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Experimental Study of Loop Heat Pipe Performance with Nanofluids

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ABSTRACT

Heat pipes are widely used in various industries such as automotive, electronics, and many more. Heat pipes are used as cooling devices for electronic parts in machines that emit a large amount of heat, which can damage the devices. The heat pipes used in this investigation are loop heat pipes. These pipes can transport heat over a long distance and operate against gravity. The working fluid used in this investigation is nanofluid. Nanofluid is one of the types of working fluid that is considered to have better thermal performance than conventional fluids. Nanofluid is made of nanoparticles with base-fluid. This investigation studies the thermal performance of loop heat pipes using different types of nanofluids. Nanofluid fluids used in this study are diamond nanofluid, aluminium oxide nanofluid and silica oxide nanofluid. The effect of mass concentration of nanoparticles in the base-fluid is also studied. The results showed that as the mass concentration of nanofluids increased, the thermal resistance for diamond nanofluid and aluminium oxide nanofluid decreased, but the opposite occurred for silica oxide nanofluid but still better results than pure water. This shows that diamond and aluminium oxide nanofluids shows better thermal conductivity as it has lower total thermal resistance and thermal enhancement rate compared to other nanofluids. Diamond nanofluid also had higher heat capacity than aluminium oxide nanofluid as it had a lower vapour line temperature reading.

1. Introduction

The development of heat pipes is growing rapidly to meet the demand of industries including automotive, air conditioning, and many more which require the use of machines. Heat is produced while these machines operate. Extreme amounts of heat can damage the machine components. Therefore, thermal management [1] is needed to cool the devices down so they can operate more efficiently. Heat pipes work by transferring energy from one point to another using working fluid or coolant. In this experiment, the heat from the evaporator is transferred by the nanofluid to be cooled by the condenser. Heat pipes are highly effective thermal conductors due to their high heat transfer

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coefficient for condensation and boiling. There are many types of heat pipes available such as Pulsating Heat Pipes (PHP), Variable Conductance Heat Pipes, Vapor Chambers, Diode Heat Pipes and Pressure Controlled Heat Pipes.

Loop heat pipes (LHPs) are widely used for cooling devices. LHP can be described as a heat transfer device that relies on the evaporation and condensation of a working fluid, and uses capillary pumping forces to ensure fluid circulation [1]. LHPs use capillary action when operating to remove heat from the heat source. An LHP consists of four main components, which are the evaporator, which is connected to a heat source, the vapor line where the vapor flows, the condenser where the heat is released, and the liquid line where condensed liquid flows back to the evaporator. The advantages of LHPs are that they can operate against gravity and transmit heat for long distances [2]. Ambirajan *et al*. [2] stated that LPH performance is far less sensitive to gravity compared to other types of heat pipes. Thus, ground testing (in a spacecraft) and ground applications are possible. Other wick structures cannot lift the returning working fluid efficiently along the pipe for non-vertical orientations. Loh [3] studied the effect of the wick structure and pipe orientation on heat pipe performance, using mesh, groove and metal powder. The test went through a 180° rotation, stopping at inclinations of 60°, 30°, 0°, -30°, -60° and -90°. The temperature differential was high when the orientation was at -90° and the flow was against gravity, as the working fluid was unable to be lifted in the heat pipe due to gravity. LHPs have been widely researched to address the need of highly efficient heat transfer mechanisms for aerospace technology, which is less sensitive to the alteration of the orientation of the gravity field [4]. It is also stated that other advantages of LHPs include the small diameter transport line that allows for a complex tube layout and the feasibility of incorporating flexible sections in the transport lines. This helps provide thermal management efficiency. LHPs are very important in spacecraft thermal control structures and also in submarine and avionics cooling. Studies that use miniature LHPs (mLHPs) with ammonia filling, found that mLHPs can be used in terrestrial applications as their thermal performance was found to be independent of orientation. Due to their small dimensions, the effect of orientation on the operation of mLHPs is insignificant and can be safely considered to be orientation-free [5].

Chaudry [6] stated that LHPs have major advantages compared to conventional heat pipes including the ability to transfer thermal energy over a larger space efficiently without issues with the channel of the liquid or vapor lines. Furthermore, LHPs have better heat flux potential and robust operations. Therefore, LHPs play a major role in meeting the global demand for thermal management of high-end electronic devices. Other drivers of the development of LHPs are to solve for pressure losses experienced in conventional heat pipes due to the viscosity of fluid used, the flow of liquid through the porous structure and the length of the pipe. Heat transfer could also be badly affected over long distances.

The LHP is designed to control the working fluid to always fill the wick. The LHP will encounter failure if there is no working fluid in the wick. In LHP, heat first enters the evaporator at the primary wick and starts evaporating the working fluid in the primary wick. Surface tension will prevent the liquid from turning back to the secondary wick, where the liquid is placed to ensure there is always water supply to the primary wick. The vapor from the primary wick will flow through the vapor line to the condenser. At the condenser, the heat is dissipated and the vapor will condense to become liquid. The liquid will then flow through the liquid line back to the evaporator.

