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EXPERIMENTAL STUDIES OF METAL OXIDE SUSPENDED NANOFLUIDS ON THE ENHANCEMENT OF THE THERMAL PERFORMANCE OF HEAT PIPES

Summary

Heat transmission by means of heat pipes is one of the fastest and most efficient thermal management technologies. The performance of typical thermal systems that use heat transfer fluid (HTF) can be improved by incorporating nanoparticles into the HTF (nanofluid). This work describes an experimental examination of metal oxide suspended nano-sized particles such as zinc oxide (ZnO) and copper oxide (CuO) in deionized water as the base fluid (DI water). The nanoparticle levels used for this investigation are 0%, 1%, 2% and 3% by weight. Experiments were carried out at all levels of nanofluids with heat pipe inclinations ranging from horizontal to vertical. The rheological measurements of the two nanofluids under a wide range of temperatures and shear rate were studied. The thermal performance of a heat pipe with water-based nanofluids is expected to improve more than that of a normal heat pipe. The thermal efficiency of a heat pipe using nanofluids was examined at various tilt angles. The results show that a heat pipe at a tilt angle of 60° generates superior effects. Temperature distribution along the length of the heat pipe under different power input conditions was presented using varied weight proportions of nanofluids (ZnO & CuO).

Key words: *heat pipe, thermal, nanofluids*

1. Introduction

Generally, heat pipes are known as double-phase heat communication systems with significantly better operational thermal conductivity than solid materials like metals. For a variety of reasons, heat pipes are commonly employed in many energy transfer systems, including fuel cells, desalination systems, solar collectors, and water heaters [1-4]. The working fluid, flow regime, geometry, angle of inclination, filling ratio, and other influencing elements of any heat pipe, in general, affect its thermal functioning. An appropriate working fluid is necessary for the functioning of a heat pipe, depending on the purposes and temperature ranges. One of the most recent methods for enhancing heat transfer in a heat pipe is the use of nanofluids. According to studies, adding nanoparticles to fluids can improve their thermo-physical characteristics [5-6]. The augmentation of ordinary fluids such as water, organic fluids, oils, and phase change materials (PCM) by dispersing nanoparticles has attracted much interest in recent years [7-9]. Nanofluids (NFs) are suspensions of metal or metal oxide particles or fibres with average diameters ranging from 1–100 nm. Most well-known nanoparticles (NPs) are manufactured using a range of processes such as chemical vapour deposition, inert gas condensation, spray-drying, and rapid expansion in supersonic nozzles, such as Al_2O_3, CuO, Au, Ag, TiO_2, and ZnO. These nanoparticles may be introduced to aqueous or alcohol base-fluids to obtain nanofluids [10-13]. CuO nanoparticles were chosen as the fuel additive due to their superior physical and chemical characteristics, such as thermal heat conductivity, high heat capacity, low thermal expansion, and high melting temperature when compared to other nanoparticles [14].

The convection heat transfer coefficient of graphene oxide-distilled water nanofluid along a circular copper tube indicates the mean enhancement of the convection heat transfer coefficient was 29% at a flow rate of 1.5 l/ min with 5073.244 W/m^2 heat flux for the nanofluid with 0.01 vol % GO concentration [15]. In general, the key influencing features of any heat pipe, such as the working fluid, flow regime, geometry, angle of inclination, filling ratio, and so on, govern its thermal functioning. Depending on the purposes and temperature ranges, an appropriate working fluid is required for the operation of a heat pipe. Nanofluids are one of the most recent methods for improving heat transmission in a heat pipe. According to research, the addition of nanoparticles can improve the thermophysical properties of fluids [16]. The use of graphene-based nanofluid improved the cooling performance of vehicle radiators and demonstrated that smaller parts can remove heat from the system at the same rates. The heat transfer coefficient values increased as a result of the use of graphene-based nanofluid. [17]. In terms of fluid characteristics, the merit number is a helpful indication for estimating the maximal heat transmission capability. Chaudhry et al. [18] examined and calculated the merit number, M, values for five different working fluids at temperatures ranging from 293 K to 393 K: water, acetone, ammonia, heptane, and pentane. Water displayed the highest merit number among all the working fluids. Some of the studies reported on the inclination of the heat pipe as follows. The copper heat pipe was found to be effective with acetone as a working fluid and the optimum inclination angle of the heat pipe for a maximum rate of heat transfer was found to be 60° [19]. The thermal performance of the heat pipe increases with an increase in the inclination angle from 0° to 60°, and then the thermal performance decreases at a 90° inclination angle. The lowest temperature difference between the evaporator and condenser occurred when the inclination angle increased from 50° to 70° [20]. Optimum values are obtained at a 111.6 W power input, 55% filling ratio, 1.1% nanofluid concentration, and 58.5° inclination angle. The thermal performance of a heat pipe using CuO/ H2O nanofluids as a working fluid is higher than that of the base fluid [21]. The capillary, boiling, working fluid, viscosity limits, and geometry are some of the physical phenomena that limit the performance and ability of heat pipes to transmit heat. To overcome the aforementioned constraints and improve the thermal performance of heat pipes, special attention should be paid to the design of the heat pipe and the selection of the working fluid. This gap in research provides a framework for framing the goals of the present project. The primary goal is to look at the ability of nanofluids to improve the thermal performance of heat pipes. In addition, variations of the inclination angles of heat pipes under different conditions are covered in this work. In this connection, deionized water (DI water) was used as the base fluid for the experimental investigation of metal oxide suspended nanoparticles, such as zinc oxide (ZnO) and copper oxide (CuO). The thermal performances of ZnO and CuO nanofluids were also investigated in comparison to DI water. The influence of the tilt angle on the thermal efficiency of the heat pipe and the distribution of the temperature along the length of the heat pipe under different power input conditions were studied. The novelty of this work is the inclination provided to the conventional heat pipe system. The inclination angle affects the heat transfer characteristics of the heat pipe using water and nanofluids.

