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Comparison of copper and glass oscillating heat pipes with Fe_2O_3 under magnetic field

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Abstract

This paper presents the findings from an experimental investigation on the performance effect of magnetic field when applied to oscillating heat pipes (OHPs) using kerosene with Fe_2O_3 nanoparticles as the working fluid. Two types of OHPs were used in this investigation: copper surface OHP and glass surface OHP. The temperature distribution and heat transfer rate through the OHPs were monitored and recorded with and without the magnetic field. In addition, the effect of surface condition on heat transfer for the copper and glass OHPs was investigated. The results have shown that the heat transfer performance of the OHPs improved with the addition of nanoparticles. This improvement was greatly enhanced by the application of magnetic field especially at the higher heat load regions and was more superior for the copper OHP with Fe_2O_3 nanofluid.

Keywords: oscillating heat pipes; nanoparticles; heat transfer enhancement and magnetic field

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1 INTRODUCTION

New technological developments as well as industrial process intensifications have increased the need for smaller and more efficient heat exchange components. Pulsating or otherwise known as oscillating heat pipes (OHPs) are passive heat transfer systems that can offer simple and reliable operation (no moving parts and vibration-free) with high effective thermal conductivity. OHPs were first invented in the early 1990s by Akachi [1] and present promising alternatives for the removal of high localized heat fluxes to provide a necessary level of temperature uniformity across the components that need to be cooled. When the temperature difference between evaporator and condenser exceeds a certain threshold, the gas bubbles and liquid plugs begin to oscillate spontaneously back and forth. The amplitude of oscillations is quite strong and the liquid plugs penetrate into both condenser and evaporator. The heat is thus transferred not only by the latent heat transfer like in other types of heat pipes, but also by sweeping of the hot walls by the colder moving fluid and vice versa. Hence, the heat transfer mechanism between the rising liquid films along a vertical wall is an interesting research phenomenon in OPHs. A number of investigations concerning this have been made from both theoretical and applied viewpoints [2–6]. While most of OHPs use copper tube, no data on flow of liquid over a flat vertical wall with rough surfaces have been published. Only some of the features of their operation in contrast to OHP have been investigated [7–10]. Major aspects that remain to be studied include geometry and layout of the inner surface with and without roughness of, in this case, copper and glass OHPs. In this paper, the performance of smooth and rough surface OHPs has been investigated with glass surface OHP representing the smooth surface while the copper surface OHP representing the rough surface. Heat transfer of copper as a rough surface is 1.5 times higher than for a glass pipe which could be regarded as a smooth surface. The large number of experimental and theoretical studies mentioned above, all have been performed for heat transfer on OHP. However, many current OHP designs involved surfaces that are rough rather than smooth. In fact, no OHP surfaces are totally smooth and turbulence promoters are often introduced to improve heat transfer rates. Relatively, few papers have been published so far on the effect of surface roughness on heat transfer in OHP.

Literature review shows most studies on heat transfer in smooth surfaces have consisted of experimental measurements resulting in only partial understanding of the effect of roughness, and no paper related to the effect of roughness in magnetic field has been found. However, as demonstrated by Incropera [11], increases in surface roughness can cause a large increase in heat flux for the nucleate boiling regime. A rough surface has numerous cavities that serve to trap vapor, providing more and

