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Heat transfer rate of a closed-loop oscillating heat pipe with check valves using silver nanofluid as working fluid[†]

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Abstract

This research 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). The CLOHP/CV was made from copper tubing with an internal diameter of 2 mm. Two check valves were inserted into the tube. The tube had 40 meandering turns. The length of the evaporator was 50, 100, and 150 mm. The lengths of the evaporator, adiabatic, and condenser section were equal. The concentration of silver nanofluid was 0.25, 0.5, 0.75, and 1 %w/v, and the operating temperature was 40, 50, and, 60°C. It was found that the heat transfer rate of the CLOHP/CV using silver nanofluid as a working fluid was better than that the heat transfer rate when pure water is used because the silver nanofluid increases the heat flux by more than 10%.

Keywords: Nanofluid; Oscillating heat pipe; Check valve; Heat transfer

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1. Introduction

A heat pipe is a type of heat exchanger that is very easy and straightforward to use. Heat pipes used for heat transfer have been improved over time. Over the years, researchers have continuously explored new methods of heat transfer enhancement. The results of employing different cooling liquids proved to be one effective way of improving the system's overall performance. Nanofluid is a new working fluid for heat exchangers which does not pollute because it uses water as a base fluid. Nanofluids are engineered by suspending ultra-fine metallic or nonmetallic nanometer dimension particles in base fluids (water, oil, and ethylene glycol).

In 2006, Shung et al. [1] studied the effect of silver nanoparticle size. Using varying concentrations of silver nanofluids in a heat pipe led to an increase in the heat pipe wall temperature. In 2007, Yu Hsing Lin et al. [2] studied the effect of silver nanofluid on a pulsating heat pipe's thermal performance using a copper tube with internal diameters of 2.4 and 3 mm. The fill ratio was 60% while the heating power was 85W. The average temperature difference of the evaporator and the condenser was compared with that of pure water, which was less than 7.79°C. The thermal resistance was less than 0.092° C/W. It proved that a nanofluid was suitable for application in a heat pipe.

A closed-loop oscillating heat pipe with check valves (CLOHP/CV) was improved from the convenience heat pipe. Advantages of the CLOHP/CV include simplicity of construction, as it uses just a single tube, no wick structure, high thermal performance, capability of operation in any position, and operational flexibility. The heat flux of CLOHP/CV was found to be better than those of the closed-loop oscillating heat pipe (CLOHP) and the closed-end oscillating heat pipe (CEOHP) by (Pipatpaiboon et al. [3]). Therefore, CLOHP/CV and silver nanofluid were

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selected for use in this study.

2. Experimental setup and procedure

2.1 Nanofluid preparation

Nanofluid is produced by metal or metal oxide nanoparticles suspended in base fluids such as oil or water. It involves many methods such as changing the pH value of the suspension, using surfactant activators, and using ultrasonic vibration. The nanoparticles suspended in base fluids are stable for a long time. For this research, nanofluid was prepared by a sonicator for five hours. The sonicator had a bath type, operating frequency, and power source of 43 kHz, AC100, and 120V/AC220~240V 50/60 Hz, respectively. Nanoparticles were prepared by SIGMA-ALDRICH, Inc., USA. The silver nanopowder used in this study has a particle size of <100 nm, 99.5% (metals basis). The silver nanoparticles were suspended into DI water with concentrations of 0.25, 0.5, 0.75, and 1 %w/v. Stability was up to 48 hours. Fig. 1 shows silver nanoparticles with DI water before and after using the crest ultrasonic sonicator.

2.2 Experimental Setup

An important factor that has to be considered in building a CLOHP/CV is the design of the tube diameter. For this research, the maximum inner diameter of CLOHP/CV can be defined in Eq. (1) [4].

$$d_{\max} < 2\sqrt{\frac{\sigma}{\rho_l g}}\ , \tag{1}$$

where $d_{\max}$ is the maximum inner of the capillary tube (m), σ is surface tension of the fluid (N/m), ρ_l is density of the fluid (kg/m^3), and g is acceleration of gravity (m/s^2).