2. Experimental Procedure

2.1 Methodology

The approach flowchart for the experiment is depicted in Figure 1. This step includes the selection of nanofluids, the preparation of nanofluids, and characterizations.

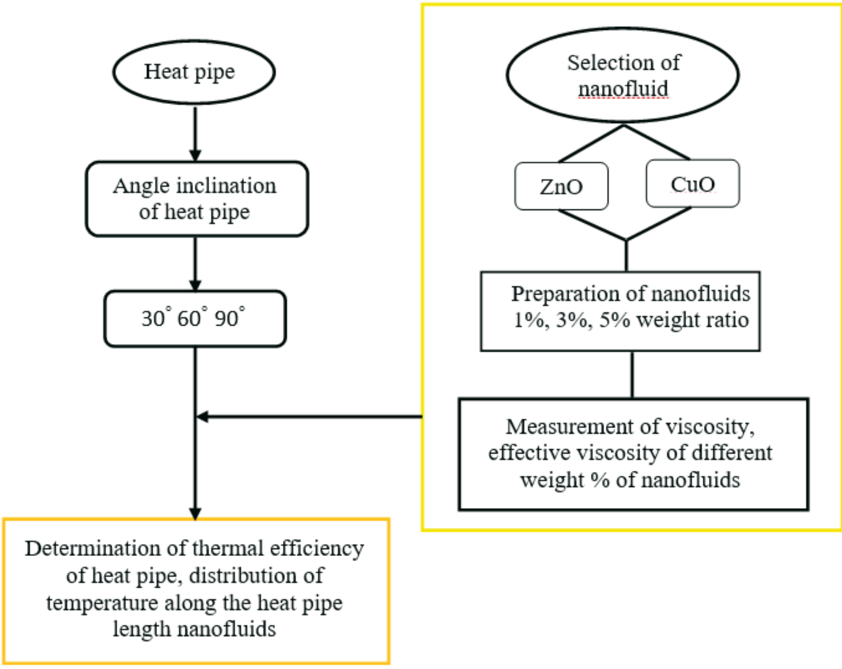

Fig. 1 Flowchart of the experimental methodology

2.2 Nanofluid Preparation

The first critical stage in creating fluids with increased thermal conductivity is the creation of nanofluids. The nanoparticles used in this study, ZnO and CuO, were obtained from the Quantum Materials Corporation in Bangalore, India. The two-step process is the most commonly used method for manufacturing nanofluids, as seen in Figure 2. The detailed description of the nanoparticles produced by the supplier are given below.

Table 1 Properties of nanoparticles

Properties	Zinc Oxide	Copper Oxide
Molecular formula	ZnO	CuO
Nanoparticle shape	Spherical	Spherical
Average size	90 nm	50 nm
Density	5.6 g/cm^3	6.5 g/cm^3
Appearance	White	Black
Purity	>87%	>90%
Thermal conductivity	42 W/(m K)	32 W/(m K)

The dry nanoparticles CuO are measured on a digital weighing scale. The prescribed quantities taken for this work are 1%, 2% and 3 wt %. The dried nanoparticles are then allowed to dissolve in DI water, although the strong particle contact force may cause a collision and aggregation of nanoparticles. The agglomeration of nanoparticles is the main challenge. To avoid such events, mechanical stirring is conducted while the nanoparticles are suspended and then the liquid is ultrasonically mixed for four hours to ensure thorough mixing and to avoid agglomeration. The same technique is followed for the manufacture of ZnO nanofluid.

