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Experimental study on the effect of inclination angle on heat transfer enhancement of a ferrofluid in a closed loop oscillating heat pipe under magnetic field

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ABSTRACT

This paper elaborates on the findings of study on the effect of Fe_2O_3/Kerosene nanofluid to the copper closed-loop oscillating heat pipe under the magnetic field for inclination angles ranging from 0° to 90°, under different heat inputs (10–90 W). The heat pipe's heat transfer coefficient was measured without and with the magnetic field. Moreover, the vapor temperature was assessed directly at the center of the oscillating heat pipe by exposing the ferro-nano particles to a magnetic field. It was shown that Fe_2O_3 nanoparticles could improve the thermal resistance and subsequently thermal performance as well as the pipe's heat transfer coefficient, especially under the magnetic field. The heat pipe's heat transfer coefficient increased as the input heat flux increased. The results also demonstrated that the heat pipe's inclination angle had a significant effect on performance of heat pipe. The critical angle was 75° as the heat transfer coefficient increased due to higher inclination angle.

1. Introduction

Better thermal management is needed as electronic devices with higher performance are introduced, their heat output of which may surpass the heat transfer potentials of the existing heat pipe designs. Oscillating Heat Pipes (OHPs), also known as Pulsating Heat Pipes (PHPs), can remove higher heat fluxes due to better heat spreading performance. OHPs, developed by Akachi [1], do not necessitate a pump or extra power to work, because they are passive heat transfer devices. The long meandering tube of OHPs is heated and chilled at several locations along its length. The oscillation principle for the working fluid constitutes the basis of these devices, and the capillary tube undergoes a phase change phenomena. The tube diameter should be as small as possible so that the vapor and liquid plugs are still present. Heat transfer is the result of fluid's normal oscillations between the condenser and evaporator sections. OHPs, unlike classic heat pipes, do not require a wicking assembly for liquid transfer and are able to work at greater heat fluxes. Compared to conventional heat pipes, their performance is higher and they may be employed to solve the upcoming LED [2], electronic cooling [3], drying [4], heat recovery [5] and fuel cell [6] problems.

A number of investigations concerning the horizontal OHP have been done from both theoretical and applied point of view [7,8]. Most of the OHPs are made vertically and a large number of research studies have explored vertical OHP [9–11]. However, the studies by Khandekar, Schneider, Schafer, Kulenovic and Groll [12] and Lotfi and Shafii [13] showed that efficiency as well as thermal resistance of an OHP depend on the orientation, filling ratio, inner diameter and number of OHP bends.

On the other hand, the experimental studies of Taslimifar, Mohammadi, Afshin, Saidi and Shafii [14] and Mohammadi, Taslimifar, Saidi, Shafii, Afshin and Hannani [15] demonstrated that magnetic field results in flow circulation that can improve heat transport owing to thermomagnetic convection changes and effects in ferrofluid's magnetic properties as temperature changes. Ferrofluids are called smart functional fluids because of their exceptional characteristics, establishing concurrent magnetic and fluid properties. That is why these are used in bioengineering, aerospace and mechanical engineering [16,17].

The previous studies imply that ferrofluids are good coolants [18,19]. Yet, the ferrofluids' convection heat transfer in an inclined OHP requires more investigations. Hence, in the present study, a ferrofluid comprising of Kerosene and Iron (III) oxide was applied

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Nomenclature

A	area (m)
D	diameter (m)
I	electric current (A)
V	electrical voltage (V)
f	friction factor
q	heat flux (W m^{-2} K^{-1})
Q	heating power (W)
h	heat transfer coefficient (W m^{-2} K^{-1})
L	length (m)
T	temperature (K)
Re	Reynolds number
R	thermal resistance (K W^{-1})

Greek symbols

Δ	uncertainty
ρ	density (kg m^{-3})
μ	dynamic viscosity (kg m^{-1} s^{-1})

Subscripts

ad	adiabatic
c	condenser
e	evaporator
i	inner
in	input
loos	loos
mean	mean

to an inclined, closed-loop OHP at the presence of the magnetic field to evaluate the thermal efficiency of the system and find the critical OHP angle. This is the angle at which the maximum heat transfer is achieved [20]. The changes of thermal resistances, difference in vapor temperature between the evaporator and the condenser as well as heat transfer coefficient in different angles at a filling ratio of 50% were analyzed. Also, two semi-empirical correlations for Nusselt number have been derived in presence or absence of the magnetic field. The outcomes of the current investigation are expected to assist the readers to design more efficient OHPs, charged with nanofluid.