(a) (b)

Fig. 1. Silver nanoparticles with DI water; (a) before using the crest ultrasonic sonicator, and (b) after using the crest ultrasonic sonicator.

The structure of the check valves in this study (Fig. 2) consists of four sections: ball, case, conical valve seat, and ball stopper. The advantage of a check valve is that it controls the liquid slug flow in one direction. The ball, which is made to control flow direction, is inserted in the middle of all compounds.

Fig. 3 shows the CLOHP/CV used in this study. The system was made of a copper capillary tube bent into 40 meandering turns and filled with water or 0.25, 0.5, 0.75, and 1 %w/v silver nanofluid at a filling ratio of 50% of the tube's volume total. It was made up of three sections (evaporator, adiabatic, and condenser section), with two check-valves set up along the CLOHP/CV in a position shown in Fig. 4. The evaporator, adiabatic, and condenser section lengths were 50, 100, and 150 mm, respectively.

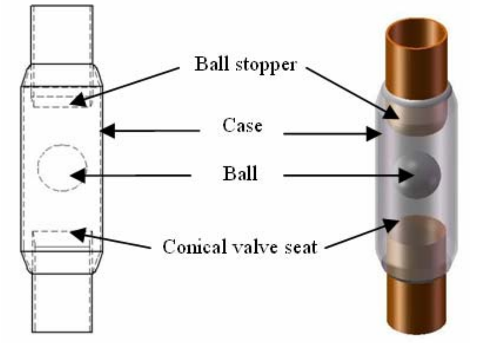

Fig. 2. Structure of the check-valve.

Fig. 3. CLOHP/CV.

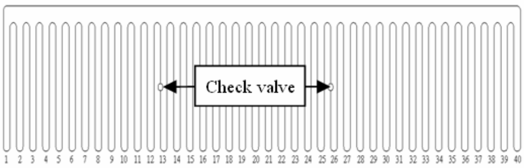

Fig. 4. The position of the check-valves on the oscillating heat pipe.

2.3 Experimental procedure

CLOHP/CV was set into a test rig and adjusted to an inclination angle set (0, 20, 40, 60, 80, and 90 degree from horizontal axis) for experimentation as shown in Fig. 5. Fig. 6 shows the experimental procedure of this study. A hot bath (TECHNE TE-10D with ±0.1° C accuracy) and a cold bath (EYELA CA -1111, volume 6.0 liters with an operating, temperature range of -20° C to 30° C and ±2° C accuracy) were filled with water. Afterwards, water in the hot bath was released into the evaporator section and water in the cold bath was released into the condenser section by controlling the flow rate at 0.5 liter/minute. The temperature in the adiabatic section was observed just as the temperature reached the operating temperature set at 40, 50, and 60^{o} C. The temperatures at every measuring point were then recorded by a data logger (Yokogawa DX200 with ±0.1° C accuracy).

The test was repeated with varying parameters such as evaporator length, concentration of silver nanofluid, inclination angle, and operating temperature. Next, the heat transfer and the heat transfer rate of the CLOHP/CV at the condenser section were calculated using Eqs. 2 and 3, respectively.

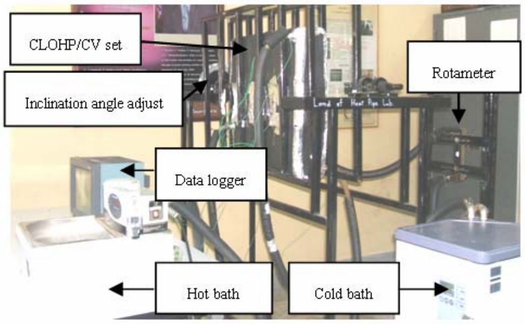

Fig. 5. Experimental setup.

