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Heat Transfer in a Loop Heat Pipe Using Fe_2NiO_4-H_2O Nanofluid

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Abstract. Nanofluids are stable suspensions of nano fibers and particles in fluids. Recent investigations show that thermal behavior of these fluids, such as improved thermal conductivity and convection coefficients are superior to those of pure fluid or fluid suspension containing larger size particles. The use of enhanced thermal properties of nanofluids in a loop heat pipe (LHP) for the cooling of computer microchips is the main aim of this study. Thus, the Fe_2NiO_4-H_2O served as the working fluid with nanoparticle mass concentrations ranged from 0 to 3 % in LHP for the heat input range from 20W to 60W was employed. Experimental apparatus and procedures were designed and implemented for measurements of the surface temperature of LHP. Then, a commercial liquid cooling kit of LHP system similar as used in experimental study was installed in real desktop PC CPU cooling system. The test results of the proposed system indicate that the average decrease of 5.75°C (14%) was achieved in core temperatures of desktop PC CPU charged with Fe_2NiO_4-H_2O as compared with pure water under the same operating conditions. The results from this study should find it's used in many industrial processes in which the knowledge on the heat transfer behavior in nanofluids charged LHP is of uttermost importance.

1 Introduction

As a new kind of heat transfer working fluid, the nanofluid is a new technology attempt to use the special properties of this functional fluid to enhance the phase-change heat transfer in heat pipes, and will have wide application prospect. 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. As known, water has been widely used as industrial heat transfer fluid for a long time, but due to higher thermal conductivities of metals compared to water, suspensions of nano-sized solid particles especially metal or metallic oxides particles in water, have been used as heat transfer fluid with higher thermal conductivities. Due to this fact, many studies on various water-based nanofluids have been carried out in the past years [1]. For example, application of water-based nanofluids in a heat exchanger exhibits an increased heat transfer coefficient compared to pure water [2, 3]. Seyf and Feizbakhshi [4] study on a numerical investigation of the application of CuO-H_2O nanofluids in micro-pin-fin heat sinks and found a significant

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enhancement in heat transfer. Hajmohammadi et al. [5] consider Cu and Ag water based nanofluids for the flow and heat transfer of nanofluids over a permeable flat plate with convective boundary condition. In the cases of injection and impermeable surface, increasing the nanoparticles volume fraction result in augmentation of convection heat transfer rate. However, in the case of suction, adding Cu and Ag particles reduces the convection heat transfer coefficient at the surface. Overall, many researchers have been devoted to exploiting water-based nanofluids. The research on application of nanofluids in heat pipes was firstly published in 2003 [6]. Many articles have been published since then, involving micro-grooved heat pipe, mesh wick heat pipe, sintered metal wick heat pipe, oscillating heat pipe (OHP), and loop heat pipe (LHP) [7-12]. The applied nano-materials included metal, metal oxides, diamond, carbon nanotubes and several other materials.

The fundamental studies of nanofluids applied in heat pipes are still in its initial stage, most of research works are carried out experimentally to focus on finding out key factors affecting the reliable application of nanofluids in the heat pipes and some experimental results cannot be unified yet. The type, size of heat pipes and operating conditions of heat pipes, the kind of base fluids, the material and size of nanoparticles all varied in very wide ranges among these experiments. Therefore, it is difficult to quantitatively make the comparison among different experimental data and then the most existing research conclusions are qualitative. Study on optimization of operating parameters such as nanoparticle mass concentrations and heat inputs is also rare.

Most of the previous works considered on conventional heat pipes such as micro-grooved heat pipe, mesh wick heat pipe and oscillating heat pipe, and there is far less work conducted for LHPs. As LHPs are demonstrated to be a reliable and great potential for electronic cooling applications, the use of nanofluids could represent a gain in their performance simply by adding a certain volume of nanoparticles to the working fluid. Furthermore, since LHPs utilize the phase change of the working fluid to transport the heat, the selection of nanofluid is of essential importance to promote the thermal performance of LHPs. Due to limited study on thermal performance of LHP charged with nanofluid has been reported in the past, more investigations are needed.

Moreover, heat pipes charged with nanofluids are not only of academic interest but also of industrial interest. Recently, the number of companies that observe the potential of the technology of heat pipes filled with nanofluids is increasing. In the realm of electronics cooling, some companies are conducting research to use nanofluids instead of water for cooling CPUs in desktop computers. Up to now, studies concerning application of nanofluids in LHPs for cooling desktop computers in real life have been limited to academic and theoretical study. Accordingly, in the present study, all the aforementioned issues on application of nanofluid in LHP are addressed experimentally and a real computer setup with a quad-core processor has been used to determine the effect of use of Fe_2NiO_4-H_2O nanofluid on the cooling system in real practical condition.

