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Thermal performance of inclined screen mesh heat pipes using silver nanofluids☆

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ABSTRACT

This study presents the effect of silver nanofluid on thermal performance of inclined screen mesh heat pipe in cooling applications. Four cylindrical copper heat pipes containing two layers of screen mesh were fabricated and tested with distilled water and water based silver nanofluids with mass concentrations of 0.25%, 0.5% and 0.75% as working fluids. The experiments were performed at four inclination angles of 0°, 30°, 6° and 90°. The main focus of this study is to investigate inclined heat pipe performance with nanofluid. Experimental results indicate that the thermal performance of heat pipes was improved with nanofluids compared to water and thermal resistance of the heat pipes decreased with the increase of nanoparticle concentration. Moreover, the thermal performance of the heat pipes at inclination angle of 60° is found to be higher than other tested inclination angles, which shows the effect of gravity on heat pipe performance.

1. Introduction

Heat pipe as a two phase heat transfer device, with high effective thermal conductivity in comparison with common thermal conductors such as metal rods and fins, plays a vital role in many industrial applications including cooling of electronics, power generation, aerospace and chemical processes. Large quantities of heat with minimum temperature gradient are transported by vaporization and condensation of a working fluid and also capillary force action for pumping the liquid back to the evaporation section. However, traditional heat transfer fluids like water and alcohols have been extensively used in heat pipes, their poor thermal properties become a primary obstacle limiting the thermal performance of heat pipe-heat exchangers. Nanofluids, as a new class of heat transfer fluids, are proposed and developed over the past decade for heat transfer applications. It has been revealed that nanofluids have greater heat transfer characteristics than traditional heat transfer fluids [1–8]. A novel idea which has been suggested is to utilize nanofluid as a working fluid in heat pipes to enhance heat pipes thermal efficiency. During recent years, researchers have concentrated mainly on investigation of nanofluids on heat pipe performance at different working conditions [9–16]. Different types of nanofluids such as water based copper, aluminum oxide and silver nanofluids have been used in the common types of heat pipes primarily include cylindrical heat pipes [17,18], oscillating heat pipes [19,20] thermosyphons [21] and pulsating heat pipes [22] and it has been shown that nanofluids can effectively improve the heat transfer performance of heat pipes. Kang et al. [23] studied the effect of silver nanofluids on thermal performance of a sintered heat pipe experimentally. They investigated the effects of nanoparticles size and concentration on thermal performance of the heat pipe. They found that the wall temperature difference of the heat pipe using nanofluid decreased 0.56–0.65 °C at an input power of 30–50 W. Wang et al. [24] performed experiments to investigate the effect of CuO nanofluids on a cylindrical miniature grooved heat pipe. They found that heat transfer coefficient and maximum heat flux were increased significantly for the heat pipe with nanofluid. Asirvatham et al. [25] carried out an experiment to study the heat transfer performance of a screen mesh heat pipe using silver nanofluids with average nanoparticle diameter of 58 nm. They found that using nanofluid enhanced the heat pipe thermal efficiency. The thermal resistance decreased by 76% for silver nanofluid with volume concentration of 0.009%. Do et al. [26] studied the thermal performance of screen mesh heat pipe using water based Al_2O_3 nanofluids. Based on their experiments, the thermal resistance at the evaporator-adiabatic section decreased by 40% at volume concentration of 3% compared with water. Furthermore, the maximum heat flux with nanofluid was found to be higher than that with water. Effect of inclination angle on the thermal performance of heat pipe with nanofluid has been investigated in some experimental studies as summarized in Table 1.

It can be seen that the inclination angle affects the thermal performance of the heat pipes remarkably. In this study, effect of inclination angle on thermal performance of the heat pipes with silver/water nanofluids at three different mass concentrations of 0.25%, 0.5% and

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Nomenclature

A	area, m
h	heat transfer coefficient, W/m^{2}K
k	thermal conductivity, W/mK
L	length, m
Q	heat input, W
R	thermal resistance, K/W
T	temperature, K

Subscripts

a	adiabatic
c	condenser
deg	degree
e	evaporator
eff	effective
vap	vapor

0.75% is studied experimentally and the results are compared with those of the heat pipe with water. The aim of this study is to evaluate the feasibility of using water based silver nanofluids in inclined heat pipes and assesses its thermal performance.