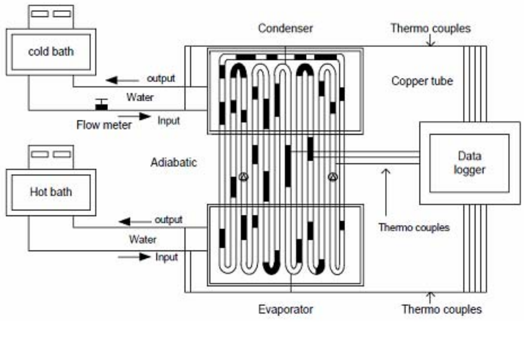

Fig. 6. Diagram of the experimental procedure.

3. Result and discussion

The temperature change of the condenser section's inlet water and outlet water was measured to calculate the heat flux of CLOHP/CV. The heat transfer rate of CLOHP/CV at the condenser section can then be calculated by Eq. (2) as follows:

$$Q = \dot{m} C_P (T_2 - T_1) , \tag{2}$$

where $\dot{m}$ is the mass flow rate of fluid at the condenser part (kg/s), Cp is the specific heat at constant pressure (kg/kJ·K), and T_1 and T_2 are the temperatures at the inlet condenser part and the outlet condenser part, respectively.

In this experiment, the heat flux was calculated using Eq. (3) below:

$$q = \frac{Q}{\pi D_o L_C N} , \tag{3}$$

where Q is the heat transfer rate (W), D_O is the outside diameter of the capillary tube (m), L_C is the condenser length (m), and N is the number of meandering.

Apart from determining heat flux, thermal conductivity of the nanofluid was also determined in order to estimate the increase in thermal conductivity. The thermal conductivity of solid-liquid mixtures was introduced by Wasp (1997) [5]. Therefore, in case of silver nanofluid, using Wasp's equation as Eq. (4) yields the following:

$$\frac{k_{eff}}{k_f} = \frac{k_p + 2k_f - 2\alpha(k_f - k_p)}{k_p + 2k_f - \alpha(k_f - k_p)} . \tag{4}$$

The volume fraction (α) of the particles is defined as

$$\alpha = \frac{V_p}{V_f + V_p} . \tag{5}$$

The experimental data of 120 data are also shown in this paper.

3.1 The effect of inclination angles on the heat transfer rate of CLOHP/CV

In Fig. 7, the effect of inclination angles on the CLOHP/CV with an aspect ratio of 25, a heat transfer rate at 90°, and water in all concentrations used as the working fluid was higher than other inclination angles. Furthermore, the heat transfer rate of the CLOHP/CV using silver nanofluid as the working fluid was higher than when water was used. Therefore, the best value of heat transfer rate was 8.88 kW/m^2 (aspect ratio (L_e/D_i) of 25 and concentration of 0.5 %w/v at 90° from the horizontal axis). In Fig. 8, results of the heat transfer rate were similar to the results of an aspect ratio of 25. The best heat transfer rate of an aspect ratio set at 50 was 4.13 kW/m^2 (inclination angle at 90° and silver nanofluid at 0.5 %w/v as working fluid). In Fig. 9, the best heat transfer rate was 7.69 kW/m^2 (inclination angle of 90° and silver nanofluid concentration of 0.5 %w/v as the working fluid). As the thermal conductivity of the base fluid increased, the suspension of nanoparticles increased the heat capacity of the fluid. Moreover, the inclination angle of the CLOHP/CV has an effect on the heat transfer rate because of a pressure difference (ΔP_g) brought about by the hydrostatic head of liquid being positive, negative, or zero. This depended on the fluid's density, acceleration from gravity force, tube length, and inclination angle of the CLOHP/CV to the horizontal axis. The pressure difference may be determined from Eq. (4):

$$\Delta P_g = \rho_l g l \sin\Phi , \tag{6}$$

where ρ_l is the liquid density (kg/m^3), g is the acceleration due to gravity (9.81 m/s^2), l is the heat pipe length (m), and ϕ is the angle between the heat pipe and the horizontal axis (ϕ is positive when the condenser is lower than the evaporator).