Further development of LHPs has introduced many variations of mechanisms such as large and powerful LHPs, controllable LHPs, LHPs with high heat flux, ramified LHPs, reversible LHPs, LHPs with flat evaporators and mLHPs. This study uses LHPs with flat evaporators as they are commonly object to be cooled in industry. Furthermore, these LHPs use interfaces for heat transfer that are usually made of high thermal conductivity materials such as aluminum and copper, and have high thermal conductivity characteristics, which enhance heat transfer.

Research has been done to study the effect of the filling ratio on the performance of mLHP using distilled water as working fluid with different diameter transport lines. The filling ratios used were 20%, 30% and 50%, with a heat load of 20W–380W. Research found that a filling ratio of 30% was the optimum filling ratio for this heat pipe, which produced the lowest evaporator wall temperature of 94.3^{o}C at the highest heat load of 380W [7].

Gunnasegaran [8] studied the application of nanofluids in LHPs for the cooling of computer microchips. The working fluid used was Fe_2NiO_4-H_2O with mass concentrations ranged from 0% to 3% and heat input ranging from 20W to 60W. The temperatures of the heat pipe were taken from various parts of the LHP, with all experiments done under the same operating conditions. The results showed a decrease in the core temperature of the desktop PC CPU by a further 5.75°C using Fe_2NiO_4-H_2O nanofluid compared to using pure water. Nguyen et al. [9] studied LHPs using a flat evaporator. The flat evaporator had dimensions of 41mm for the outside diameter and 15mm for thickness, and used a copper powder wick. The design of the evaporator was studied to improve deficient subcooling of liquid in a compensation chamber, which decreased the operating limitations of the LHP. The LHP achieved a total thermal resistance of 0.39 °C/W. There was a study by Celata [10] that used a flat disk evaporator with a diameter of 50mm and thickness of 13mm using water as the working fluid, while the loop and wick were made of stainless steel. The test was carried out at a horizontal elevation for configurations both above and below the compensation chamber. It was found that placing the evaporator above the compensation chamber maximized heat transfer and maintained temperature below 150 °C, while the performance of the evaporator below the compensation chamber was not very significant. The total thermal resistance achieved in this experiment was between 3.33 °C/W and 50.7 °C/W.

Zhou and Li [11] studied two-phase flow characteristics inside a LHP under favorable gravity conditions. The flow of bubble formation was studied based on time and heat input. The higher the heat input, the more bubbles were produced as time increased. The shape of the bubble flow changed as the temperature increased, with bubbly flow, slug flow, churn flow, wavy flow, annular flow and mist flow being produced. The minimum LHP thermal resistance achieved was 0.068 °C/W at 500 W.

Traditional fluid, or base-fluid, consists of water, ethylene glycol, and oil and is used as working fluid in heat pipes for thermal management as it is able to act as a medium for heat transfer. Working fluid is generally used in the power generation, transportation and air-conditioning sectors. In line with the advancement in technology, the requirement for more efficient transfer of heat for cooling devices has led to the development of nanofluid, which has better thermal conductivity and enhances heat transfer. There was a study conducted by Zhang [12] on the effect of working fluids using a pulsating heat pipe. The working fluids used were FC-72, ethanol and deionized water. The results were recorded using a high-speed data acquisition system and showed that the thermal oscillation amplitude for FC-27 was much smaller compared to other fluids. This was possibly because of the lower latent heat of evaporation for FC-72. The optimal filling ratio for better heat transfer for all the liquids used was 70%. FC-72 had a lower minimum heating power than water, which showed that water had better overall thermal performance once the heating power was greater than the minimum value. However, FC-72 was recommended for usage in low-heat-flux conditions due to its lower minimum heating power.

The processes of condensation and evaporation of the working fluid are the key factors that determine the thermal conductivity of the working fluid. Working fluid vaporizes in the evaporator and condenses in the condenser zone to transfer heat. Recently, the most commonly used working fluid in heat pipes are fluid-based [26]. Examples of fluid-based working fluid include distilled water, ammonia and alcohol. Usage of ammonia and alcohol amplifies the heat transfer performance. In recent times, the usage of nanofluids is popular to boost heat transfer performance. Much research has been done on the improvement of heat transfer performance of heat pipes using nanofluids as working fluid. Nanofluids are made up by two components, which are base fluids and nanoparticles. The base fluids could be from water organic liquids such as ethylene and triethylene-glycols, oils and lubricants bio-fluids, while the nanoparticle materials consist of chemically stable metals such as gold and copper, metal oxides such as alumina and silica, oxide ceramics such as Al_2O_3 and CuO, metal carbides, metal nitrides such as AIN and SiN, carbon in various forms such as diamond and graphite, and functionalised nanoparticles [13]. Nanoparticles have higher thermal conductivity than base fluids as the particles are much smaller and with sizes significantly below 100nm. Furthermore, the presence of nanoparticles increases heat transfer performance of base liquid. Several literatures show an increase in thermal conductivity by 20% with low nanoparticles concentration (1–5 vol %). Factors that affect heat enhancement are mainly the dimensions, shape, volume fractions or mass concentration in the suspensions and thermal properties of particle materials. There was a study conducted on mLHPs using graphene-water nanofluid as the working fluid. The mLHP used in the study was a 20x20mm square flat evaporator with a filling ratio of 30%, which resulted in a heat load range of between 20–380W. The results showed that nanofluids improved the thermal performance of mLHPs and lowered evaporator interface more than the use of distilled water [14].