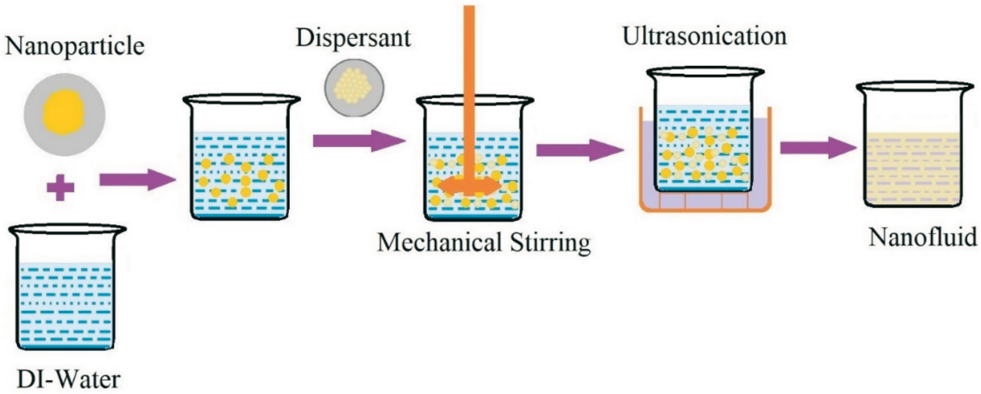

Fig. 2 Procedure for the preparation of nanofluid

2.3 Heat Pipe – Experimental Procedure

The heat pipe is separated into three sections: an evaporator, an adiabatic component, and a condenser. More testing was conducted at varying heat input sources and three distinct tilt degrees. Figure 3 depicts the heat pipe with a tilt angle.

The heat pipes used in this investigation were manufactured from copper of a length of 500 mm, and a wick made up of sintered copper wick of 3.5 mm thickness. The outer pipe diameter and pipe wall thickness are 33.0 mm and 7.0 mm respectively. The heat pipe is filled with the working fluid, and the electric source with an adjustable power input gives the heat input to the evaporator section of the heat pipe. The heat then covers the working fluid and converts the phase of the fluid from liquid to vapour. The evaporator section is equipped with two K-type thermocouples on the centreline and two more thermocouples on the outer surface of the heat pipe. The working fluid receives heat from the heat source through the evaporator section and the phase change of the working fluid occurs. The heat then flows to the condenser section through the adiabatic section and is rejected to the sink. The condenser section is also equipped with two K-type thermocouples on the centreline and two more thermocouples on the outer surface of the heat pipe. The system's cooling capacity was established by measuring the coolant's intake and exit temperatures, as well as its flow rate, with thermocouples put directly into each liquid stream. The K-type thermocouples were used as standard sensor probes for heat pipe performance monitoring and were mounted (numbered as shown in Fig. 3) to the outer and inner surfaces of the evaporator, adiabatic, and condenser sections, and the temperatures of the heat pipe wall surface were monitored. The sensitivity analysis described by Kline et al. [22] and Taylor [23] can be used to evaluate the uncertainty. If N number of trials are conducted for the measurement of temperatures, then the uncertainty in the measurements can be calculated by using the following equations. Standard deviation of the mean is calculated as

$$s = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(T - T\text{avg}\right)}\ . \tag{1}$$

From the obtained standard deviation (S), the standard uncertainty of type A can be determined as

$$u\left(x_i\right) = \frac{s}{\sqrt{N}}\ . \tag{2}$$

Then, the extended measurement uncertainty (U) can be calculated as

$$U = k \cdot u\left(x_i\right), \tag{3}$$

where the value of k is usually 2, which corresponds to a level of statistical uncertainty of 95.44%. Thus, the uncertainties for the measurement of temperature and heat input are determined as ± 0.45°C and ± 10 W, respectively.