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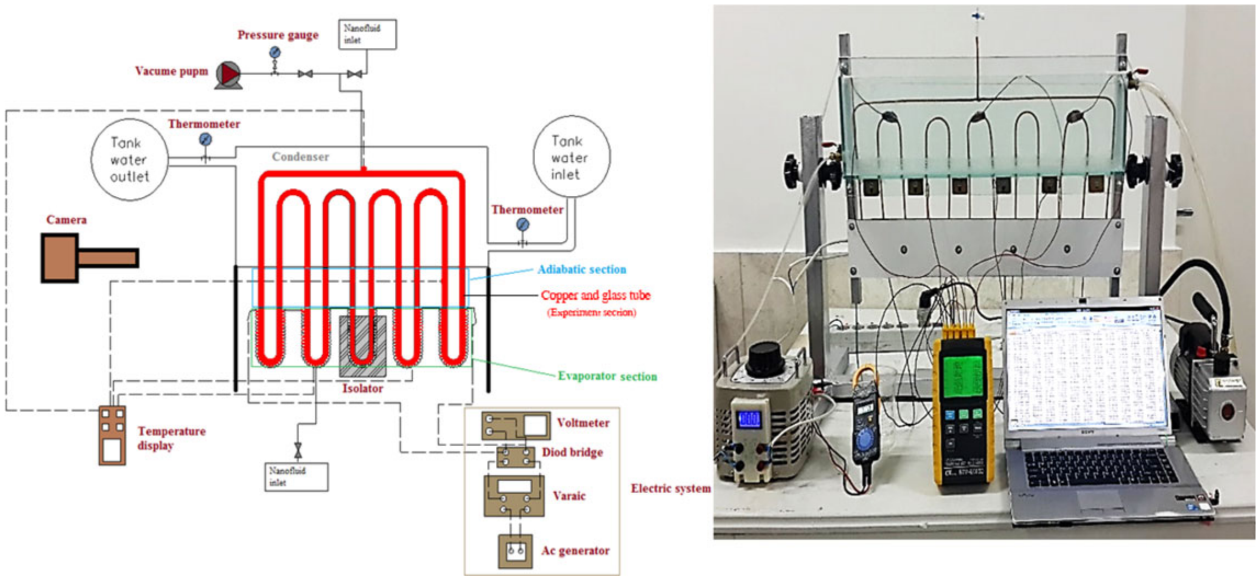

Figure 1. *Schematic and picture of the experimental setup.*

large sites for bubble growth. It follows that the nucleation site density for a rough surface can be substantially larger than that for a smooth surface. Experiments were conducted to investigate the effect of surface roughness on the heat transfer in OHP for which no comprehensive investigation has previously been reported. The experiments were carried out for copper and glass OHPs.

2 EXPERIMENTAL PROCEDURE

Prior to charging the working fluid into the copper OHP, the apparatus was evacuated, by placing it under a suction pressure of 0.1 Pa for 15 min using a vacuum pump connected to a three-way valve. Following this initial evacuation, the three-way valve was used to isolate the vacuum pump and to allow the working fluid to be charged into the OPH, see Figure 1.

In order to simulate a number of different heat loads on the evaporator section, an electric plate-type heater with a maximum power rating of 250 W was used and connected to the mains through a Variac transformer. The Variac controlled the voltage input into the heater, thus controlling the heat output from the heater. To minimize heat losses to the surrounding, a thick wool insulation was used over the heater plate and over the adiabatic section.

The heat input was calculated using the measurements obtained from the heater electrical monitoring system which consisted of a standard voltmeter and a current ammeter. The voltage and current uncertainties were found to be ± 0.4 V and ± 0.015 A, respectively.

The temperatures at various parts of the system (evaporator, adiabatic and condenser sections) were monitored using a set of type-K thermocouples connected to a portable data logging and display system. Four thermocouples were attached to the evaporator section, four thermocouples were attached to the adiabatic section and four thermocouples were used to measure the surface temperature of condenser section. The uncertainty of measuring the temperature using the temperature monitoring arrangement was found to be ± 1 K. It should be mentioned that, according to our error analysis, the cumulative error is $<10\%$. The geometric parameters for the OHPs are given in Table 1.

Table 1. *Heat pipe configuration.*

OHP container	Copper and glass
OHP length	380 mm
Condenser length	100 mm
Adiabatic length	100 mm
Evaporator length	100 mm
Outer diameter	3 mm
Wall thickness	1.25 mm
Inner diameter	1.75 mm
Liquid filled ratio	50%
Total length of OHP	4.4 m

For the current investigation, kerosene as carrier, oleic acid as a surfactant and nanoparticles of Fe_2O_3 with 5 vol.% were used. Table 2 presents the properties of the Fe_2O_3 nanoparticles used in this investigation. The Fe_2O_3 nanoparticles were added into the base fluid and then the base fluid with Fe_2O_3 nanoparticle was continuously mixed using a magnetic stirrer. It was also sonicated with the ultrasonic oscillator for 1 h.

