to the working fluids being able to simply and quickly undergo a phase change to vapor. The CLOHP/CV with fins had heat transfer rates that were higher than the CLOHP/CV without fins. The fin increases the surface to enhance heat transfer.

Effect of inclination angles on the thermal effectiveness

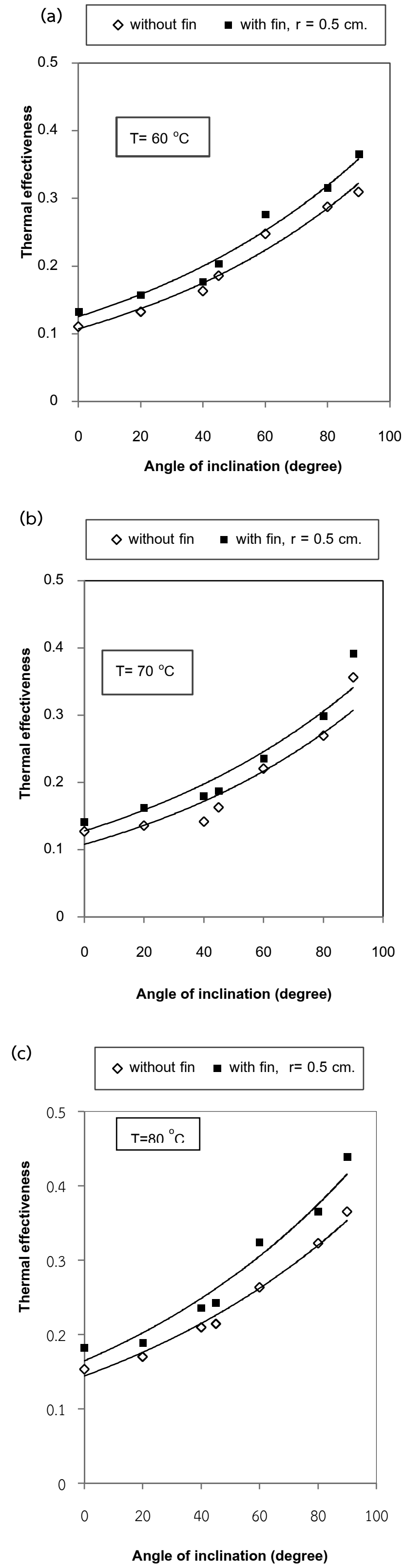


Figure 10 **(a-c)** Effect of inclination angles and presence or absence of fins on the thermal effectiveness of a CLOHP/CV at evaporator operating temperatures of 60, 70 and 80°C respectively.

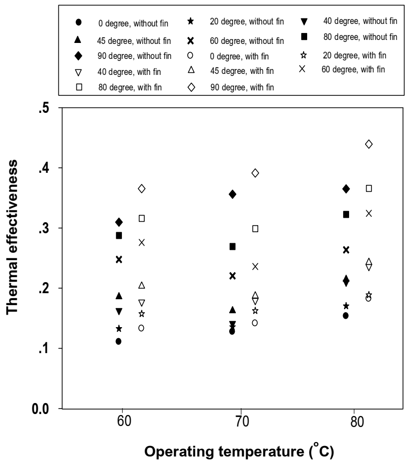


Figure 11 Effect of operating temperature and inclination angle on the thermal effectiveness of the CLOHP/CV.

Fig. 10 (a-c) shows the effect of inclination angle and presence or absence of fins (radius of fin is 0.5 cm) on the thermal effectiveness of the CLOHP/CV using water as the working fluid. The operating temperatures were 60, 70 and 80°C at an air velocity in the condenser section of 0.5 m/s. It was found that when the inclination angle increased from 0, 20, 40, 45, 60, 80 to 90°, the thermal effectiveness also increased. Fig. 11 shows the effect of operating temperature and inclination angle on the thermal effectiveness**.** It was found that when the operating temperature increased from 60, 70 to 80°C, the thermal effectiveness for both the CLOHP/CVs increased, but the CLOHP/CV with fins had a thermal effectiveness that was higher than the CLOHP/CV without fins. The thermal effectiveness may be determined from equation (10), in which the CLOHP/CV with fins will have a higher heat transfer rate, the thermal effectiveness was also higher than in the CLOHP/CV without fins.

Conclusion

Experimental investigations were carried out on a passive heat transfer enhancement technique with annular fins. At various inclination angles of a CLOHP/CV the thermal performance was determined. Based on the analysis of the experimental investigations presented in this paper, the conclusions are as follows:

For both CLOHP/DVs, the heat transfer rate and the thermal effectiveness increased as the inclination angle increased because the higher inclination angle had more vapor bubble flow than the lower inclination angle**.** The operating temperature had an effect on the heat transfer rate and thermal effectiveness for both the CLOHP/CVs because when the operating temperature increased the working fluid boiled there was a latent heat increase.

The heat transfer rate and the thermal effectiveness of the CLOHP/CV with fins at all inclination angles and all temperatures were higher than those of the CLOHP/CV without fins. The fins increased the surface are thereby enhancing heat transfer.

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