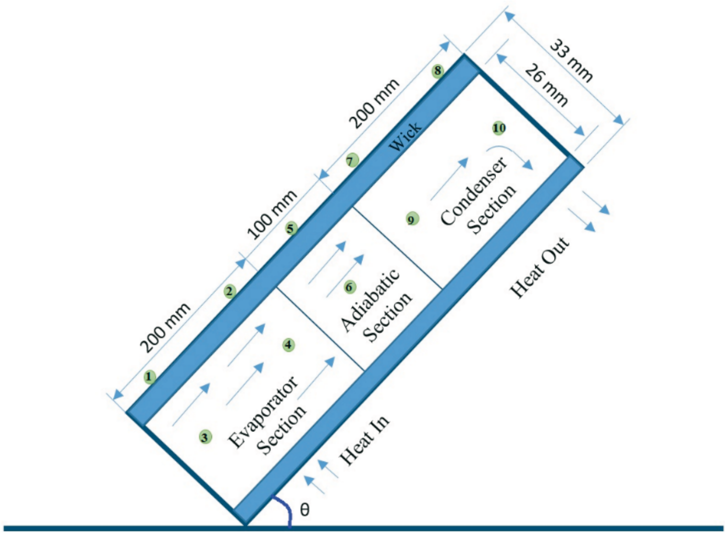

Fig. 3 Position of heat pipe with tilt angle

2.4 Characterization

Rheological measurements of nano-fluids were obtained using a stress-controlled hybrid rotational rheometer (ARES-G2) with a concentric cylinder of 30 mm in diameter. The experiment was carried out using a 5.485 mm distance between the bob and the cylinder. During the test, a twelve-channel temperature recorder (BTM-4208SD) with a 0.5 °C uncertainty was employed to record the temperature during transient and steady state operation. The uncertainty analysis is obtained by calculating errors in the data measurements. Some major factors that can cause errors in temperature measurement may include environmental conditions, sensor calibration and accuracy, lead wire, emissivity, radiation, electrical composition and conduction. The errors in temperature were calculated as ± 0.25 °C. The thermal performance of the THP was presented using data acquired from thermocouples positioned in the evaporator and condenser. The evaporator temperature and condenser temperature may be estimated by taking the average of four distinct temperatures recorded, by their respective thermocouples. The following equation Eq. (4) gives the thermal efficiency.

$$\eta_{thermal} = \frac{\text{Heat removed by the condenser}}{\text{Heat input to the evaporator}} = \frac{\boldsymbol{Q_r}}{\boldsymbol{Q_i}} \tag{4}$$

Heat transfer/removed $Q_r = mc_\mathrm{p}\Delta T$ W

Heat input $Q_i = V \cdot I$ W

Heat pipe thermal performance was studied at three distinct angles (30°, 60°, and 90°).

3. Results and Discussion

The temperature reliant on the viscosity of the nanofluids was discovered within the range of temperature 20-60 °C permitted to anticipate the fluid properties of these nanofluids throughout the working temperature of the heat pipe. At identical temperature measurement settings, Figure 4 compares the viscosity of the two nanofluids with the viscosity of the base fluids. Both results indicate that the temperature dependency of viscosity is more prominent at 3 wt. % of loading. The particle-particle interaction of nanofluids may lead to an increase in viscosity, which is more noticeable at lower temperatures and diminishes as the temperature rises. Similar results were interpreted by Purna et al. [24].

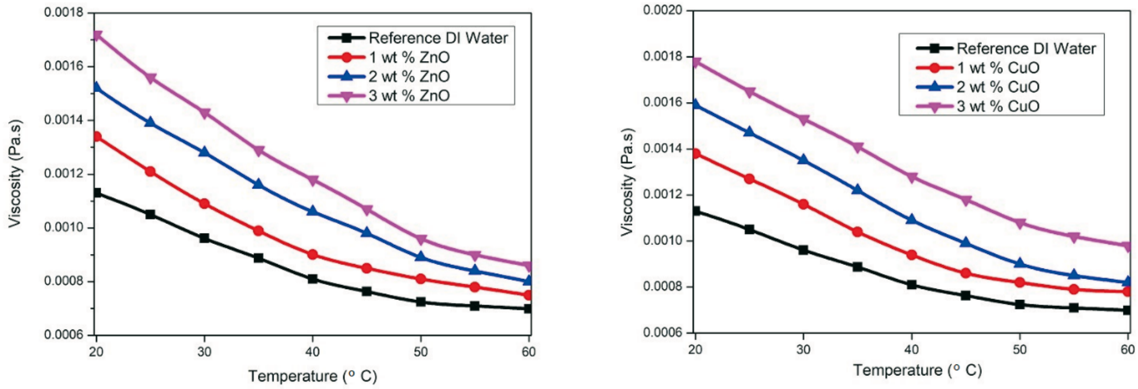

Fig. 4 Viscosity of nanofluids vs. temperature measurement

Figure 5 depicts the rheological measurement of nanofluids against a wide range of shear rate from 0.1 to 1000 s^{-1}. With an increasing shear rate, the particle-particle interactions of the nanofluids weaken and even break down, resulting in Newtonian behaviour, as reported in Mohammed Zayan et al. [25]. At all loading levels, both nanofluids exhibited Newtonian behaviour within the given range of the shear rate.

The heat pipe's thermal efficiency is assessed based on the experiments conducted, and a graph is generated for the various tilt angles under the conditions of 100 W heat input which is presented in Figure 6. The thermal conductivity of nanofluids rises as the weight concentrations increase. Thermal efficiency grows as the angle of tilt rises from 0 to 60°, and then declines after 60°, as correlated with Senthilkumar et al. [26].