3 EXPERIMENTAL RESULTS

The mean condenser temperature ($T_{c\text{-mean}}$) was calculated using the readings from the four condenser thermocouples according

Table 2. *Properties of iron oxide nanopowder (Fe_2O_3).*

Details: iron oxide nanopowder (gamma—Fe_2O_3—high purity)	
99.5%	Purity
20 nm	APS
40–80 m^2/g	SSA
Red brown	Color
Spherical	Morphology

to Equation (1). Owing to the relatively high water flow in condenser section, the temperature is constant during the experiment. The mean evaporator temperature ($T_{e\text{-mean}}$) was also calculated using the readings from the four evaporator thermocouples according to Equation (2) and are used in this research to show the startup performance of ferrofluid used in OHPs.

$$T_{C-\text{mean}} = \frac{T_{C1} + T_{C2} + T_{C3} + T_{C4}}{4} \tag{1}$$

$$T_{E-\text{mean}} = \frac{T_{E1} + T_{E2} + T_{E3} + T_{E4}}{4} \tag{2}$$

The thermal resistance of the OHP is a measure of thermal performance, which is shown as follows:

$$R = \frac{T_e - T_c}{Q_{in}} \tag{3}$$

where T_e is the wall temperature of the evaporator and T_c is the wall temperature of the condenser. Q_{in} is the input heat load onto the OHP that is calculated from the input current and voltage as follows:

$$Q_{in} = VI \tag{4}$$

where V is the input voltage that enters the electrical flat heater and I is the current measured by the digital ammeter.

Figure 2 shows the temperature difference between the evaporator and condenser sections for the copper OHP versus the heat input. As expected, the temperature difference increased with increasing heat input. The addition of Fe_2O_3 nanoparticles under magnetic field reduced the temperature difference between the evaporator and the condenser.

The thermal resistance versus the heat load for each OHP was plotted on one graph, and the results are shown in Figure 3 for the copper OHP and in Figure 4 for the glass OHP.

It is clear from the above figures that overall thermal resistance of the Fe_2O_3 nanofluid-charged OHPs is lower than that of the kerosene-only OHPs. This means, the addition of Fe_2O_3 nanoparticles enhanced the heat transfer of the OHPs. The addition of magnetic field resulted in a further reduction of the thermal resistance and this is more prominent at the higher heat load regions. This is thought to be due to the ability of the magnetic field to destabilize the vapor film formed on the heat transfer surface at higher heat loads, i.e. the addition of Fe_2O_3 nanoparticles enhanced the heat transfer of the OHP and the application of the magnetic field results in further heat transfer enhancement.

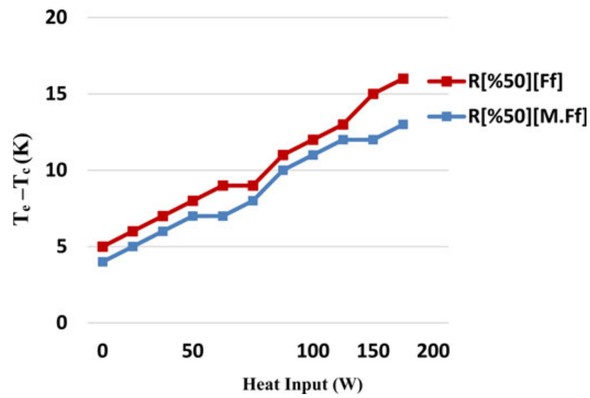

Figure 2. *Vapor temperature difference between evaporator and condenser sections versus heat input for the copper OHP with Fe_2O_3 nanofluid.*