A study on the effect of nanofluids on thermal characteristic of mLHPs was also carried out. The nanofluid used was water-copper nanofluid, which resulted in a reduction of 12.8% in the evaporator wall temperature and of 21.7% in thermal resistance. Meanwhile, the heat transfer coefficient of the evaporator increased 19.5% when the working fluid was replaced with deionized water with a mass concentration of 10% when a heat load of 100W was used [15]. Heris [16] stated that heat transfer coefficient increases as the concentration of nanoparticles in nanofluids increased. His study used aluminum oxide nanofluid inside a circular tube. Nanofluid with 2.5% of volume fraction was found to have the highest thermal performance. The increase in heat transfer coefficient due to presence of nanoparticles was much higher than the single-phase heat transfer correlation used with nanofluid properties. Overall, it was concluded that nanofluids were suitable to be used with working fluids to increase heat transfer performance, and performance was affected by the mass concentration or volume fraction of nanoparticles and the heat input. Due to this development, many researchers have studied the thermal characteristics of the nanofluids, by focusing on the effective thermal conductivity and convective heat transfer coefficient of nanofluids. It was found that the presence of less than 1% of nanoparticles volume fraction in conventional working fluid could double the thermal conductivity [17]. This has led to many companies researching and developing nanofluids for electronic cooling instead of using water, due to the ability of nanofluids to remove heat and manage the component at uniform temperature. With so many efforts to develop liquid cooling technologies, nanofluid could be the best solution to use for hot spot cooling systems and high heat flux devices such as phones, computers and others. Working fluid needs to be selected properly as it is one of the important components in heat transfer enhancement that can decrease the thermal resistance of heat pipes, and be a good heat transfer medium compared to water, which has minimal effects. Thermal management in electronic devices will benefit by using fluids that have higher heat transfer coefficients and thermal conductivity. In this study, the effect of heat transfer performance of nanofluids in LHPs is based on two variables, which are mass concentration and heat input. There is also is also a computational investigation of using nanofluid in heat exchanger by Y. K. Lee [27]. Copper and alumina nanoparticle is used to be dispersed in water-based fluid. Volume concentration was set 0.5 %, 1.0 %, 1.5 %, 2.0 %, 2.5 %, and 3.0 %. The optimum efficiency of domestic water heat exchanger when 1.5 % copper or alumina volume concentration. The application of nanofluid is very recommended for enhancing the heat transfer in the domestic water heating system

While selecting nanofluid, it is necessary to ensure the nanoparticle suspension is stable and suitable for heat transfer applications. Nanofluids characteristics are based on several factors such as particle volume fraction or mass concentration, base liquid and the dispersed stages, morphology and dimension of the nanoparticles that exist in the base fluid. There are a few studies regarding the nanofluids used in this research, which are diamond nanofluid, aluminum nanofluid and silica oxide nanofluid. There was a study by Ma [18] on the effect of diamond nanofluid on the heat transfer transport capability in an oscillating heat pipe. The diamond nanofluid was added directly to the high-performance liquid chromatography (HPLC)-grade water. The volume ratio used was 1.0%. Thermal conductivity of the nanofluid was found to increase to 1.0032 W/m K from 0.5813 W/m K. The enhancement of heat transfer performance can also be seen by the diamond nanofluid reducing the temperature difference between the evaporator and the condenser from 40.9 °C to 24.3 °C at a heat input of 80W. The lower the temperature difference, the better the heat transfer by the nanofluid from the condenser to the evaporator. This shows that the thermally excited oscillating motion that occurs in the OHP can keep nanoparticles suspended in the base fluid. As the oscillating motion increases with heat input, the temperature differential will also become bigger. There was also a study that used aluminum oxide nanofluid with a 35nm diameter mixed with pure water. The mass concentrations used in this study were 0%, 1% and 3%. The results showed that increasing the nanofluid concentration decreased the temperature difference, and improved the value of vapor and rate of transnational speed between the condenser and evaporator. The study showed that nanofluid with 3% mass concentration had a lower thermal resistance than that of 1% mass concentration. Results showed that the thermal resistance of the heat pipe was reduced due to the formation of a vapor bubble at the liquid–solid interface [19].

There is substantial research on the use of nanofluid in many applications. To the best of the author's knowledge, there are a few nanofluids that are yet to be evaluated. This research will cover the study of thermal performance of using nanofluids in LHP. Various heat input and mass concentration of nanofluids will be used. The comparison between nanofluid will also be discussed.