2. Experimental apparatus and procedure

2.1. Working fluid

Commercial stable Ag nanofluid (NF) with 0.75 wt.% was purchased and nanofluids with 0.5 wt.%, and 0.25 wt.% were prepared by diluting the original suspension. All nanofluids were stable for six months without any visual precipitation. Transmission electron microscopy (TEM) analysis of the Ag nanoparticles (NPs) size and morphology was performed using JEOL 2100 at 200 kV acceleration. Average hydrodynamic particle size distribution of Ag nanoparticles was assessed by Beckmann–Coulter Delsa Nano C system. The thermal conductivity of nanofluids was measured by using TPS 2500 instrument, which works based on transient plane source (TPS) method. The viscosity of Ag nanofluids was evaluated using DV-II + Pro-Brookfield viscometer.

Morphology of Ag nanoparticles was analyzed by TEM and the micrograph is displayed in Fig. 1. As one can see from TEM micrograph Ag nanoparticles have spherical morphology, with estimated average size of 30 nm. It is also important to analyze the size of Ag nanoparticles in the base working fluid media. For this purpose, dynamic light scattering (DLS) analysis was carried out and the result is shown in Fig. 2. Based on DLS the hydrodynamic size for Ag nanoparticles in water media was estimated in the range of 15–650 nm with an average hydrodynamic size of 165 nm. The difference between primary size obtained from TEM and solvodynamic size estimated by DLS may be due to use of surface modifiers in the commercial suspensions. These additives are used to stabilize the Ag nanoparticles in water base working fluid. Thermal conductivity and viscosity of water based silver nanofluids are listed in Table 2. Moreover, the experimental results are compared with Maxwell and Einstein correlations for thermal conductivity and viscosity, respectively. For better understanding of nanoparticle concentration effect on thermal conductivity and viscosity, a wider range of concentration (0–2 wt.%), compared to the range employed in this study (0–0.75 wt.%), is used for nanofluid property evaluation. The results exhibit that the thermal conductivity and viscosity of the nanofluid are dependent on the concentrations of nanoparticles. It is observed that the thermal conductivity of the nanofluid increased by 6.6%, 8% and 9% for the nanoparticle concentrations of 0.5 wt.%, 1 wt.% and 2 wt.%, respectively. Comparing the thermal conductivity results with those of predicted with Maxwell equation, it is found that the model underestimates the thermal conductivity of Ag nanofluid where the differences between the predicted and measured results are 6%, 7% and 8% for the nanoparticle concentrations of 0.5 wt.%, 1 wt.% and 2 wt.%, respectively. According to the results, viscosity of the silver nanofluids increases about 3% for all three concentrations compared to that of the base fluid. Comparing the results with the predicted ones with Einstein Model, about 2% difference between experimental and predicted results is observed, which means that Einstein model is able to predict the viscosity of the Ag nanofluid at very low concentration with good accuracy.

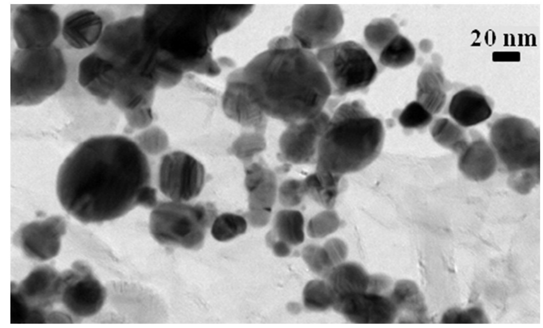

Fig. 1. TEM images of silver nanoparticles.

2.2. Experimental apparatus

The experimental test facilities consist of a cooling system with constant temperature bath, a pump (Gear pump, MCP-Z, Ismatec, Switzerland) and flow meter (Coriolis flow meter, CMFS015, Micromotion, Netherlands), a power supply (DC power supplier, PSI 9080-100, Elektro-Automatik GmbH, Germany), a data acquisition system (Agilent 34970A, Malaysia) and the main test section as shown in Fig. 3. The heat pipe is made of a copper tube with length of 20 cm, diameter of 6.35 mm and wall thickness of 0.71 mm. Each heat pipe has 2 layers of 150 mesh (150 strands per inch or 25 mm). Aperture size and wire diameter of screen mesh are 0.106 mm and 0.063 mm, respectively. For the optimum performance and reliability in terms of charge amount and pressure inside the pipes, all heat pipes were built, evacuated and filled at Thermacore Co. which is one of the heat pipe manufacturers in Europe. The evaporator, adiabatic and condenser sections of the heat pipe were 50 mm, 100 mm and 50 mm long, respectively. At the evaporator section, an electrical cartridge heater provides uniform heat flux to the copper heating blocks attached to the heat pipe. The condenser section was cooled by circulating water in a constant-temperature cooling bath at the temperature and flow rate of 288 K and 51 kg/h, respectively for keeping steady cooling conditions in the condenser section. The

Table 1
Inclination angle effect on heat pipe with nanofluid studied in literature.