2. Experimental procedure and repeatability

The device was emptied before charging the fluid into the OHP by applying 0.1 Pa suction pressure for 15 min via a vacuum pump joined to a 3-way valve. Next, the vacuum pump was isolated using the 3-way valve to charge the fluid into the OHP (see Fig. 1).

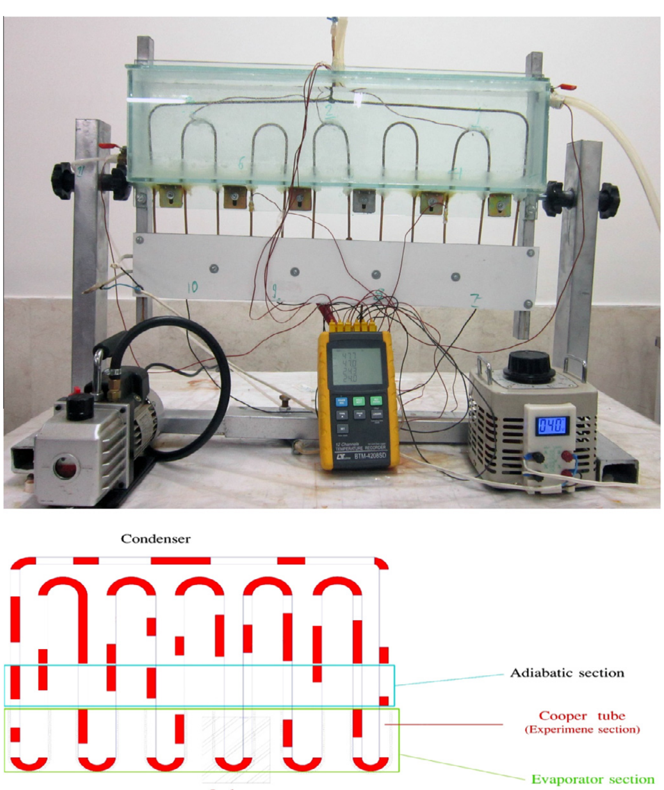

Fig. 1. Schematic of the experimental setup.

To explore effect of different heat loads on the evaporator segment, an electrical monitoring system and a Variac were used to connect an electric heater to the source of electricity. The standard current and volt meter data were used to calculate the heat input. Tests were done under different heat inputs of 10–90 W. The uncertainties in the current and voltage were ±0.015 A and ±0.4 V, respectively.

A set of K-type thermocouples coupled with a display system and a portable data logger was used to monitor temperature at condenser and evaporator. Defined by the temperature monitoring plan, the uncertainty of temperature measurement was obtained as ±1 K. Table 1 presents the OHP's geometric parameters presented in.

Less than ±0.1 °C variation in temperature for 10 min is called the steady state [21]. After that, the power is amplified to the subsequent level and the heat pipe's performance is evaluated. This process is repeated for 10–90 W heat inputs and 0–90° pipe inclinations and the results are documented.

The nanoparticles of Fe_2O_3 (2 Vol.%,), the Oleic acid as a surfactant and the Kerosene as base fluid, were used in the present study.

Table 1
The configuration of the heat pipe.

OHP container	Copper
OHP length	380 mm
Adiabatic length	100 mm
Condenser length	100 mm
Evaporator length	100 mm
Inner diameter	1.75 mm
Outer diameter	3 mm
Wall thickness	1.25 mm
Liquid filled ratio	50%

Table 2
Properties of the Ferro-nanopowder.

Details: Iron Oxide nano powder (gamma – Fe_2O_3 – high purity)	
Purity	99.5%
APS	20 nm
SSA	40–80 m^2/g
Color	Red brown
Morphology	Spherical