3.2 The effect of operating temperatures on the heat flux of CLOHP/CV

As described in 3.1, the best inclination angle to heat flux was 90°. Therefore, in this case, the CLOHP/CV was tested at an inclination angle of 90° from the horizontal axis. The effects of operating temperatures on the heat flux of CLOHP/CV are shown in Figs. 10, 11, and 12. The heat flux increased when the operating temperature increased, especially when silver nanofluid was used as the working fluid. Moreover, using silver nanofluid yielded a higher heat flux compared to using water as the working fluid. The best heat flux was 13.19 kW/m^2 at an aspect ratio of 25, an operating temperature of 60° C, and a silver nanofluid concentration of 0.5 %w/v. The

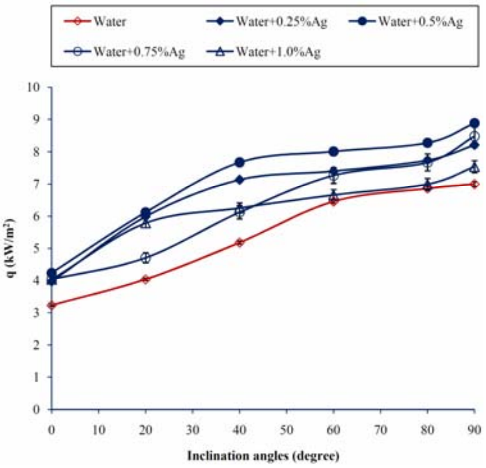

Fig. 7. Inclination angle of CLOHP/CV on the heat transfer rate at an aspect ratio of 25.

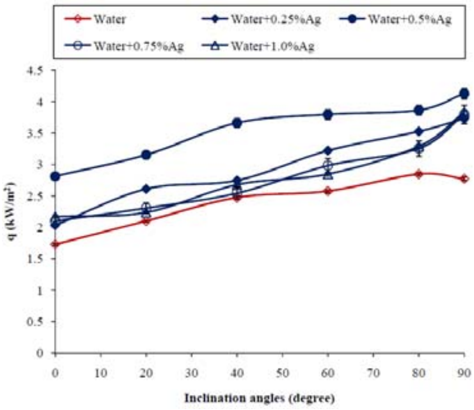

Fig. 8. Inclination angle of CLOHP/CV on the heat transfer rate at an aspect ratio of 50.

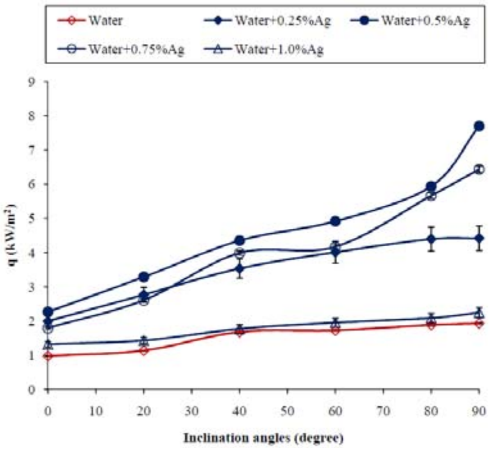

Fig. 9. Inclination angle of CLOHP/CV on the heat transfer rate at an aspect ratio of 75.

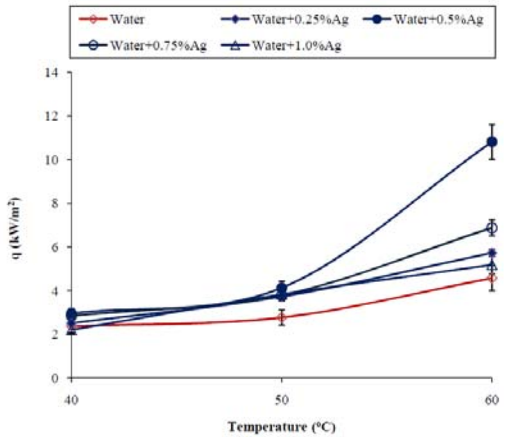

Fig. 10. The operating temperature on the heat transfer rate of CLOHP/CV at an aspect ratio of 25.