Author	Nanofluid	Size and concentration	Observations
Wang et al. [27]	Water/CuO	50 nm & 0.5–2.0 wt.%	The inclination angle of 45° corresponds to the best thermal performance for heat pipes
Hung et al. [15]	Water/Al_2O_3	20 nm & 0.5–3.0 wt.%	The tilt angle that maximizes the thermal performance of the heat pipe ranges from 40° to 70°
Teng et al. [28]	Water/Al_2O_3	20–30 nm & 0.5–3.0 wt.%	The optimal thermal efficiency for heat pipes occurred at 60°
Liu et al. [29]	Water/CuO	50 nm & 0.5–2.0 wt.%	The inclination angle of 45° corresponds to the best thermal performance for heat pipes
Senthilkumar et al. [30]	Water/Cu	40 nm & 100 mg/lit	Best thermal performance is reported at 45°

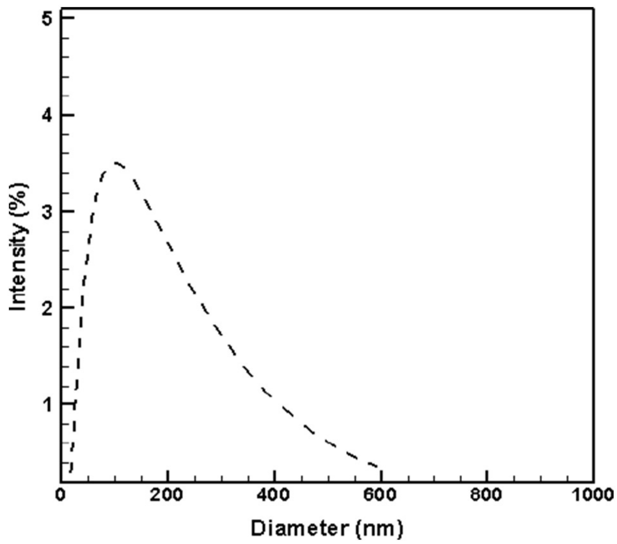

Fig. 2. Hydrodynamic size distribution of Ag NPs in NFs measured by DLS.

temperatures of the heat pipe surface were measured using five K-type thermocouples by mounting two thermocouples at the surface of the evaporator, one at the surface of the adiabatic section and the rest at the surface of the condenser section.

3. Data reduction

The water based Ag nanofluid with mass concentrations of 0.25%, 0.5% and 0.75% was used to investigate the evaporator heat transfer coefficient and thermal resistance of the heat pipe. The temperature drop between evaporator and condenser and consequently the thermal resistance of a heat pipe is of particular interest to evaluate its thermal performance. The overall thermal resistance of the heat pipe is calculated from:

$$R = \frac{T_e - T_c}{Q} \tag{1}$$

where Q, T_e and T_c are heat input, evaporator and condenser wall temperatures, respectively. Also, the evaporator heat transfer coefficient is calculated by:

$$h_e = \frac{Q_e}{A_e \Delta T_e} \tag{2}$$

where the evaporator temperature difference is defined as:

$$\Delta T_e = T_e - T_{vap}. \tag{3}$$

In Eq. (2) Q_e is the heat input to the evaporator section and T_{vap}.is vapor temperature which can be measured from the surface of the adiabatic section [24]. Although, the inner wall surface temperature of the evaporator should be used in the calculation of the evaporator heat transfer coefficients. Since the radial thermal resistance of the heat pipe wall is very low (~10^{-3} °C/W) the measured outer surface temperature can be used instead with good accuracy. Finally, the heat pipe effective thermal conductivity is defined as [31]:

$$K_{eff} = \frac{L_{eff}}{A_c R} \tag{4}$$

where A_c is the total surface area for the heat input in the evaporator section and heat removal in the condenser section of heat pipe and L_{eff} is effective transport length calculated by [31]:

$$L_{eff} = 0.5\, L_e + L_a + 0.5\, L_c. \tag{5}$$

The uncertainties in the measurement of the heat input, thermal resistance, heat flux and heat transfer coefficient are calculated as described in [27], using the Eqs. (6–9) below:

$$\frac{\Delta Q}{Q} = \sqrt{\left(\frac{\Delta V}{V}\right)^2 + \left(\frac{\Delta I}{I}\right)^2} \tag{6}$$

$$\frac{\Delta R}{R} = \sqrt{\left(\frac{\Delta Q}{Q}\right)^2 + \left(\frac{\Delta(\Delta T)}{\Delta T}\right)^2} \tag{7}$$

$$\frac{\Delta q}{q} = \sqrt{\left(\frac{\Delta V}{V}\right)^2 + \left(\frac{\Delta I}{I}\right)^2 + \left(\frac{\Delta A}{A}\right)^2 + \left(\frac{\Delta Q_{loss}}{Q_{loss}}\right)^2} \tag{8}$$

$$\frac{\Delta h}{h} = \sqrt{\left(\frac{\Delta q}{q}\right)^2 + \left(\frac{\Delta(\Delta T)}{\Delta T_{vs}}\right)^2}. \tag{9}$$

The accuracy of the thermocouple was ±0.2 K. The maximum uncertainties of the voltage and the current were both 0.1% while the uncertainty of the heating area was 0.7%. Also, energy balance between heat source and heat sink was measured to calculate the percentage of heat input which removes from the condenser. The uncertainties of the heat loss and wall superheat were found to be less than 5% and 2%, respectively. Therefore, the maximum uncertainties of the heat input, thermal resistance, heat flux and heat transfer coefficient are 2.7%, 4.7%, 5.9% and 7.9%, respectively.

4. Result and discussion

To investigate the thermal performance of inclined heat pipes using nanofluids, four different screen mesh heat pipes containing distilled water as a reference and three water based silver nanofluids at mass concentrations of 0.25%, 0.5% and 0.75% were tested. The heat input was increased consecutively and the heat pipe wall surface temperatures were measured and recorded at steady conditions, approximately after 20 min. Fig. 4 shows the thermal resistance of the heat pipes using water and Ag nanofluids at both vertical and horizontal states. At all inclined states the condenser of the heat pipe is located at higher level than evaporator. As can be seen, the thermal resistance of the heat pipes decreases with increasing nanoparticles mass concentration at both states. Also, it is apparent that the thermal resistance of the heat pipes is lower at vertical state compared with horizontal one. The average thermal resistance decreased by 3%, 10% and 19% at mass concentrations of 0.25%, 0.5% and 0.75%, respectively compared with water for horizontal heat pipes. For vertical heat pipes the reduction in average thermal resistance is found to be 4%, 11% and 20% at mass concentrations of 0.25%, 0.5% and 0.75%, respectively. These results reveal that the thermal performance of the heat pipe can be effectively improved utilizing Ag nanofluids instead of water.

The reasons of such enhancement in thermal performance of the heat pipes are due to the working fluids, the heat transfer surface and

Table 2
Thermal conductivity and viscosity of water based silver nanofluid (293 K).

Concentration	Thermal conductivity (W/m K)		Viscosity (Pa s)	
	Exp.	Maxwell	Exp.	Einstein
Basefluid	0.598	–	1.003×10^{-3}	–
0.5 wt.%	0.638	0.5988	1.0318×10^{-3}	1.0042×10^{-3}
1 wt.%	0.645	0.5997	1.0321×10^{-3}	1.0054×10^{-3}
2 wt.%	0.652	0.6014	1.0325×10^{-3}	1.0078×10^{-3}

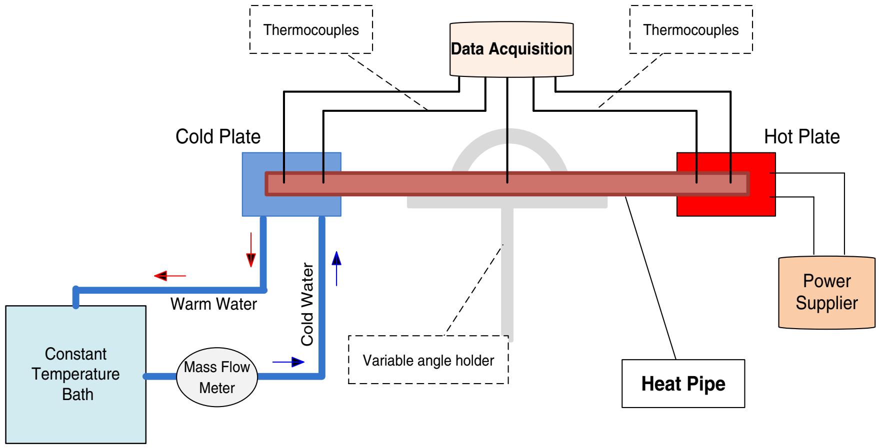

Fig. 3. Schematic diagram of the experimental setup.

