Experimental analysis and FEM simulation of loop heat pipe charged with diamond nanofluid for desktop PC cooling

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Abstract. This paper discusses the impact of diamond nanofluid on heat transfer characteristics in a Loop Heat Pipe (LHP). In this study, diamond nanoparticles in water with particle mass concentration ranged from 0% to 3% is considered as the operational fluid within the LHP. The experiments are carried out by manufacturing the LHP, in which the setup consists of a water tank with pump, a flat evaporator, condenser installed with two pieces of fans, two transportation lines (vapor and liquid lines), copper pipe sections for attachment of the thermocouples and power supply. The uniqueness of the current experimental setup is the vapor line of LHP which is made of transparent plastic tube to visualize the fluid flow patterns. The experimental results are verified by Finite Element (FE) simulation using a three-dimensional (3D) model based on the heat transfer by conduction where the LHP as a whole is modeled by assuming it as a conducting medium without taking into account the events occurring inside the LHP. The LHP performance is evaluated in terms of transient temperature distribution and total thermal resistance ($R_t$). The experimental and simulation results are found in good agreement.

1. Introduction

Nowadays, the world is in a constant energy crisis and energy seldom lacks. It would be very useful to find a way to use energy more efficiently. Energy recovery is a very important thing to consider. Loop heat pipe (LHP) is an equipment with high efficiency used to transfer the heat from one place to the other. Normally conventional fluids are used in LHPs to remove the heat based on a temperature range for its particular operating conditions [1]. The lower thermal conductivity of these working fluids limits the thermal performance enhancement of the LHPs. Fluid, with nanoparticles is referred to as nanofluid, a term proposed by Choi [2]. The term “nanofluid” refers to a two-phase mixture with its continuous phase being generally a liquid and the dispersed phase constituted of “nanoparticles” i.e., extremely fine metallic particles of size below 100 nm. In other words, the large surface-area-to-volume ratio also increases the stability of the suspensions. Thus, the nanofluid is a promising heat transfer fluid in variety of applications.

Numbers of experimental investigations have demonstrated the use as nanofluid with higher effective thermal conductivity and critical heat flux [3 and 4]. These advantage is applications such as heat transfer...
devices. Recently, many researchers have presented the heat transfer characteristics of heat pipe using nanofluids. In contrast, only a few investigations on thermal performance of heat pipe charged with diamond nanofluid are available and LHPs have never used the diamond nanofluid as working fluid and this has motivated the present study. To the best of authors’ knowledge; most of the research works are carried out experimentally and hence validating the experimental findings is difficult [5, 6, and 7]. Thus, the present study deals with experimental investigation to evaluate the thermal performance of LHP using diamond (diamond–$\text{H}_2\text{O}$) nanofluid for various mass concentrations, which ranged from 0% to 3% under forced convection mode and the results are verified by simulation using FEM (ANSYS 14 software). The results of interests such as total thermal resistance and transient temperature distribution in the LHP are reported to illustrate the effect of nanofluid concentration on LHP performance.

2. Materials and methods

2.1. The experimental setup

Fig. 1 illustrates the schematic diagram of experimental setup for LHP. The main function of this experiment rig is to determine the thermal performance of LHP charged with diamond–$\text{H}_2\text{O}$ nanofluid with mass concentration ranged from 0%-3% as a working medium. In this experiment, the K-type thermocouples are installed on the pipe/wall in different locations of the loop, including the copper base plate ($T_B$), the evaporator ($T_E$), the vapor line ($T_V$), the condenser section ($T_C$) and the liquid line ($T_L$). The temperatures measured by the thermocouples are collected through a data acquisition (Agilent 34970A) with sample rate of 1 Hz and connected to a PC to collect the data. The experiments are conducted under a heating power of 40 W. The airflow velocity is fixed as 4 m/s and the coolant flow rate is 750 liters per hour, controlled by adjusting the flow control valve. In order to study the transient temperature distribution, temperatures at each 750 s from the start of the experiment, are also noted, until the steady state.