2. Methodology

2.1. Experimental setup

Heat transfer properties such as thermal resistance and the temperature along the wall of LHP was studied. The LHP system was constructed with equipment that helps heat transfer. LHPs contain components such as an evaporator, a condenser that is attached with fins and blower fans, a regulating pump to change the flow rate and the pressure of working fluid, a liquid storage tank, vapor and liquid lines made up of copper pipe lines, a liquid line comprising of a shorter transparent pipe line, thermocouples linked from the segment of copper line to a Pico data recorder device, an adjustable power supply and a computer holding the Pico recorder software. The experimental setup schematic diagram is shown in Figure 1. Each of the equipment attached to the experimental setup arrangement of LHP had a particular function to achieve the aims of this research. Table 1 shows the design specifications and requirements of the LHP rig setup. The adjustable pump was used to generate force of a specific velocity and pressure of the working fluid starting from liquid storage tank to all parts of the LHP. The flow of working fluid flow is shown in Figure 1. The power supply was Direct Current (DC) with a capacity of 30 V – 3 A and provided heat input for the evaporation of working fluid at the base underneath the evaporator. The pipe line was made of copper to maintain the distribution of temperature in a stable state because of the material's good thermal conductivity.

However, a transparent plastic pipeline was used for a short length of the liquid line to see the real physical occurrences in the LHP. There was a total of six thermocouples known as the ‘K-Type’ thermocouples set at six main positions shown as green dots in the LHP rig setup represented in Figure 1. To quantify the temperature distribution, thermocouples were placed at selected sites of the LHP structure. The outcomes were recorded and collected by the data acquisition system at a degree of one data per second to remove any errors that occurred throughout the experiment.

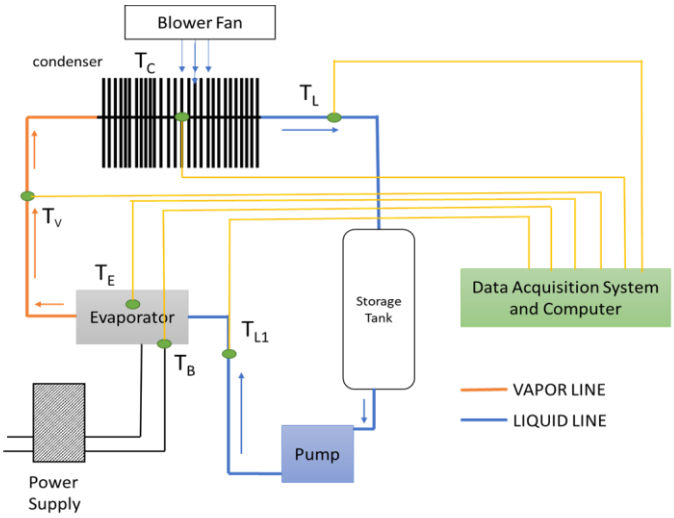

Fig. 1. Schematic diagram of experimental rig setup of LHP.

Table 1
Specification of LHP

Specification	Dimension/material
Adjustable Pump	
Flow rate (litre/hour)	750
Delivery head (mm)	1800
Storage tank	
Material	Aluminium faceplates
Volume (litre)	0.75
Dimension (mm)	149 X 100 X 85
Evaporator	
Dimension (mm)	L50 X W50 X H4
Condenser	
Material	Aluminium
Dimensions (mm)	L321 X W100 X H1
Liquid line	
Material	Copper
Outer Diameter (mm)	15
Inner Diameter (mm)	13.5
Length (mm)	500
Vapour line	
Material	Copper
Outer Diameter (mm)	15
Inner Diameter (mm)	13.5
Length (mm)	830

The thermocouple under the evaporator (T_B) quantified the temperature of the heat flux provided by the regulating power supply to the evaporator to its base surface. The evaporator surface was set as thermocouple (T_E) and the vapor line was set as thermocouple (T_V), respectively. Furthermore, the condenser surface with fins was set as thermocouple (T_C). Finally, another two thermocouples (T_L) and (T_{L1}) were set as the condenser and evaporator sections, along the liquid line. After all thermocouples were set, the temperature from all six points collected by the thermocouples was then linked to the computer for the data assembly with the assistance of a data acquisition device.

2.2. Nanofluid preparation

The nanofluids were prepared by adding nanoparticles to the base fluid. The concentration of nanofluids mixed with the base fluid was limited by a specific percentage for each respective nanofluid. Meanwhile, the calculation of the mass concentration of nanofluids is specified in Equation (1) [25]. Pure water was chosen as the base fluid. There were three nanofluids chosen for this experiment, which were silica oxide nanofluid, aluminum oxide nanofluid and diamond nanofluid.

$$\%\text{mass concentration}= \frac{W_{nano}}{W_{base}+W_{nano}} \times 100\% \tag{1}$$

where,

W_{nano} = mass of nanoparticles (in gram)
W_{base} = mass of base fluid (in gram).