the system properties [32,33]. Thermal conductivity and surface tension as the working fluid properties, wettability and surface roughness as the heat transfer surface properties and finally system pressure, orientation and the fluid surface interaction as the system properties can affect the thermal behavior of the heat pipes significantly. Using nanofluid instead of water can increase the effective thermal conductivity and decrease the solid–liquid contact angle which increases the capillary force and makes the liquid extend in the wick. Moreover, it is observed in nearly every study that a complex nano/micro porous layer of the nanoparticles forms on the surface of the wick. Such porous layers can alter the surface wettability and roughness and also increase the heat transfer area on the surface [33–40] which shows the important role of this layer on heat transfer capability of the heat pipe. Fig. 5 shows the SEM image of the wick surface for the heat pipe with Ag nanofluid. The heated surface characteristic depends on the nature of the wick after the micro/nano porous layer formation. A normal spread of nanoparticles on the porous layer results in increasing the wettability and capillary force [32]. This layer makes the rewetting process much easier which helps the working fluid to return back to the evaporator at higher rate. Hence, it is found that substituting the Ag nanofluids for water as the working fluid improves the thermal performance of the heat pipe significantly.

The inclination angle influences the heat transfer performance of the heat pipes. Fig. 6 shows the impact of heat pipe orientation on evaporator heat transfer coefficients. The relative heat transfer coefficient is the ratio of evaporator heat transfer coefficient of inclined heat pipes to that of the horizontal one and the results belong to the heat pipe with 0.75 wt.% of Ag nanofluid. Experimental results indicate that the increase of tilt angle can enhance evaporator heat transfer coefficient. This may be due to the gravity assists in returning the condensed liquid to the evaporator which increases the amount of working fluid in the evaporator and consequently reduces the capillary limit and enhances the evaporation rate and speed up the two phase heat transfer circulation. Another finding from this figure is that the relative evaporator heat transfer coefficient has weak relation to the heat flux, but strongly depends on the inclination angle. The average enhancement in evaporator heat transfer coefficients of inclined heat pipes compared with the horizontal one are 18%, 22% and 10% for 30°, 60° and 90°, respectively, which shows the effect of inclination angle on evaporation heat transfer for the screen mesh heat pipe using Ag nanofluids. Considering the effect of gravitational force between evaporator and condenser sections, it is expected to have the best thermal performance at vertical heat pipes because of increasing the speed of backflow to evaporator section, but, it is found that the inclination angle of 60° corresponded to the best thermal performance. These results are in agreement with the results in literature in which it is reported that the best thermal performances are attained at the inclination angle of 45–60° as summarized in Table 1.

The inclination angle corresponding to the best thermal performance can be clearly seen in Fig. 7. This figure shows the ratio of the thermal resistance of inclined heat pipes with nanofluids to that of the