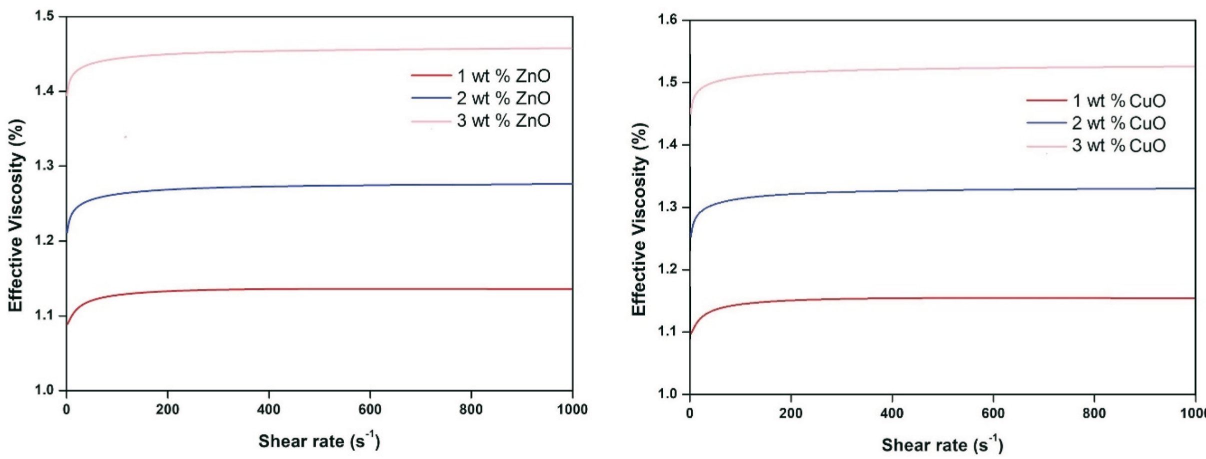

Fig. 5 Effective viscosity of nanofluids vs. shear rate

The gravitational force between the evaporator and condenser sections increases from 0 to 60°, raising the working medium temperature and allowing additional heat to be extracted in the condenser portion. When a heat pipe's angle of inclination exceeds 60°, its thermal efficiency begins to drop. The creation of a liquid layer inside the condenser increases thermal resistance, and because gravity is inefficient, all the motion of bubbles and slugs must be done by pressure forces. Similar observations were found by Himel Barua et al. [27].

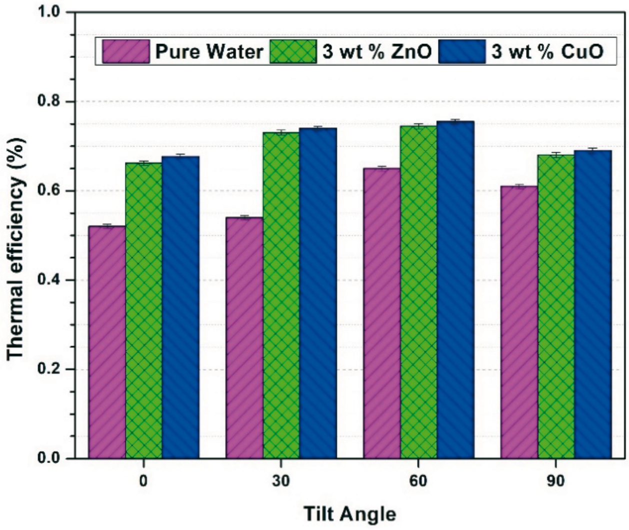

Fig. 6 Thermal efficiency of the heat pipe with nanofluids with respect to various positions of the heat pipe

When comparing nanofluids with Zno and CuO nanoparticles, the CuO nanofluids have higher thermal efficiency, which could be due to the presence of copper nanoparticles in the copper nanofluid having a significant influence on improving heat transfer owing to its high heat capability and the greater thermal conductivity of the working fluid. These findings are in good agreement with Lin-Qiu et al. [28].

The experimental trials were carried out using multiple identical heat pipes filled with DI water, ZnO, and CuO nanofluids at 1%, 2%, and 3% concentrations, respectively. The heat pipe's power input was progressively increased to the required power level. The surface wall temperatures of all sections of the heat pipe were measured using thermocouples at five distinct points, and the average value was used.