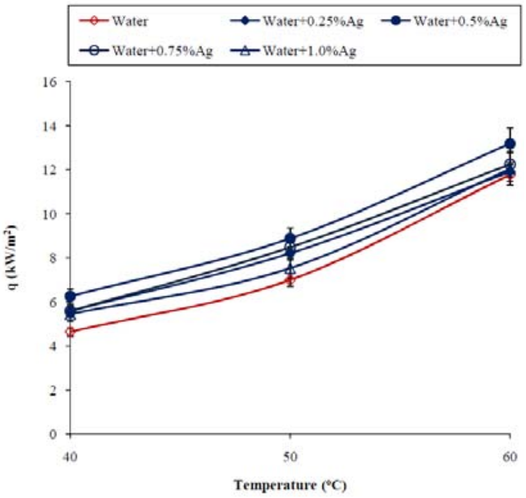

Fig. 11. The operating temperature on the heat transfer rate of CLOHP/CV at an aspect ratio of 50.

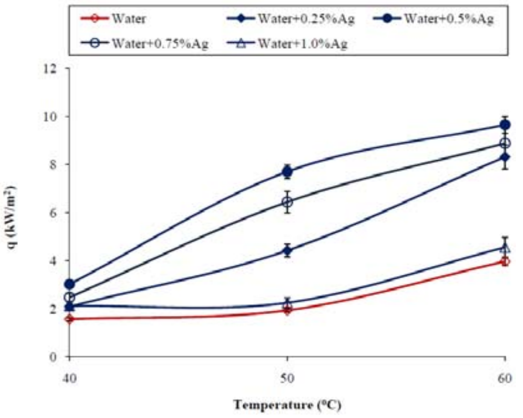

Fig. 12. The operating temperature on the heat transfer rate of CLOHP/CV at an aspect ratio of 75.

thermal conductivity of the base fluid was increased by the silver nanoparticles. The suspension of nanoparticles resulted in an increase of the surface area and the heat capacity of the base fluid. Moreover, the temperature affected the heat flux of the CLOHP/CV because boundary force decreased when the temperature increased. Moreover, the boiling form was changed with increased operating temperature. Meena et al. [6] mentioned the flow pattern; it was separated into four types: annular flow occurring at low temperature, low thermal conductivity, fluid, and high aspect ratio. The heat flux of the slug flow was better than the annular flow, the heat flux of the bubble flow was higher than the slug and annular flow, and the best heat flux was dispersed flow. It occurred at a high temperature and a low aspect ratio. With the same fluid, the flow pattern at the inner tube changed from annular flow to slug, bubble, or dispersed flow when the operating temperature was increased. In this study, water and water mixed with silver nanoparticles were used as the working fluids. The base fluid was the same working fluid as that used by Meena et al. Therefore, when the operating temperature increased, the flow pattern also changed. It can change from annular flow to slug flow or bubble flow. Moreover, the aspect ratio of 25 was the best of all aspect ratios in this study because it was found to be suitable for boiling. This is because the adiabatic length at an aspect ratio of 25 was shorter than that at aspect ratios of 50 and 75. Therefore, the vapor plug transferred heat with ease from the evaporator section to the condenser section because the distance between the evaporator section and the condenser section was small. The result of this study was improved and then compared with the result of Y.H. Lin et al. Yu Hsing Lin et al. [2]. It was found that the heat transfer was in the same direction as shown in Fig. 13.