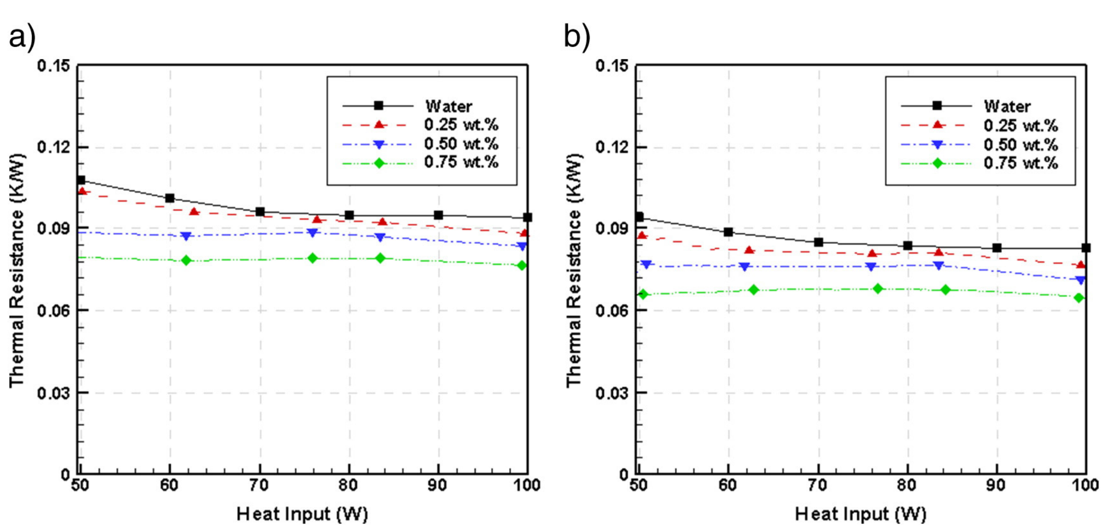

Fig. 4. Thermal resistance of the heat pipes at (a) horizontal and (b) vertical states.

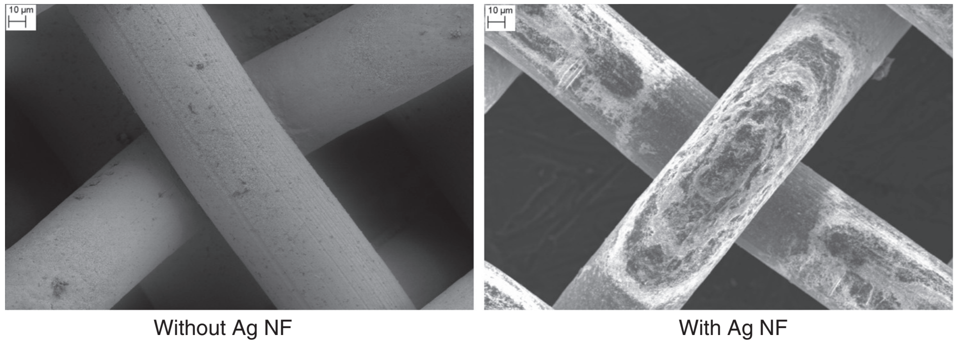

Fig. 5. SEM images of the wick surface for the heat pipes with and without Ag NF.

horizontal heat pipe with base fluid. Experimental results reveal that the thermal resistance of the heat pipe decreases with increasing the nanoparticle concentration in all inclination angles. In addition to nanoparticle concentration effect, results show that inclination angle has a positive effect of heat pipe performance compared with horizontal state and at each concentration the lowest thermal resistance belongs to the inclination angle of 60°.

Based on the results, the relative thermal resistance decreases with increasing the inclination angle up to 60°, but, beyond 60°, increasing the inclination angle increases the relative thermal resistance gradually. This thermal behavior is mainly because of the gravitational force effects on the speed of backflow to evaporator section and the heat exchange time at condenser section as well. Increasing the inclination angle makes the condensed liquid flow back to the evaporator at higher speed. It means that gravity effect helps the capillary action of the wick to circulate the working fluid. Besides this positive effect of the gravity, increasing the backflow speed decreases the heat exchange time at condenser which reduces the heat dissipation efficiency with the heat sink at condenser section and consequently increases the wall temperatures. Hence, the complexity in formation of the liquid film with uneven thickness and its effect on the gas–liquid interface in addition to the positive effect of the gravity in returning the condensate fluid to the evaporator rapidly and negative effect of heat exchange time reduction cause the heat transfer characteristic reach its best at a certain inclination angle, which is 60° in this study.

The effects of the inclination angle and nanoparticle concentration on the maximum heat flux (MHF) are illustrated in Fig. 8. The relative maximum heat flux which is defined as the ratio of MHF of nanofluid to that of the basefluid increases with increasing the nanoparticle concentration, but, has a weak relation to the inclination angle. About 18%–32% enhancement in MHF is observed which shows nanofluid's great potential to increase heat transfer capability of heat pipes. The reason may be explained by the changes of evaporator surface characteristics by forming a porous layer and improvement of nanofluid's thermophysical properties with temperature.