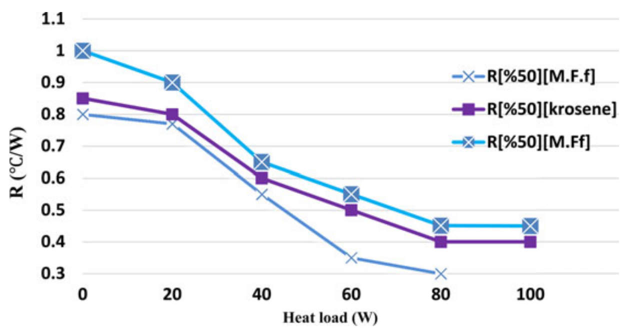

Figure 3. *Comparison of thermal resistances between base fluid (kerosene) and nanofluids with magnetic field (M.Ff) and without magnetic field (Ff), filling ratio = 50% in copper OHP.*

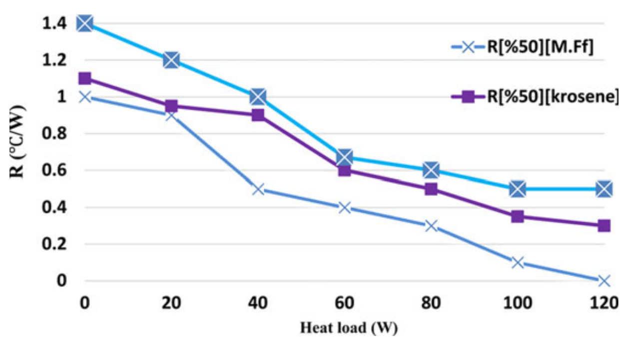

Figure 4. *Comparison of thermal resistances between base fluid (kerosene) and nanofluids with magnetic field (M.Ff) and without magnetic field (Ff), filling ratio = 50% in glass OHP.*

In order to evaluate the effect of using magnetic field on the heat transfer performance of nanofluids charged OHPs, the performance enhancement efficiency η was evaluated using the following equation:

$$\eta = \frac{\bar{R}_{\text{base fluid}} - \bar{R}_{\text{nanofluid}}}{\bar{R}_{\text{base fluid}}} \times \%100 \tag{5}$$

where $\bar{R}_{\text{base fluid}}$ is the thermal resistance of the OHP charged with only the base fluid (kerosene) and $\bar{R}_{\text{nanofluid}}$ is the thermal resistance of the OHP charged with the nanofluid. Using the definition shown above, η values were determined and the percentage enhancements of the two OHP surfaces with and without magnetic fields are presented in Figures 5 and 6. It is clear from both figures that the percentage enhancement increased with the application of magnetic field for both OHPs. This increase in percentage enhancement is much greater at the higher heat load regions reaching 19 and 22% when the magnetic field was applied to glass and copper OHPs, respectively, at the 90 W heat load.

Figures 5 and 6 could be interpreted as that the thermal resistance of Fe_2O_3 charged working fluid under magnetic field is lower than that in the absence of magnetic fluid, hence higher Nusselt numbers and therefore increased heat transfer coefficient and higher thermal conductivity. It could also be concluded that heat transfer by Fe_2O_3 under magnetic field depends on several factors including evaporator surface condition which, in turn, depends on surface roughness; as a result, it increases or decreases the vapor movement, and drag force, due to Lorentz force, increases or decreases the release accumulated by the bubble on the inner wall of the evaporator.

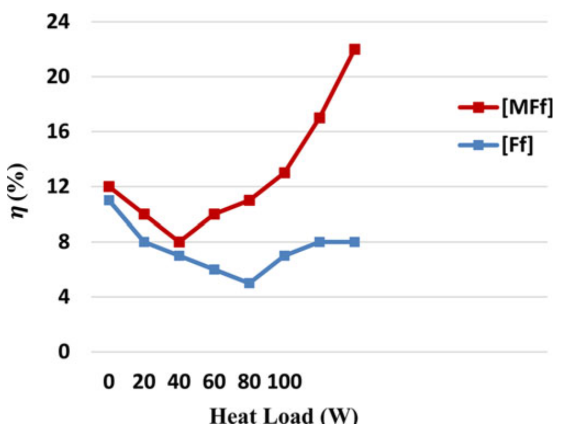

Figure 5. *Percentage enhancement using magnetic field (M.Ff) compared with non-magnetic field (Ef) for a copper OHP with a filling ratio of 50%.*