2.3. Thermal analysis

In this experiment, the main parameter being researched was total thermal resistance (R_{th}). The general equation for R_{th} is shown in Equation (2). R_{th} was calculated as the summation of thermal resistances at the evaporator itself, evaporator base, condenser, vapor line, and liquid line. The difference of temperature between two parts is symbolized as ΔT and heat input is denoted as Q.

$$\mathrm{Rt} = \frac{\Delta T}{Q} \tag{2}$$

The thermal resistance at several segments of the LHP such as the evaporator base, evaporator, vapor line, condenser and liquid are presented in Equation (3) to (7). The equation of thermal resistance for evaporator base is determined as:

$$R_B = \frac{T_B - T_E}{Q} \tag{3}$$

where, the temperature at the evaporator base and evaporator surface are symbolized as (T_B) and (T_E), respectively. The equation of thermal resistance for evaporator surface is as follows:

$$R_E = \frac{T_E - T_V}{Q} \tag{4}$$

where, the temperature at the evaporator surface and vapour line are symbolised as (T_E) and (T_V), respectively. The equation for calculating the thermal resistance for the vapour line is as follows:

$$R_V = \frac{T_v - T_c}{Q} \tag{5}$$

where, the temperature of the vapour line and condenser is symbolised as (T_v) and (T_c), respectively. The equation to calculate the thermal resistance for the condenser is as follows:

$$R_C = \frac{T_C - T_L}{Q} \tag{6}$$

where, the temperature of the condenser and liquid line is symbolised as (T_C) and (T_L), respectively. The equation to calculate thermal resistance for the liquid line is as follows:

$$R_L = \frac{T_L - T_{L1}}{Q} \tag{7}$$

where, the temperature of liquid line to condenser and liquid line to evaporator is symbolised as (T_L) and (T_{L1}), respectively. Hence, the summation of thermal resistance from Equations (3) to Equation (7) is the value of total thermal resistance (R_T) as stated in Equation (8). The thermal circuit is designated in Figure 2 for better understanding of the calculation of total thermal resistance.

$$R_T = R_B + R_E + R_V + R_C + R_L \tag{8}$$

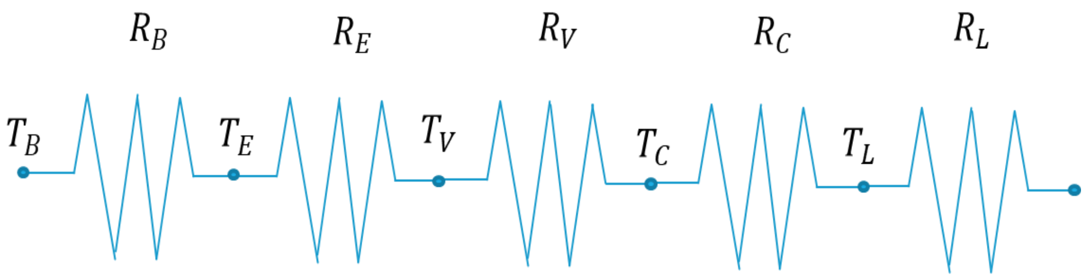

Fig. 2. Thermal resistance network of LHP.

3. Results and discussion

3.1 Thermal resistance analysis

Thermal analysis was carried out for all working fluid and nanofluids including pure water, silica oxide, aluminium oxide and diamond with three varying mass concentrations of 0.5%, 1.0% and 3.0%. Investigation on the total thermal resistance was done to determine the heat transfer enhancement of LHP using nanofluids. The evaporator was heated at 40W, and the LHP helped to cool down the evaporator which kept increasing in temperature. The temperature was taken at six points along the LHP.

The total thermal resistance, R_T was determined by using the data from the points throughout the transient temperature distribution in the LHP rig setup during the experiment, and the equation to calculate the thermal resistance. The values are plotted in Figure 3. The total thermal resistance of pure water with 0% of nanoparticle had the highest value compared to other fluids containing nanoparticle at 3.301 °C/W, which indicated that pure water had the lowest thermal performance to act as working fluid in LHPs. Meanwhile, the total thermal resistance decreased as mass concentration increased from 0.5% to 3.0% for aluminium oxide and diamond nanofluids, respectively, which showed that these liquids were better for heat transfer performance than pure water. The highest measure for thermal resistance for each nanofluid at 0.5% mass concentration were 3.1875 °C/W and 3.108 °C/W for aluminium oxide and diamond nanofluid, respectively. The lowest measure of total thermal resistance at 3.0% mass concentration were 3.14655 °C/W and 3.08725 °C/W for aluminium oxide and diamond nanofluid, respectively.

However, the results of total thermal resistance using silica oxide differed as the value increased as the mass concentration of nanoparticle increased from 0.5% to 3.0%, showing decreasing thermal performance and higher total thermal resistance than other nanofluids. The lowest measure of total thermal resistance for silica oxide at 0.5% mass concentration was 3.1935 °C/W, while the highest value at 3.0% mass concentration was 3.2881 °C/W. In conclusion, diamond nanofluid had the best thermal performance as it had the highest thermal conductivity and enhanced heat transfer abilities of LHP. Silica oxide nanofluid had the highest value of total thermal resistance and generated low thermal conductivity for reduced heat transfer property but still showed an improvement compared to pure water.