The effective thermal conductivity of the heat pipes as a function of nanoparticle concentration of Ag nanofluids and tilt angles is shown in Fig. 9. It is shown that an inclination angle of 60° achieved the highest effective thermal conductivity while all the heat pipes with inclination angles higher than 0° have higher effective thermal conductivity compared with the horizontal pipe. The average enhancement in effective thermal conductivity for the inclined heat pipes compared with the horizontal one is found to be 7.5%, 11% and 4% for 30°, 60° and 90°, respectively. It shows the effect of gravity on heat pipe performance improvement.

Finally, the experimental results are compared with the empirical relation proposed by Mousa [41]. This correlation is proposed for the percentage reduction of heat pipe thermal resistance with nanofluid compared with water.

$$RR = 0.84\phi - 0.3\phi^2 \quad (10)$$

where RR and ϕ are the percentage reduction of the thermal resistance and volume concentration of nanoparticles. The nanoparticle volume

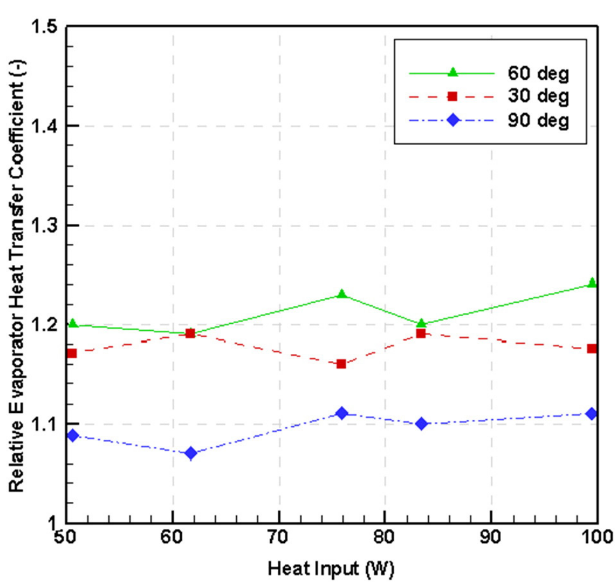

Fig. 6. The ratio of evaporator heat transfer coefficient of inclined heat pipes to that of the horizontal one for heat pipe with 0.75 wt.% Ag NF.

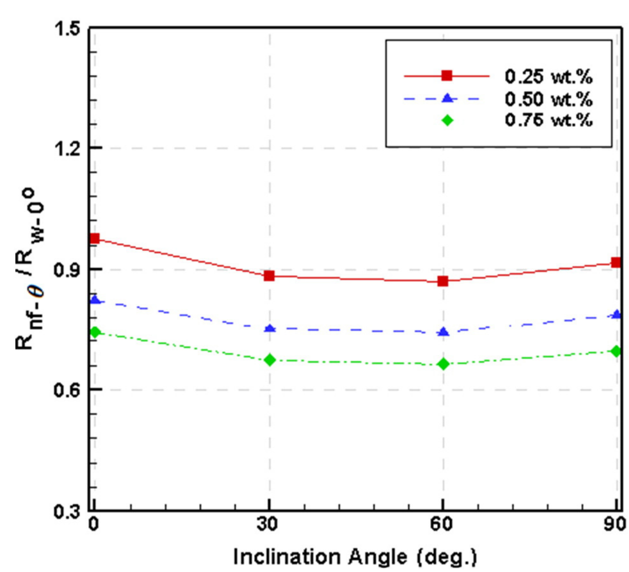

Fig. 7. The ratio between thermal resistance of inclined heat pipes with Ag NFs and that of the horizontal heat pipes with base fluid (50 W).

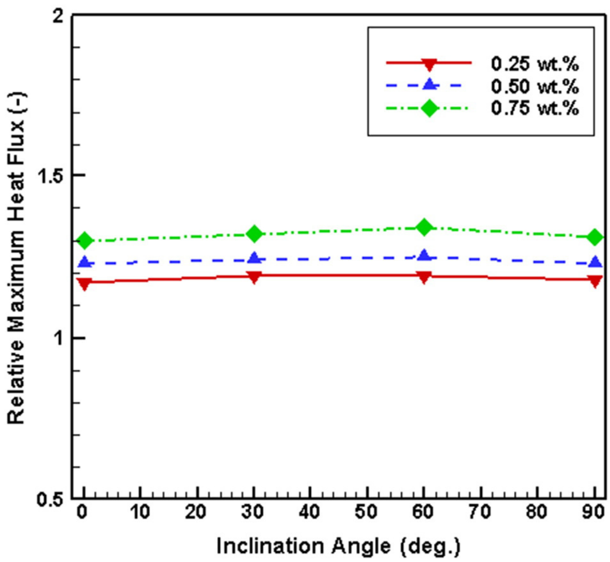

Fig. 8. Relative maximum heat flux of heat pipes with Ag NFs.