![Figure 1. Schematic diagram of experimental apparatus.](image-url)
2.2. Nanofluid preparation

In the present study, three mass concentrations of 0.5%, 1.0% and 3.0% are tested for diamond-H$_2$O nanofluids. Deionized water is used as the base liquid. The diamond nanoparticles that used for investigation have an average size of 13 nm and density of 3.95 g/cm$^3$. The diamond nanoparticles with 5 g, 10 g and 30 g are used to prepare 1000 ml of diamond-H$_2$O nanofluid, which corresponds to 0.5%, 1.0% and 3.0% particle mass concentration, respectively. Diamond nanoparticles are weighted very accurately using a sensitive balance with a 0.1 mg resolution. The particle mass concentration of diamond-H$_2$O nanofluid in the present study is calculated using Eq. (1) as follows [8].

\[
\text{\% mass concentration} = \frac{W_{\text{diamond}}}{W_{\text{bf}}} \times 100 \%
\]

Where,
- $W_{\text{diamond}}$ = Amount of diamond nanoparticles in gram
- $W_{\text{bf}}$ = Amount of base fluid in gram

2.3. Thermal analysis

The objective of the current study is to study the total thermal resistance ($R_t$) and the temperature distributions of the LHP using diamond-H$_2$O nanofluid as working fluids for heat input of 40 W under steady state and transient conditions. The results obtained from experimental investigation used to verify by FEM simulation. The nanoparticle mass concentration that yields the minimum $R_t$ is then found out, and the effective thermal conductivity ($k_{eff}$) of evaporator section, vapor line and liquid line is calculated and the various steps to estimate $R_t$ are as follows.

The heat flux ($\dot{q}$) that applied on the bottom of base plate can be expressed as:

\[
\dot{q} = \frac{Q}{A_b}
\]

where $Q$ denotes the heat input and $A_b$ is the area of base plate. The thermal resistances of the LHP are defined as [9]: The thermal resistance between the copper base plate and the evaporator section ($R_b$) is:

\[
R_b = \frac{T_b - T_e}{Q}
\]

where $T_b$ denotes the temperature at the copper base plate and $T_e$ is the temperature at the evaporator.

The thermal resistance of the evaporator section ($R_e$) is:

\[
R_e = \frac{T_e - T_v}{Q}
\]

where $T_v$ is the temperature at the vapor line.

The thermal resistance of the vapor line ($R_v$) is:

\[
R_v = \frac{T_v - T_c}{Q}
\]

where $T_c$ is the temperature at the condenser section.

The convective thermal resistance of the condenser ($R_c$) is:

\[
R_c = \frac{T_c - T_i}{Q}
\]

where $T_i$ is the temperature at the liquid line.

The thermal resistance of the liquid line ($R_l$) is:

\[
R_l = \frac{T_l - T_a}{Q}
\]

where $T_a$ is the ambient temperature.
According to the thermal resistance network as shown in Fig. 3, the $R_t$ of the system is given by:

$$R_t = R_b + R_e + R_v + R_c + R_i$$

(8)

The heat transfer coefficient ($h$) for LHP is obtained from Eq. (9) as follows:

$$h = \frac{Q}{50A_f(T_e - T_a)}$$

(9)

where 50 is the number of fins and $A_f$ is the surface area of aluminum rectangular fin.

3. 3D numerical heat conduction model

The purpose of simulation in the present study is to verify the experimental observations. Accordingly, a three-dimensional (3D) model is designed by assuming the whole LHP as a conducting medium without taking into account the events occurring inside the LHP. The simulation is performed in commercial FEM software package, ANSYS, for LHP charged with diamond nanofluid of 1% mass concentration. The 3D model of the complex LHP assembly is built in Pro Engineer Wildfire 4.0 and is exported to ANSYS 14. The LHP consists of copper base plate (heat source), evaporator, vapor line, condenser with 50 aluminum rectangular fins and liquid line. The high effective thermal conductivity of LHP is meshed with 1 mm element edge length, whereas the copper base plate and aluminum fins have coarse meshes of 4 mm edge length, forming a total of 205523 triangular elements. The heat flux of 16000 W/m² applied on the bottom of the base is calculated by $Q/A_b$, where $Q$ is 40 W and $A_b$ is the base surface area (0.0025 m²). The initial temperature is taken as 22 °C and the total time steps (thus the number of iterations) are taken as 1200. The heat transfer coefficient of LHP, calculated using Eq. (9) is taken as 138 W/m².K, which corresponds to LHP charged with 1% diamond-H₂O nanofluid. It is to be noted that the value of $k$ for evaporator section, vapor and liquid lines of the LHP charged with 1% diamond-H₂O nanofluid is the effective thermal conductivity ($k_{eff}$).