Table 2
Thermal analysis between nanofluids

Mass Concentration (%)	Nanofluids (°C/W)		
	Silica Oxide	Aluminum Oxide	Diamond
0	3.301	3.301	3.301
0.5	3.1935	3.1875	3.108
1	3.2035	3.1505	3.0953
3	3.2816	3.14655	3.08725

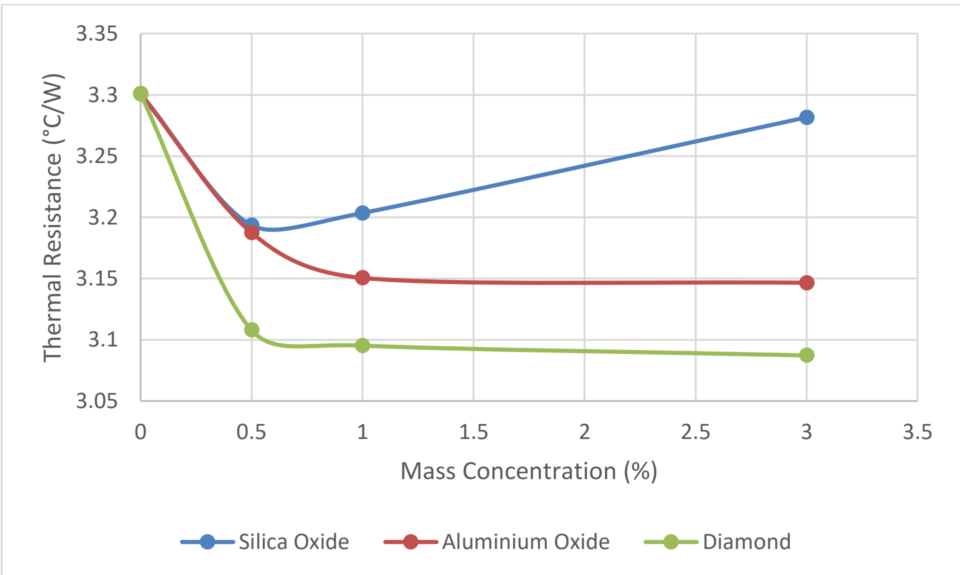

Fig. 3. Mass concentration versus thermal resistance with different nanofluids.

The extra evidence of the effects of adding silica oxide, aluminium oxide and diamond nanoparticles on the thermal performance compared with pure water is shown in Figure 4.

Table 3
Thermal enhancement rate using nanofluid

Mass Concentration	Thermal Enhancement Rate (%)		
	Silica Oxide	Aluminum Oxide	Diamond
0.5	3.26	3.44	5.85
1	2.95	4.56	6.23
3	0.59	4.68	6.48

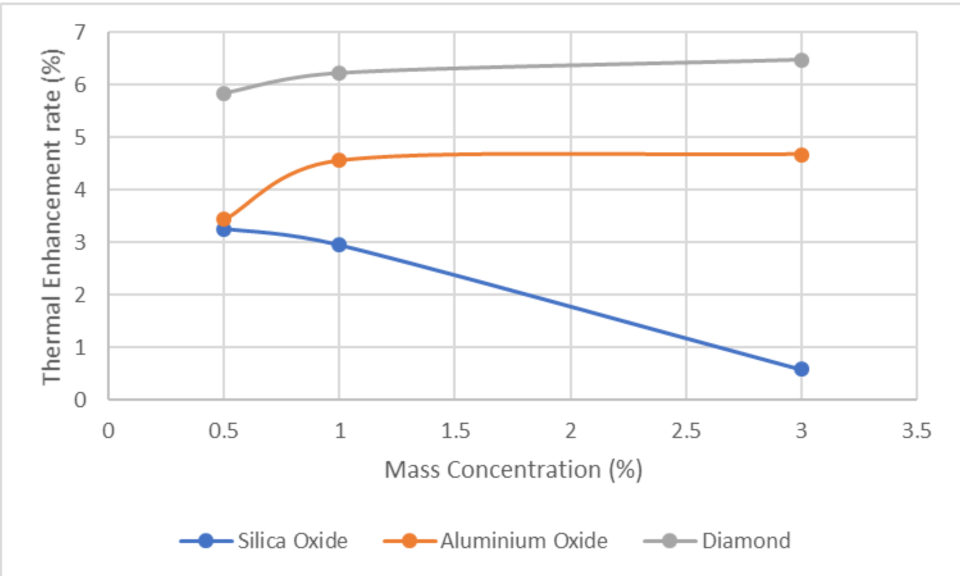

Fig. 4. Mass concentration versus thermal enhancement rate with different nanofluids.

There are few causes for the decreasing thermal resistance of nanofluids within LHP. Shukla *et al*. [20] stated that heat pipes with nanofluid have greater wall temperature drops compared to using pure water. This wall temperature drop affects the thermal resistance reduction. Moreover, nanofluids have higher convective heat transfer coefficients than pure water. This increases the performance of the heat transfer of nanofluid for particular heat pipes.

Next, the reduction of thermal resistance is the result of the formation of vapour bubbles at the liquid-solid interface. The bigger the size of bubble formation the higher thermal resistance that prevents the heat transfer between solid to liquid surfaces. Moreover, the presence of nanoparticles scattered the vapour bubble formation. Therefore, the size of bubble formation is smaller when using fluids with suspended nanoparticle [19].

A research by Yu *et al*. [17] stated that thermal resistance is affected by particle shape, distribution, concentration, shell structure and contact resistance. Various published research on nanofluid found that thermal conductivity enhancement increases as mass concentration rises. The reducing thermal performance of nanofluids compared to pure water was also studied. For example, Chon *et al*. [21] studied aluminium oxide nanofluid with various concentrations, and found that nanofluids with mass concentration of 4% had a higher thermal conductivity enhancement compared to those with mass concentration of 1%. Therefore, the results obtained by this experiment was in line with this research.