2 Materials and methods

2.1 The experimental setup

The schematic diagram of experimental setup for LHP under investigation is shown in Fig. 1. The main function of this experiment rig is to determine the thermal performance of LHP charged with Fe_2NiO_4-H_2O nanofluid with mass concentration ranged from 0 to 3% as a working fluid. The LHP shown in Fig. 1 installed with a power supply (W5 Series 30A-720A) and a flat evaporator with a total dimension of 50 mm x 50 mm x 4 mm. A water tank with 0.75 liter glass vessel equipped by drain valve is used as liquid reservoir. The whole LHP is made of copper. The internal and external diameters of both vapor and liquid lines are 13.5mm and 15mm, respectively. The condenser section is made of 50 aluminum rectangular fins and cooled by installing two pieces of screwed fans. To maintain steady state cooling conditions in the condenser section, the temperature and flow rate of the cooling liquid are fixed at constant value. To minimize the heat loss, the whole LHP is insulated by using glass wool. A copper block with heat rods inside is used to simulate the heat source, and the contact area between the evaporator and the heat source is 50 mm x 50 mm. In this experiment, the K-type thermocouples with an accuracy of ± 0.1°C 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 heat input ranged from 20 W to 60 W by adjusting the variable transformer. The best estimated coolant flow rate and airflow velocity of condenser in present experiment is found to be 5 ml/min and 6 m/s, respectively, are used throughout the entire study. All the sensors are adjusted according to the desired heat input.

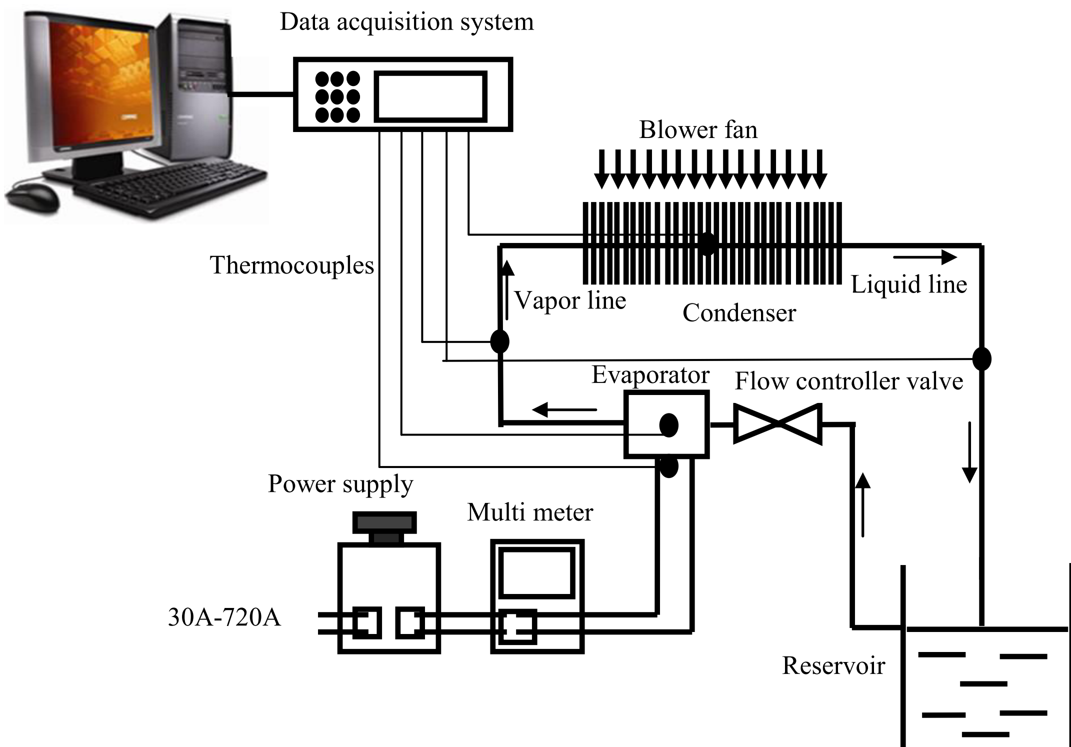

Figure 1. Schematic diagram of experimental apparatus.