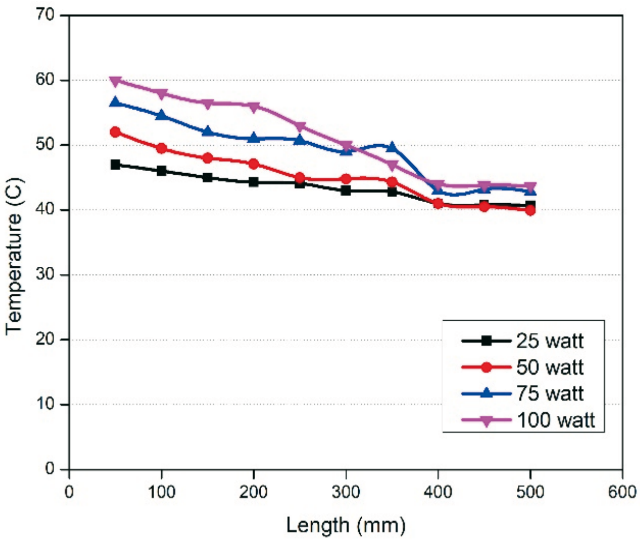

Fig. 7 Temperature distribution along the length of the heat pipe using DI water as a working fluid

Figures 8 and 9 show the distribution of wall temperature vs length of heat pipe for varied power inputs and operating fluids. The heat pipe's performance and capacity for heat transmission are influenced by the outer surface temperatures, which may be increased by careful selection of the working fluid, heat pipe design, and slope angle. As observed in both figures, increasing the power input causes a rise in the wall temperature. Temperature differences between the evaporator and condenser portions grow continuously as the rate of heat input increases. For the power input of 100 W, the temperature difference between the evaporator and condenser section is observed as 16.3 °C, 14 °C, 11.1 °C and 8 °C for the heat pipe charged with DI water, 1% ZnO, 2% ZnO and 3% ZnO, respectively. In other words, the percentage decrease in temperature between the evaporator and condenser section is observed as 27.4%, 20.5%, 16.4% and 11.3% for the heat pipe charged with DI water, 1% ZnO, 2% ZnO and 3% ZnO, respectively. Furthermore, for the heat pipe charged with DI water, 1% CuO, 2% CuO, and 3% CuO, the temperature differential between the evaporator and condenser section is 16.3 °C, 13 °C, 10 °C and 6.3 °C, respectively. In other words, the percentage decrease in temperature between the evaporator and condenser section is observed as 27.4%, 18.8%, 14.3% and 8.8% for the heat pipe charged with DI water, 1% CuO, 2% CuO and 3% CuO, respectively.

Table 2 Percentage decrease of temperature in comparison with DI water

Wt.% of working fluid	Temperature difference between evaporator and condenser (°C)				Percentage decrease in comparison with DI water (%)			
1%	ZnO	14	CuO	20.5	ZnO	20.5	CuO	18.8
2%	ZnO	11.1	CuO	16.4	ZnO	16.4	CuO	14.3
3%	ZnO	8	CuO	11.3	ZnO	11.3	CuO	8.8

When the performance of two nanoparticles, ZnO and CuO, was evaluated, CuO demonstrated the highest reduction in the overall temperature difference between the evaporator and condenser under the same power input conditions. Similar results were reported by Nandhakumar et al. [29].