3.3 The concentration of silver nanofluid on the heat flux of CLOHP/CV

The result of this study demonstrated that with each concentration of silver nanofluid, the heat flux was different. Of these, the concentration of 0.5 %w/v was the best of all concentrations for the heat flux at all operating temperatures, all aspect ratios, and all inclination angles. In previous research [7], when the concentration of the nanofluid increased, the heat flux also increased. However, in this study the opposite occurred because a nanofluid was used in the CLOHP/CV. This is because the heat flux of

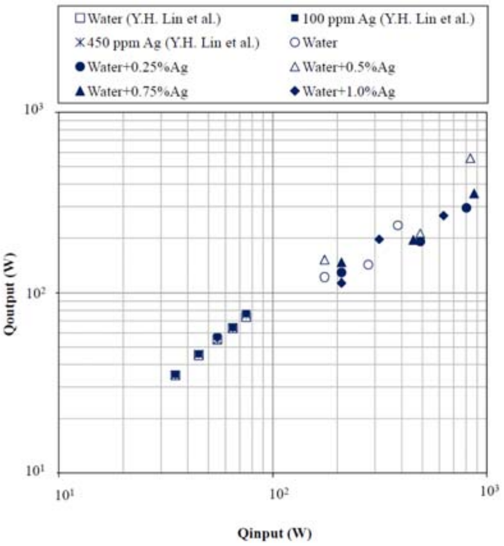

Fig. 13. A comparison of the heat transfer rates of this study and those of Y.H. Lin et al. [7].

CLOHP/CV depended on the limit of the working fluid viscosity. The higher concentration will make the viscosity higher. The higher viscosity makes it difficult to produce bubbles, and the force of the friction causing obstruction of the liquid slug becomes larger. Therefore, the concentration of silver nanofluid can be increased to some point in order to support the heat flux of CLOHP/CV. Between the concentrations of silver nanofluid at 0.25 and 0.75 %w/v, sometimes the heat flux of the silver nanofluid with a concentration of 0.75 %w/v was higher than at a concentration of 0.25 %w/v. This is because the thermal conductivity of the base fluid was influenced by the fluid's heat transfer rather than the effect of viscosity. If the heat flux of silver nanofluid at a concentration of 0.25 %w/v was higher than that at a concentration of 0.75 %w/v, this was because viscosity was influenced by the heat transfer of the fluid rather than being brought about by the effect of thermal conductivity.

4. Conclusion

It can be summarized that the best inclination for using CLOHP/CV was 90° from the horizontal axis. The operating temperature had an effect on the heat flux of the CLOHP/CV, and the heat flux using silver nanofluids at all concentrations were higher than with water. As a result, the thermal conductivity of the base fluid was increased. The suspension of nanoparticles can increase the heat capacity of the fluid. Nevertheless, the concentration of silver nanofluid can be increased to some point for supporting the heat flux of the CLOHP/CV because the heat flux of CLOHP/CV depended on the limit of working fluid viscosity. In this study, the best concentration of silver nanofluid for use in CLOHP/CV was 0.5 %w/v.

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Nomenclature

C_p : Specific heat capacity constant pressure (J/kg.°C)
D : Diameter of the capillary tube (m)
g : Acceleration due to gravity (9.81 m/s^2)
l : Heat pipe length (m)
L : Length (m)
$\dot{m}$: Mass per unit time (kg/s)
N : Number of meandering
Q : Heat transfer rate (W)
q : Heat flux (kW/m^2)
T : Temperature (^{o}C)
T_1 : Inlet temperature at condenser section (^{o}C)
T_2 : Outlet temperature at condenser section (^{o}C)
V : Volume (m^3)

Greek symbols

ϕ : The angle between the heat pipe and the horizontal (^{o})
ρ_l : Liquid density (kg/m^3)
α : Volume fraction

Subscripts

ad : Adiabatic section
c : Condenser section
e : Evaporator section
eff : Effective
f : Fluid
I : Inner

o	: Out side
p	: Particle

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