2.2 Nanofluid preparation

In the present work, deionized water (DI-water) is taken as the base fluid for preparation of nanofluids in a Digital Ultrasonic Cleaner TJ001. Nanoparticles (Nanopowder) are purchased from Alfa Aesar Corp., Ward Hill, MA and blended with deionized water without any surfactant. The nanoparticles used in the present experiments are Fe_2NiO_4 with an average size of 50 nm and density of 5.37 g/cm^3.

To make a desired percent mass concentration of nanofluids, the weights of deionized water and nanoparticles are measured by a sensitive balance (Ohaus Adventurer Balances) with an accuracy of 0.1 mg. The mass concentration of the powder is calculated from the weight of dry powder using the density provided by the supplier and the total volume of the suspension. For an example, 5.37 g of diamond nanoparticles, which is 1 ml based on the density provided by the vendor, are added to the 99 g (99 ml) of DI-water to make 1 percent mass concentration of Fe_2NiO_4-H_2O nanofluid.

$$\%\text{ mass concentration} = \frac{w_{np}}{w_{bf} + w_{np}} \text{ x } 100\% \tag{1}$$

Where,

w_{np} = Amount of nanoparticles in gram

w_{bf} = Amount of base fluid in gram.

The nanofluid is then stirred by a magnetic stirrer for 5 hours before undergoing ultrasonication process for one and a half hours. This is to ensure uniform dispersion of nanoparticles and also to prevent the nanoparticles from the aggregation in the nanofluids. Then, the nanoparticle/DI-water mixture is ultrasonicated using an ultrasonic cleaner. The purpose of sonication is to vibrate the nanoparticles in the base fluid so that agglomerates of nanoparticles will break up forming a suspension of isolated nanoparticles.

The nanofluids are at significantly high temperature after the sonication. The nanofluids samples that prepared are kept for observation and no particle settlement is observed at the bottom of the beaker containing nanofluids. Since no concentration gradient appears, the nanofluid employed here maintains stability for several weeks and hence surfactants are not mixed in the prepared nanofluids in present experiment. The nanofluids prepared are assumed to be a homogenous, Newtonian in behavior and their thermophysical properties are uniform and constant with time all through the fluid sample. Fig. 2 shows the transmission electronic microscope (TEM) images of the dispersed nanoparticles in water with particle mass concentration of 0.5% at magnification-105kx at room temperature. It is clear that the Fe_2NiO_4 nanoparticles show the good dispersion and very narrow size distribution.

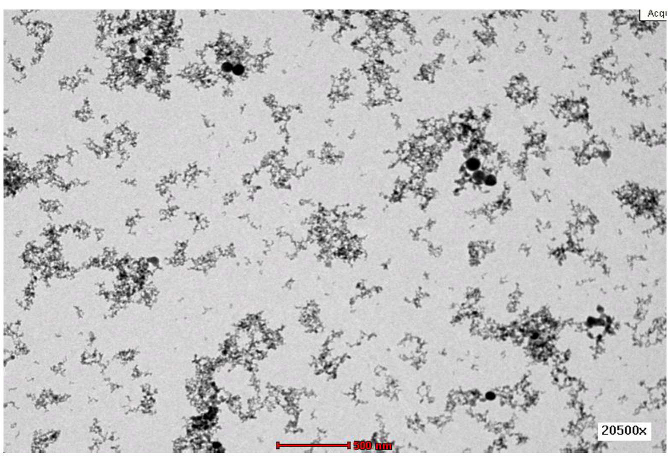

Figure 2. TEM images of Fe_2NiO_4 nanoparticles suspended in pure water.

2.3 Thermal analysis

The objective of the current study is to evaluate the total thermal resistance (R_{th}) and the temperature distributions of the LHP using pure water and Fe_2NiO_4-H_2O nanofluid as working fluids for various heat inputs under steady state and transient conditions. The thermal resistance network of the system is shown in Fig. 3.

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

$$\dot{q} = \frac{Q}{A_b} \tag{2}$$

where Q denotes the heat input and A_b is the area of base plate. The thermal resistances of the LHP are defined by Franchi and Huang [13]:

The thermal resistance between the copper base plate and the evaporator section (R_B) is:

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

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:

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

where T_V is the temperature at the vapor line.

The thermal resistance of the vapor line (R_V) is:

$$R_V = \frac{T_V - T_C}{Q} \tag{5}$$

where T_C is the temperature at the condenser section.

The convective thermal resistance of the condenser (R_C) is:

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

where T_L is the temperature at the liquid line.