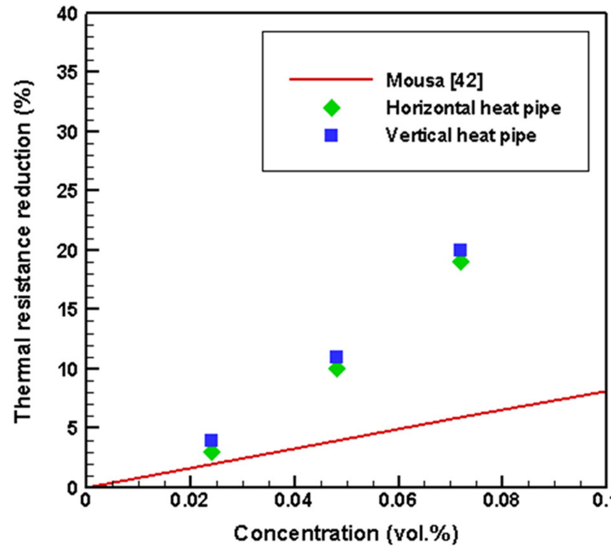

Fig. 10. Comparison between empirical relation [41] and experimental thermal resistance reduction of heat pipes as a function of NP concentration of Ag NFs.

fraction, ϕ, is calculated based on the weight concentration using the equation below [18]:

$$\%\ \text{volume fraction} = \frac{\frac{W_{np}}{\rho_{np}}}{\frac{W_{np}}{\rho_{np}} + \frac{W_{bf}}{\rho_{bf}}} \tag{11}$$

where W_{np}, ρ_{np}, W_{bf} and ρ_{bf}, are weight of nanoparticles, density of nanoparticles, weight of base fluid and density of base fluid respectively. Fig. 10 shows the thermal resistance reduction of heat pipes with Ag nanofluid compared with water. Results revealed that the empirical relation (Eq. 10) underestimates the thermal resistance reduction of heat pipes. The relative error of the empirical relation proposed by Mousa [41] is 12% according to its originator, but, the difference between experimental result and the predicted one is found to be more than 50%.

5. Conclusion

An experimental study was performed to find the effect of nanofluids on the performance of inclined screen mesh heat pipe. For this purpose, water based Ag nanofluids at three different mass concentrations of 0.25%, 0.5% and 0.75% were chosen as working fluids for heat pipes and the results were compared with heat pipe using water as the reference. Experimental results revealed that Ag nanofluids have an influence on heat pipe thermal performance and the thermal resistance of the heat pipes with nanofluid is lower than that of the heat pipe with water. Also, it is found that the thermal resistance of the heat pipes decreases with increasing the nanoparticle concentration at all inclination angles. In addition, it is observed that inclined heat pipes have lower thermal resistance than the vertical one due to gravitational force effects. Moreover, under different inclination angles of 0°, 30°, 60° and 90°, results indicate that the lowest thermal resistance belongs to the inclination angle of 60° in all concentrations. At this inclination angle, 60°, the average effective thermal conductivity of the heat pipe increases about 11% compared with the horizontal heat pipe.

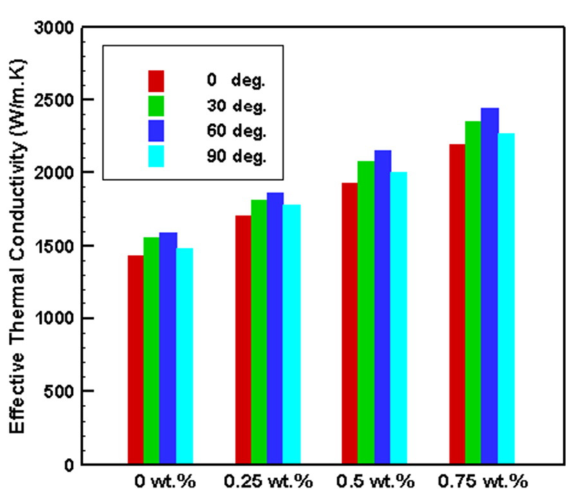

Fig. 9. Effective thermal conductivity of the heat pipes with Ag NFs as a function of inclination angles.

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