Particle materials also impact thermal conductivity of the working fluid. Yu *et al*. [17] stated that metal particles would have better heat transfer performance than oxide particles and the thermal conductivity ratio is seen to increase faster for metal particles than oxide particles. It is difficult to create metal particle nanofluids without the particles oxidising during the production process. Therefore, aluminium will have higher thermal conductivity compared to silica oxide as aluminium is a metal particle. Silicon is a metalloid and generally has properties of both metals and non-metals. Diamonds have better thermal performance than other substances because oxide particles do not bind with diamond particles.

Brownian motion occurs between nanoparticles in nanofluids, whereby there is continuous movement of the nanoparticles, and with larger surface area contact [22], more frequent collisions between particles occur. The rapid heat transfer between the particles resulted in lower thermal resistance for nanofluids compared to base fluid. Keblinski *et al*. [23] stated that the Brownian motion in nanofluids is too slow to transport heat. However, it is possible for the Brownian motion to have an indirect role in the heat transfer by nanofluids. As the particles in nanofluid are separated by a microscopic distance, particles collided frequently, thus increasing heat flow among the particles.

3.2. Investigation of vapour line temperature with various heat input

The investigation was done for aluminium oxide and diamond nanofluids only. The temperature of the vapour line was taken for various heat inputs, which were 40W, 60W and 80W to see the effect of various heat inputs in the thermal properties of working fluid that contained different mass concentrations of 0.5%, 1.0% and 3.0%.

Table 4
Vapor line temperature

Heat Input (W)	Vapor line pipe wall temperature of diamond nanofluid (°C)		
	mass concentration 0.5%	mass concentration 1.0%	mass concentration 3.0%
40	59.53	59.36	59
60	64.43	63.02	61.66
80	66.78	65.28	63.79

Figure 5 shows that as the heat input increases from 40W to 80W, the vapour line temperature also increases, across all concentrations. The lowest temperatures for the vapour line with mass concentration of 3.0% at 40W, 60W, and 80W were 59°C, 62.66°C and 67.79°C, respectively. Diamond nanofluid with mass concentration of 0.5% had the highest temperatures at 40W, 60W, and 80W which were 59.53°C, 65.43°C and 69.78°C, respectively.

Based on Figure 6, aluminium oxide and diamond nanofluid have similar results. The lower temperatures for the vapour line with mass concentrations of 3.0% at 40W, 60W and 80W were 60.31°C, 61.89°C and 64.22°C, respectively. Aluminium oxide nanofluid with mass concentration of 0.5% at 40W, 60W and 80W were 62.83°C, 64.38°C and 66.60°C, respectively.

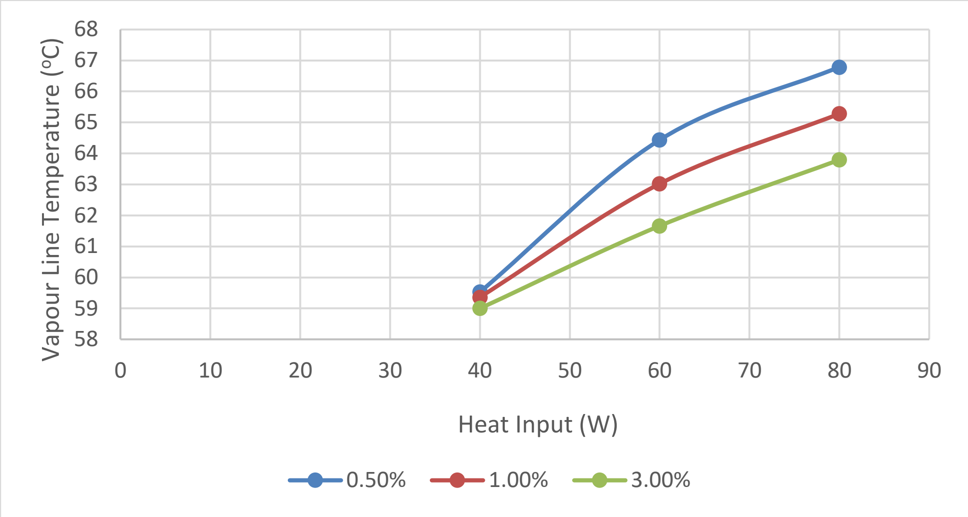

Fig. 5. Vapour line temperature versus heat input using various mass concentrations of diamond nanofluid

Table 5 Wall temperature of vapour line using different mass concentrations of aluminium oxide nanofluid at various heat inputs

Heat Input (W)	Vapour line pipe wall temperature of aluminium nanofluid (ºC)		
	Mass concentration 0.5%	Mass concentration 1.0%	Mass concentration 3.0%
40	62.83	61.5	60.31
60	65.38	64.11	62.89
80	66.6	65.31	64.22