The thermal resistance of the liquid line (R_L) is:

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

where T_A is the ambient temperature.

According to the thermal resistance network as shown in Fig. 3, the R_{th} of the system is given by:

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

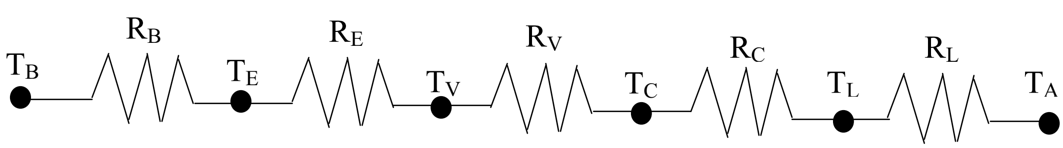

Figure 3. Thermal resistance network of LHP.

3 Proposed desktop PC CPU cooling system

The current work investigated the cooling performance of a water cooling kit with the addition of nanofluids in desktop PC CPU system. A real computer setup with a quad-core processor has been used to determine the effect of use of nanofluid on the cooling system in real practical condition. For the system setup, commercial liquid cooling kit of loop heat pipe (LHP) system similar as used in experimental study was installed in CPU. The system consisted of a quad core processor (Intel Core i5 3470). In the computer, a HeavyLoad software is used to stress all resources of a PC (like CPU, GPU, RAM, hard disk, operating system, etc.) to the maximum from normal condition in order to test if it will run reliably under heavy load (100% CPU usage). To stress the PC or server, HeavyLoad writes a large test-file to the temperature folder, it allocates physical and virtual memory, performs complex calculations and it draws patterns in its window. The temperature of the processor is measured by the internal temperature sensor while applying a constant processing load (maximum load = 100%) on the processor resulting in the highest operating temperature. The highest operating temperature of the processors in nanofluid cooled-CPU was recorded and then compared with conventional water cooled-CPU.

4 Results and discussion

4.1 Thermal resistance analysis

Fig. 4 shows the relationship between the R_{th} and nanoparticle mass concentration for various heat input. As depicted in Fig. 4, the R_{th} decreased up to 1% and increased on further increase in nanoparticle mass concentration (from 1% to 3%) at all heat inputs. Thus, there is an optimal particle concentration, which is about 1% for the Fe_2NiO_4-H_2O-charged LHP in the present experiment. Hence, the addition of Fe_2NiO_4 nanoparticles to base water more than 1% is not recommended for future study. At the optimal mass concentration of 1%, the maximum reduction in R_{th} of Fe_2NiO_4-H_2O charged LHP is about 2.654 °C/W (or 7.17%) under a heat input of 60W, is obtained as compared with pure water (0% nanoparticle mass concentration) charged LHP. It is clear from the Fig. 4 that when the heat input increases, the thermal resistance decreases and the nanoparticle mass concentration has a great impact on the R_{th}.