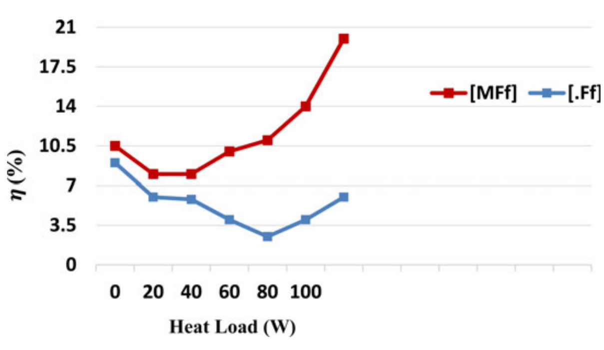

Figure 6. *Percentage enhancement using magnetic field (M.Ff) compared with non-magnetic field (Ff) for a glass OHP with a filling ratio of 50%.*

The effect of Fe_2O_3 on two-phase flow heat transfer enhancement may be illustrated through two reasons: the suspended Fe_2O_3 increased the thermal conductivity of base fluid; and the interactions among the Fe_2O_3 and itself on the one hand and between Fe_2O_3 and the inner surface of the OHP on the other hand. Also, the diffusion and collision intensification of Fe_2O_3 near the wall due to increase in the concentration of Fe_2O_3 leads to rapid heat transfer from OHP wall to Fe_2O_3.

Comparing the results for all the above figures shows that the thermal resistance in the case of copper surface OHP is lower than that for the glass surface OHP and the percentage enhancement with magnetic field in the case of the copper surface OHP is higher than that for the glass surface OHP. The reason for reducing the thermal resistance of glass OHP can be explained as follows. A major thermal resistance of OHP is caused by the formation of vapor bubble at the liquid–solid interface. A large bubble nucleation size creates a higher thermal resistance that prevents the transfer of heat from the solid surface to liquid [11]. The roughness of copper surface causes the larger bubble during the bubble formation. Bubble formation and their growth are initiated by collision between upward and downward liquid slug near the evaporative section. Such frequent collisions generate a large number of bubbles that eventually merge to form lengthy OHP tube size vapor plug. The reason for that can be explained because copper tube provides better thermal efficiency and higher number of pressure fluctuations with higher amplitude compared with the glass tube in OHPs. The transition region can be considered as the region in which the roughness emerges from a previously unaffected viscous sublayer. It is not necessary, however, to assume that the sublayer has not been changed by the presence of a submerge roughness. Perhaps, a more accepted description of the flow near the roughness element is shown in Figure 7.

This change in the turbulence level near the rough surface would have an effect on both the momentum and heat transfer

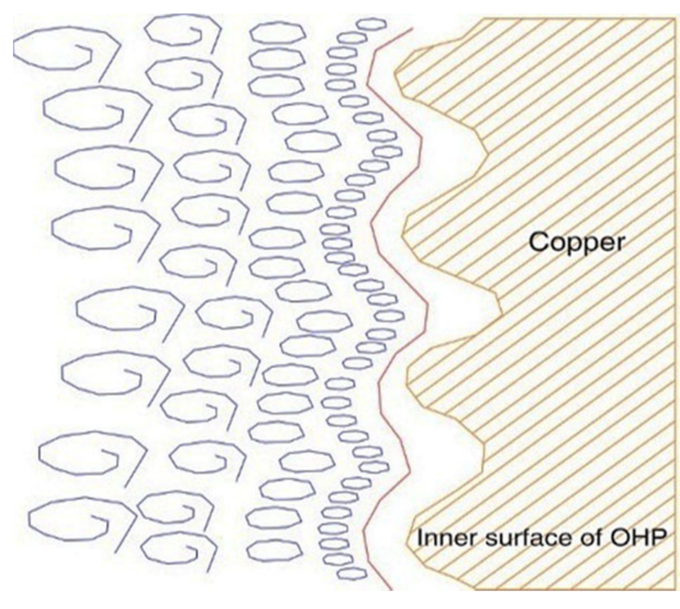

Figure 7. *Flow pattern near the rough wall.*

rates. Disruption of the viscous sublayer and penetration of turbulence into the valley regions results in rapid increases in the rates of both momentum and heat transfer. A greater increase in the latter would be expected, as proportionately more of the resistance to heat transfer occurs in the viscous region.