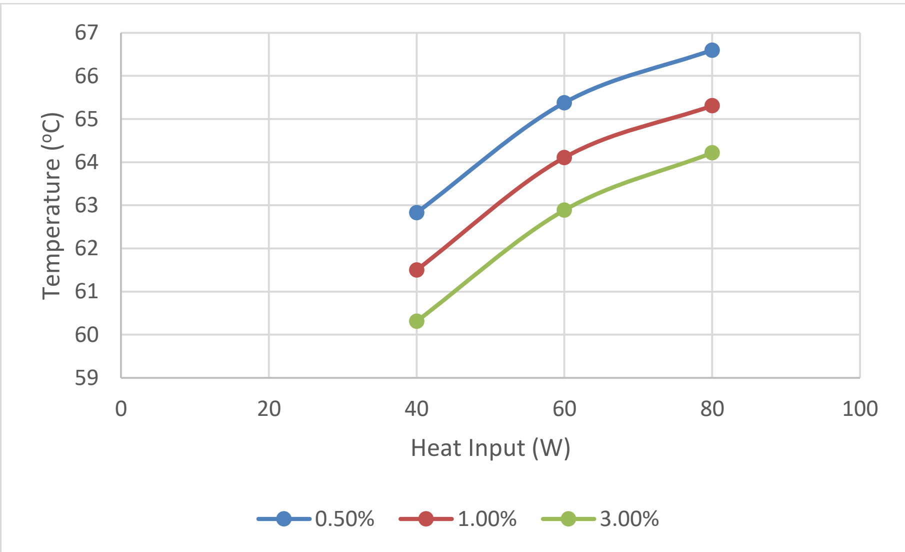

Fig. 6. Vapour line temperature versus heat input using various mass concentrations of aluminium nanofluid

Natural convection in liquid with nanoparticles is different from pure fluid. The natural convection of nanofluid is caused by the unstable density distribution of liquid due to temperature difference and the distribution of particle concentration from the sedimentation [24]. The average size of diamond nanoparticles is smaller than aluminium oxide particle. Therefore, the distribution of diamond nanoparticles is more scattered than aluminium oxide. With higher mass concentration, more nanoparticles will scatter along the LHP, resulting in higher heat transfer by convection in fluids between the evaporator and condenser. Trisaksri and Wongwises [24] also said that an increase of heat input will not affect the thermal conductivity of each nanofluid. Therefore, it is logical for the temperature of the vapour line to increase as the heat input increased.

In conclusion the study showed that both nanofluids showed the same trend, where the higher the heat input, the higher the temperature. This was because more heat was absorbed through the heat transfer between the pipe wall and the working fluid. It was also found that the higher mass concentration of nanofluids, the lower the temperature. This is because, nanofluids with higher mass concentration had higher heat capacity. Therefore, it is logical for the temperature of the vapour line to not differ much with nanofluids of better heat capacity. Based on Table 6 below, diamond nanofluids have better heat capacity than aluminium oxide as had lower temperature for every heat input at 3.0% heat concentration. Therefore, diamond nanofluids was found to the best nanofluid to be used as working fluid in LHPs.

Table 6
Wall temperature of vapour line using different mass concentrations of aluminium oxide nanofluid at various heat inputs

Heat Input (W)	Vapour line pipe wall temperature with 3.0% mass concentration of nanofluids (°C)	
	Diamond	Aluminium Oxide
40	59	60.31
60	61.66	62.89
80	63.79	64.22

4. Conclusions

This research analysed the thermal characteristics of LHP using various types of nanofluids (silica oxide, aluminium oxide and diamond nanofluids) and compared them with pure water. Despite the use of various types of nanofluids, different mass concentrations of 0.5%, 1.0% and 3.0% were used to test the thermal characteristic of nanofluids. Therefore, the findings from the experiment have helped to achieve the required objectives for this research as follows:

I. The total thermal resistance of nanofluid was proven to be lower than that of pure water. The higher the mass concentration of nanofluids, the better the thermal performance. Mass concentration of 3.0% had the lowest total thermal resistance and highest thermal enhancement rate. Overall, diamond nanofluid showed better thermal performance with the lowest total thermal resistance at 3.08725 °C/W followed by aluminium oxide and silica oxide. The thermal enhancement rate was also analysed by comparing nanofluids with pure water. Diamond nanofluid showed superior result relative to other nanofluids for thermal enhancement rate which was 0.0648 at 3.0% mass concentration.

II. The study of thermal characteristics was achieved by using the wall temperature of the vapour line with different mass concentrations as shown in Figure 5 and Figure 6. The results showed that as the heat input increased from 40W to 80W, the temperature reading also increased. This was because more heat was absorbed by the nanofluid. As the mass concentration of nanofluids increased from 0% to 3.0%, the temperature reading decreased. This was because the higher the mass concentration of nanofluids, the higher the capacity to store heat. Therefore, the vapour line wall temperature was low. Based on the comparison between diamond and aluminium oxide nanofluid, diamond nanofluid was found to have higher heat capacity than aluminium oxide nanofluid. Therefore, diamond nanofluid was superior as working fluid in the LHP.

Based on the research, the authors strongly recommend nanofluids to replace water as working fluid in LHP as they enhanced the thermal characteristics of working fluid. The mass concentration of nanofluid also needs to be considered to achieve the required heat transfer. Lastly, the objectives of this research were achieved.

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