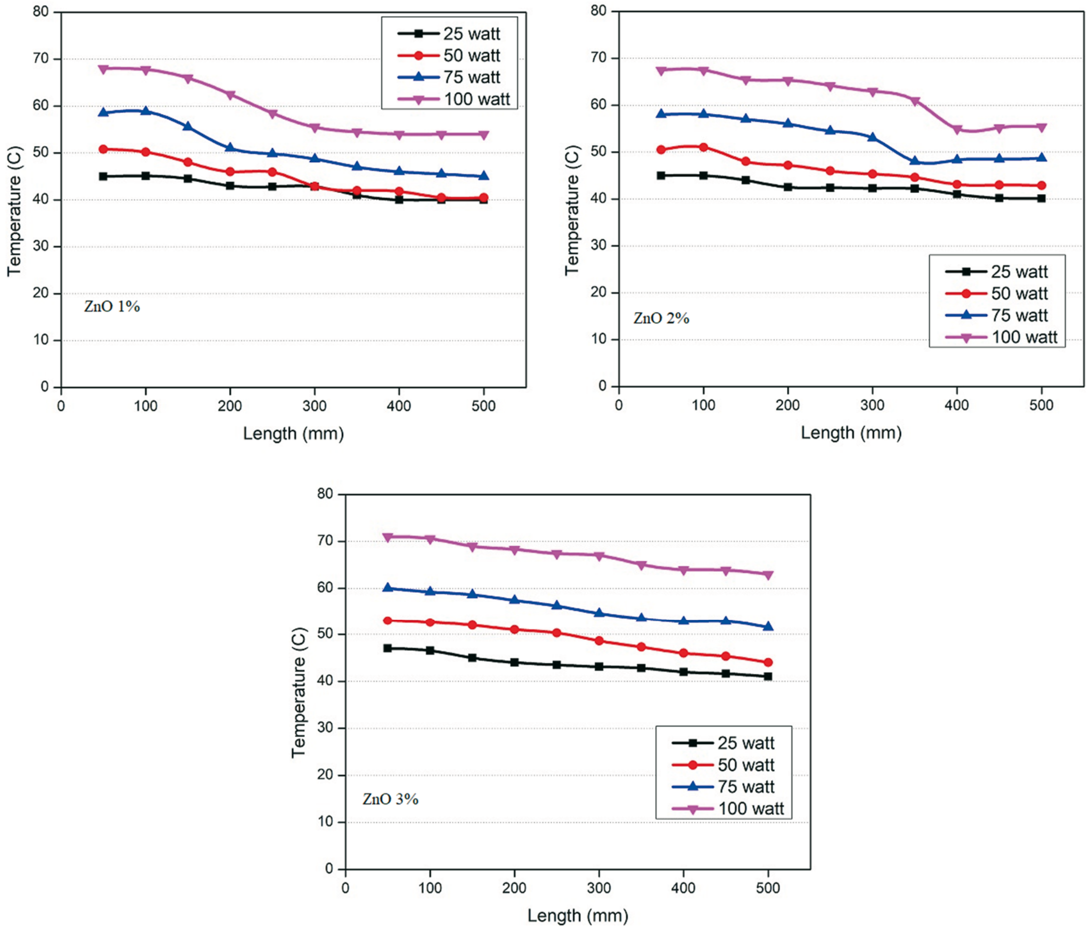

Fig. 8 Temperature distribution along the length of the heat pipe using 1%, 2% and 3% ZnO nanofluid as the working fluid

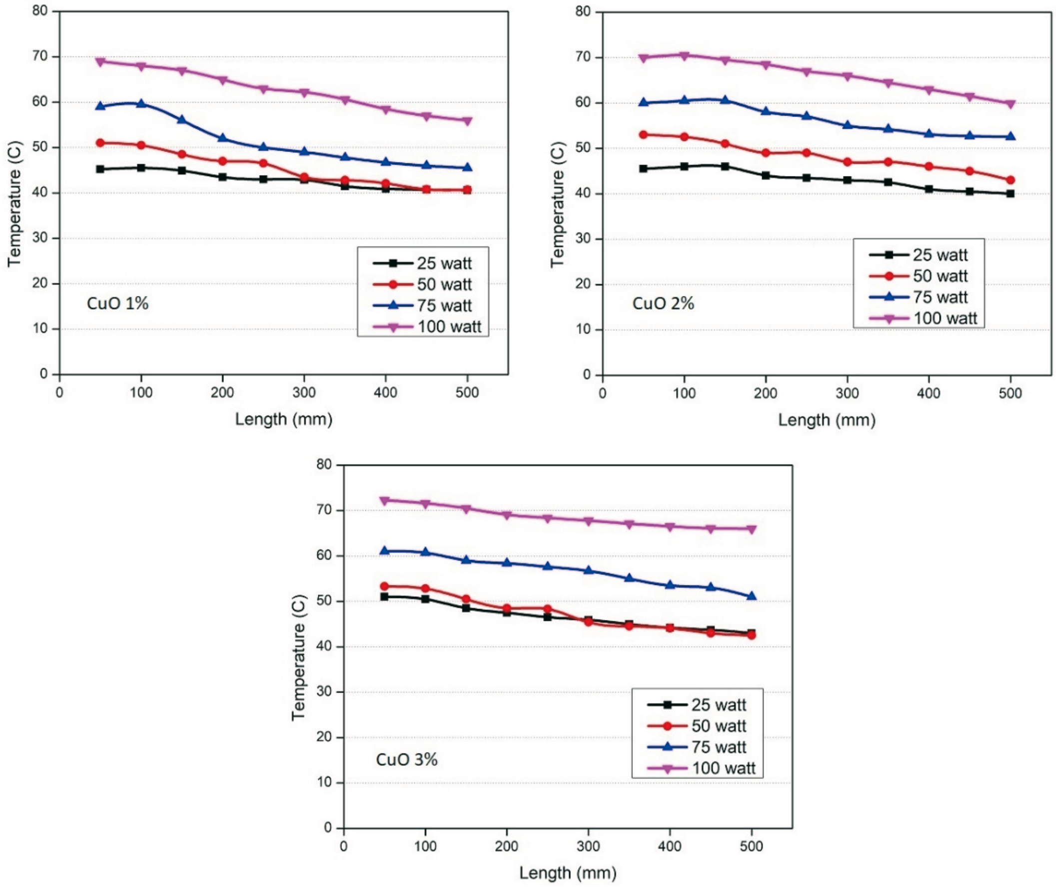

Fig. 9 Temperature distribution along the length of heat pipe using 1%, 2%, and 3% CuO nanofluid as the working fluid