CONCLUSIONS

An experimental investigation was designed, assembled, instrumented and performed to investigate the heat transfer enhancement as a result of introducing nanofluids into the working fluid (kerosene) of two surface type OHPs (copper surface OHP and glass surface OHP). The nanoparticles used for the test were iron oxide nanopowder (Gamma—Fe_2O_3—high purity). The two surface types represented rough and smooth surfaces, respectively. Further investigation was carried out on the effect of magnetic field applied onto the OHPs. From the experimental results and discussion of the performance characteristics of the copper and glass OHP surface arrangements, the following conclusions may be drawn:

(1) The heat transfer performance of OHPs improved with the addition of nanofluids and this improvement is further enhanced by applying the magnetic field, especially at high heat loads. The results indicate an increase of 16% in the heat transfer after using Fe_2O_3 nanofluid with magnetic field.

(2) It is concluded that heat transfer with Fe_2O_3 under magnetic field depends on several factors , for example, evaporator surface condition depends on surface roughness as a result, increases or decreases vapor movement and also drags force due to Lorentz force, increases or decreases the release the bubble accumulated on the inner wall of evaporator.

(3) By increasing the volumetric percentages of nanoparticles in the suspension, the heat transfer rate is increased, but this resulted in a decrease in the movement of bubbles and this issue need to be monitored as it can lead to increased pressure in the system and could lead to blockages.

(4) Overall heat transfer rates of rough surfaces such as copper increase considerably compared with smooth surfaces such as glass in OHP.

(5) Thermal resistances at the evaporator and condenser sections were influenced by important parameter such as surface roughness of OHP inner wall. Heat transfer of copper as a rough surface is increased by 1.5 times the glass values as a smooth surface.

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REFERENCES

[1] Akachi H. Looped Capillary Heat Pipe. Japanese patent. No. Hei6-97147, 1994.

[2] Wilson CA. *Experimental Investigation of Nanofluid Oscillating Heat Pipes*. University of Missouri-Columbia, 2006.

[3] Fasula C. *Oscillating Heat Pipes (OHP)*. University of Rhode Island, 2009, 46.

[4] Yulong J, Corey W, Hsiu-hung C, *et al*. Particle shape effect on heat transfer performance in an oscillating heat pipe. *Nanoscale Res Lett* 2011;**6**:296.

[5] Yulong J, Hongbin M, Fengmin S, *et al*. Particle size effect on heat transfer performance in an oscillating heat pipe. *Exp Thermal Fluid Sci* 2011; **35**:724–7.

[6] Taslimifar M, Mohammadi M, Afshin H, *et al*. Overall thermal performance of ferrofluidic open loop pulsating heat pipes: an experimental approach. *Int J Thermal Sci* 2013;**65**:234–41.

[7] Mameli M, Marengo M, Khandekar S. Local heat transfer measurement and thermo-fluid characterization of a pulsating heat pipe. *Int J Thermal Sci* 2014;**75**:140–52.

[8] Jia L. Experimental Research on Pulsating Heat Pipe. In: *Proceedings of 4th Asian Joint Workshop on Thermophysics and Fluid Science*, Busan, Korea, 2012.

[9] Huminic G, Huminic A, Morjan I, *et al*. Experimental study of the thermal performance of thermosyphon heat pipe using iron oxide nanoparticles. *Int J Heat Mass Transfer* 2011;**54**:656–61.

[10] Ghofrani A, Dibaei MH, Sima AH, *et al*. Experimental investigation on laminar forced convection heat transfer of ferrofluids under an alternating magnetic field. *Exp Thermal Fluid Sci* 2013;**49**:193–200.

[11] Incropera D, Dewitt P, Bergeman T, *et al*. *Introduction to Heat Transfer*, 6th edn. John Wily & Sons, 2009.