4. Experimental results

4.1. Flow pattern in the vapor line

Instead of saturated vapor, two different flow patterns are observed under a heat input power of 40W in the vapor line using pure water (0%) and diamond-H₂O nanofluid with particle mass concentrations of 0.5%, 1% and 3%, which is slug flow and bubbly flow, respectively. It is also observed that the nucleation size of bubble formation is getting reduced and the quantity of bubbles formation are getting increased as the mass concentration increases from 0% to 3%. From the results obtained, the lowest thermal resistance is expected in LHP using 3% diamond-H₂O nanofluid. The reason for reducing the thermal resistance of heat pipe can be explained as follows. A major thermal resistance of heat pipe is caused by the formation of vapor bubbles at the liquid-solid interface. A larger bubble nucleation size creates a higher thermal resistance that prevents the transfer of heat from the solid surface to the liquid [10]. The suspended nanoparticles inside the water tend to bombard the vapor bubble during the bubble formation. Therefore, it is expected that the nucleation size of vapor bubble is much smaller for fluid with suspended nanoparticles than that without them as reported by Tsai et al [11]. According to Huminic et al [12], as the mass concentration of suspended nanoparticles increases within the base fluid, the resultant greater bombardment of vapor bubble has amplified the amount of much smaller nucleation size of vapor bubbles formation. This fact is in good agreement with the achieved results in present study.

4.2. Thermal resistance analysis

Fig. 1 shows the relationship of total thermal resistance ($R_t$) of LHP charged with diamond-H₂O nanofluid at different mass concentrations (0%-3%). From the graph, it is observed that the $R_t$ of LHP charged with diamond-H₂O nanofluid decreases as the nanoparticle mass concentration increases and thus be responsible for better heat transfer performance instead of pure water (0%). This is due to the fact that the suspended nanoparticles in a fluid flow can increase both the thermal conductivity of fluid and convective heat transfer from fluid flow to the wall as reported by Wang et al. [13] and Xuan and
Li [3], which results in the reduction of $R_t$ of the LHP charged with diamond-H$_2$O nanofluid as discussed in the present study. A minimum value of total thermal resistance was found at mass concentration of 3.0%, which is 3.15 °C/W.

![Figure 2](image)

**Figure 2.** Total thermal resistance of LHP charged with diamond-H$_2$O nanofluids at different mass concentrations.

5. **Comparison of experimental and simulation results**

Table 1 illustrates the comparison of experimental and simulation results at steady state for LHP using diamond-H$_2$O nanofluid with particle mass concentration of 1%. The good agreement indicates the validity of the present methodology for the thermal analysis of the LHP. However, a detailed simulation by incorporating the multi-phase flow within the LHP may yield predictions that are more realistic. It is seen that, the predicted transient temperature distributions for LHP using diamond-H$_2$O nanofluid in present simulation are also well matching with the experimentally observed trends.

| Temperature (°C) | Diamond-H$_2$O (1%) | Experiment | Simulation |
|-----------------|----------------------|------------|------------|
| $T_b$           | 148.20               | 149.51     |
| $T_e$           | 75.60                | 77.47      |
| $T_v$           | 61.50                | 61.98      |
| $T_c$           | 24.89                | 25.09      |
| $T_l$           | 23.38                | 23.29      |

6. **Conclusion**

In the present study, extensive experimental and FEM simulation investigations on the LHP are performed. As nanoparticle mass concentration increasing, two different flow patterns are observed under the same heat input power in the vapor line. They are slug and bubbly. The thermal analysis of the LHP charged with diamond-H$_2$O nanofluid with particle mass concentration ranged from 0% to 3% is studied. The results of the simulation showed the positive influence of nanofluid utilizing as a heat pipe working fluid on the system thermal performance. It is found that the $R_t$ of LHP decreases when particle mass concentration of diamond-H$_2$O nanofluid increases. However, there existed an optimal
concentration of 1%, at which the reduction in $R_t$ is not apparent or remains constant thereafter. Apart from the study on thermal resistance, the transient temperature distributions obtained from experiment and FEM simulation are found in good agreement.

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