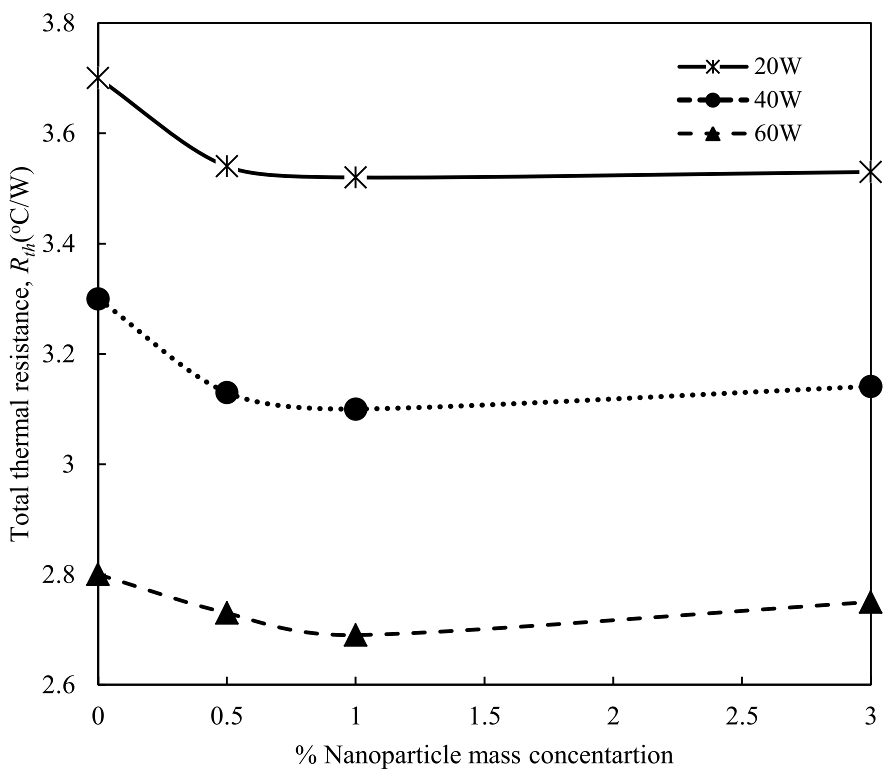

Figure 4. Influence of Fe_2NiO_4 nanoparticle mass concentrations on the R_{th} of LHP for various heat inputs.

4.2 Processor operating temperature of desktop PC CPU system

Decreasing the processor operating temperature (core temperature) of desktop PC CPU is the main purpose of using nanofluids in current proposed liquid cooling systems. This temperature is measured while applying a maximum constant processing load on the processor by using HeavyLoad software resulting in the highest operating temperature. HeavyLoad has been designed to test a computer's resistance to extreme operational conditions, such as intense CPU and RAM usage to avoid server crashes or to make sure the computer will not over heat. The internal temperature sensor of the processor is used to measure the temperature. In the current proposed systems, the pure water and Fe_2NiO_4-H_2O nanofluid is selected as a working fluid within the LHP in CPU. The Fe_2NiO_4-H_2O nanofluid with nanoparticle mass concentration of 1% is selected as the experimental results show that this type of nanofluid yields the best thermal performance. The measured core temperatures are illustrated in Table 1. As expected, adding of the Fe_2NiO_4-H_2O nanofluid with particle mass concentration of 1% to the cooling system reduced the core temperature in comparison to when pure base fluid (water) is used. The core temperature difference between pure water and Fe_2NiO_4-H_2O nanofluid and percent reduction are illustrated in Table 2. The test results showed the average decrease of 5.75°C (14%) in core temperature of desktop PC CPU with Fe_2NiO_4-H_2O nanofluid cooling system as compared with pure water.

Table 1. Processor operating temperatures.

CPU: Processor 4 Core(s)
Processor Information

Model Intel Core i5 3470 (Ivy Bridge)

Processor #	Temperature Readings for LHP charged with pure water	Temperature Readings for LHP charged with Fe_2NiO_4-H_2O nanofluid	Load
Core #0	43 °C	37 °C	100%
Core #1	43 °C	38 °C	100%
Core #2	42 °C	37 °C	100%
Core #3	39 °C	32 °C	100%

Table 2. Percent reduction in processor operating temperatures of using Fe_2NiO_4-H_2O nanofluid.

Processor #	Temperature difference between pure water and Fe_2NiO_4-H_2O nanofluid	% Reduction using Fe_2NiO_4-H_2O nanofluid
Core #0	6 °C	14.0
Core #1	5 °C	11.6
Core #2	5 °C	11.6
Core #3	7 °C	18.0

5 Conclusions

Experimental investigation on Fe_2NiO_4-H_2O nanofluid flow and heat transfer characteristics in LHP are reported in this study. The effects of using nanofluid with different particle mass concentrations at different heat inputs on the heat transfer enhancement of LHP are comprehensively studied. Based on present experimental findings, the most appropriate type of nanofluid to be utilized for the cooling system in real practical condition by using a real computer setup is Fe_2NiO_4-H_2O nanofluid with particle mass concentration of 1%. Fe_2NiO_4-H_2O nanofluid with particle mass concentration of 1% is preferable and recommended as a superior heat transfer fluid in a LHP for desktop PC CPUs cooling system as it has the lowest R_{th} among the other nanoparticle mass concentrations studied. The proposed desktop PC cooling system for industrial applications in current study, results show enhanced heat transfer in the cooling of computer microchips, as indicated in reduction of the operating temperature of processor (Core-i5 processor) when using the Fe_2NiO_4-H_2O nanofluid as compared to application of pure water under 100% of CPU usage. This finding suggests that no extra cooling fans or modifications on geometrical parts of LHP is required to dissipate the excess heat as nanofluid itself is sufficient enough to keep the computer from overheating. This would avoid noise generation by the cooling system and reduce the operation and maintenance costs as well. Therefore, nanofluid should be considered to satisfy the economy of the computer cooling system for real practical operating conditions.

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