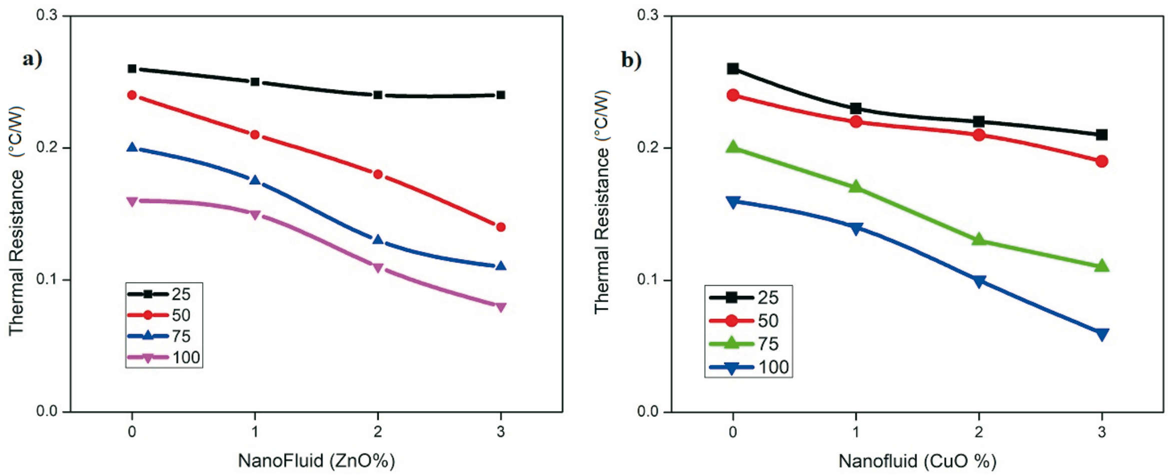

Fig. 10 Variation in the thermal resistance of DI water with 1%, 2%, and 3 wt. % ZnO and CuO nanofluid

Figure 10 shows the variation in the thermal resistance of DI water with 1%, 2%, and 3 wt. % ZnO and CuO nanofluid. Thermal resistance was found to decrease with the increase of the weight proportions of nanofluids. In addition, the thermal resistance for both the nanofluids, at all weight percentages, was also found to decrease as the power input increases. A similar observation was found by Sidhartha et al. [30]. The decrease in thermal resistance of ZnO nanofluid was found to be 6.25%, 31.25% and 50% for 1% ZnO, 2% ZnO, and 3% ZnO, respectively, compared to the DI water under the conditions of 100 W power input. Similarly, the decrease in thermal resistance of CuO nanofluid was found to be 12.5%, 37.5% and 62.5%

for 1% CuO, 2% CuO, and 3% CuO, respectively, compared to the DI water under the conditions of 100 W power input. In other words, the thermal conductivity of the nanofluid increases with the increase in its weight proportions. This may be due to the motion of the remained nano particles which would cause convection and enhance the energy transport in the nanofluids. Furthermore, Brownian motion causes microconvection in the liquid molecules around it, enhancing heat conductivity. An increase in Brownian motion, the creation of a nanolayer on the particles, and convection from the particle motion are assumed to be the causes of the rise in thermal conductivity.

4. Conclusions

The influence of various concentrations of nanoparticles on the thermal performance of heat pipes was investigated using two types of nanofluids, including DI water/ZnO and DI water/CuO nanofluids at varying nanoparticle concentrations. It is concluded that the temperature dependency of viscosity is more prominent at 3 wt. % loading. The thermal conductivity of nanofluids rises as the weight concentrations increase. When compared to the ZnO and CuO nanoparticles, the CuO nanofluids had better thermal efficiency. Thermal performance could be enhanced by increasing the volume concentration of the nanofluid, increasing the Brownian motion of the nano particles, the surface modification of the nanoparticles, and the ultrasonication of the nano particles in the working fluid.

The influence of inclination angles on the heat pipe thermal performance was investigated using water/ZnO and water/CuO nanofluids. The heat pipes performed best with the lowest thermal resistance at an inclination angle of 60°. The distribution of temperature over the prescribed length of the heat pipe was analysed using their respective plots for varied weight proportions of nanofluids (ZnO & CuO). The percentage decrease in temperature between the evaporator and the condenser section was observed as 27.4%, 18.8%, 14.3% and 8.8% for the heat pipe charged with DI water, 1% CuO, 2% CuO and 3 % CuO, respectively. It is possible to infer that metal oxide suspended nanofluids are suitable candidates for replacing traditional working fluids in heat pipes. Despite the fact that there is a large body of research reporting on the influence of nanofluids on heat pipe thermal performance, many phenomena remain unknown. This research has examined a few of the previously described phenomena, such as the rate at which heat is transported across the liquid-vapor interface and the effect of the heat pipe inclination on thermal conductivity [31, 32].

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