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Research Paper

Visualization and comparative investigations of pulsating ferro-fluid heat pipe

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HIGHLIGHTS

- Nanofluid was unstable and also agglomerated and deposited in the copper pipe; whereas, it was stable in the Pyrex pipe.
- For the Pyrex heat pipe, applying the magnetic field caused weaker performance.
- For Pyrex PHP, increasing the concentration improved the performance.
- For the copper PHP, applying the magnetic field had the best performance.
- For copper PHP, concentration of the nanofluid in each case of the magnet and input power has an optimum value.

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ABSTRACT

Pulsating heat pipes (PHPs) are among the best solutions for the electronics cooling due to their low cost, effectiveness and being passive. Experiments to study the effective factors on heat transfer performance have been designed and as a result, improvement of ferrofluid PHP performance has been achieved. Two different heat pipes made of copper and glass were prepared to investigate the behavior of magnetic nanofluids. In order to find the best condition for heat transfer performance, different concentrations of nanofluid with a filling ratio of 50% were tested in 3 different cases of magnetic field. The results indicated that the ferrofluid is more stable in the glass PHP. It also shows that the presence of magnetic field in the copper PHP has the best outcome while in the glass PHP, the absence of magnetic field results better. It was detected that using a more concentrated ferrofluid causes a better performance in the copper PHP only when the magnetic field is applied, while in the glass PHP, increasing the concentration of ferrofluid improves the performance of the PHP in all conditions of applying the magnetic field.

1. Introduction

Durability is one of the many advantages of PHPs; they require no valve, power supply, mechanical pumps or any other external tools, which makes them essentially vibration and noise free. PHPs are also popular due to their less dependence on orientation angle and gravity compared to other types of heat pipes. They have different applications in industry such as water treatment, desalination, oil and gas pipelines, dryers, PVTs and so forth.

Pulsating heat pipes are made of three different parts namely evaporator, adiabatic section and condenser. The way PHPs work is that the liquid in the evaporator evaporates by absorbing heat and after passing through the adiabatic path, its temperature drops in the condenser and it turns back into liquid phase. Afterwards, the condensed liquid goes back into the evaporator through the pipe wall. This process is repeated in a way that the continuous cycle of steam and liquid causes heat transmission.

Basically, PHPs, in addition to sensible heat transfer by the displacement of the liquid phase, use latent heat transfer mechanism by continuous phase change. This permanent phase change creates a pressure difference between the different sections of the heat pipe. The sudden pressure difference causes the movement of the liquid inside the PHP. Several factors contribute to this transformation, including temperature, applied heat power, pipe diameter, filling ratio, number of turns, thermo-physical characteristics of liquids and some others [1–7].

To increase the transmitted heat capacity of the working fluid and to improve heat pipe performance, fluids with higher conductivity coefficient are better choices due to their better heat transfer

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properties. Among different fluids, nanofluids, especially metal nanofluids are the common choices. Several nanofluids have been previously examined for this task, among which diamond [8,9], iron oxide [10], gold [11], copper [12], copper-nickel [13], titanium oxide [14], silver [14–16], silicon oxide [17,18] and aluminum oxide [18–20] can be mentioned.

Taslimifar et al. [21] studied on ferrofluid in a copper heat pipe and examined the effect of input power, ferrofluid concentration, location of the magnet and the orientation angle on its performance. In their experiment, it is shown that ferrofluid's thermal performance is better than that of distilled water. It has been interpreted that startup and stability condition of ferrofluid is better with magnet, in which thermo-magnetic shifting plays an important role. Their results represent that a high concentration of ferrofluid worsens the thermal performance, and the best thermal performance is at an angle of 67.5°.

Mohammadi et al. [22–25], studied the copper heat pipe performance with ferrofluid and indicated that using ferrofluid leads to a better efficiency compared to using distilled water and enhancement of the magnetic field improves the PHP performance. Additionally their results show that the best thermal performance happens when the magnet is placed in the evaporator section. They have emphasized that in the presence of magnetic field in the evaporator, thermal performance improves by increasing charge field or ferrofluid concentration. On the other hand, a reduction in concentration causes a reduction in viscosity. Therefore, by decreasing the concentration of ferrofluid, the PHP has a better performance in the absence of magnetic field; however, taking everything into consideration, PHP performance is remarkably better in the presence of magnetic field and a higher concentration of ferrofluid.

Yang et al. [26] studied two-phase flow in a quartz-glass PHP using distilled water and SiO_2 nanofluid as working fluids. In the case of using distilled water, vertical flow was detected. Meanwhile for the nanofluid, by increasing heat power, column flow, slug-plug flow and annular flow formed in the heat pipe. This condition caused the thermal resistance in the PHP to reduce notably while using nanofluid instead of distilled water.

Karthikeyan et al. [27], have used copper nanofluid in a PHP made of Pyrex with five turns and a diameter of 2.5 cm. Their results demonstrated that most of the copper particles deposited in the evaporator after 24 h and the rest of the particles remained in the other parts like condenser. In addition, thermal efficiency of copper nanofluid PHP was 33% better than water PHP, due to the stuck copper particles in the evaporator which improved the boiling phenomena and heat transfer.

Bhuwakietkumjohn and Rittidech [28] studied internal flow effects on heat transfer characteristics in a PHP by using ethanol and a mixture of nano silver-ethanol. They investigated the flow regime in different lengths of evaporator at various temperatures with ethanol and silver-ethanol nanofluid. Their results indicated that by using silver-ethanol nanofluid instead of pure ethanol, bubbly flow changes to slug-plug flow and annular flow transforms into dispersed bubble flow. It was also stated that nano silver-ethanol has a better thermal performance compared to ethanol.

Effect of the material that PHP is made of on the thermal performance of nanofluids in PHPs has not yet been investigated. Also there are few studies about visualization of nanofluids in PHPs. Hence, in this study we tested two different PHPs, one made of copper and the other made of glass, charged with magnetic nanofluids at a filling ratio of 50%. The effects of input heating power, nanofluid concentration and presence of a magnetic field are visualized and discussed to facilitate better design of future electronic coolers.

2. Experimental setup and test procedure

2.1. Nanofluid specifications

Ferrofluid is made based on the method described by Gandomkar et al. [29]. According to this method, tetrahydrate metal (II), chloride ($FeCl_2{\cdot}4H_2O$) and metal (III) chloride hexahydrate, ($FeCl_3{\cdot}6H_2O$) with the ratio of respectively 2–1 from Fe^{3+} and Fe^{2+} were dissolved in 240 ml of distilled water. Then the chemical deposition was developed between 70 and 90 °C and vigorous stirring after adding NH_4OH. In this ferrofluid, Cetyltrimethylammonium bromide ($C_{19}H_{42}BrN$) or CTAB with a weight ratio of 1–14 of Fe oxide acts as the surfactants.

Fig. 1 shows the analysis of the metal oxide nano particles measurements by a Particle Size Analyzer (PSA) device. The size of the particles is less than 10 nm as it is evident in Fig. 1. The stability of the nanofluid was checked for five hours and during this interval, no change was observed and nanofluid remained stable.

All nanofluids were developed with adding the surfactant and placed in the ultrasonic mixer device and then injected into the PHPs.

2.2. Experimental setup

An overview of the experimental setup is shown in Fig. 2a. Two heat pipes, one made of copper and the other made of Pyrex were prepared. Each one was one-turned with internal and external diameters of 2 mm and 4 mm, respectively. The height of the copper PHP was 45 cm, while the lengths of the evaporator, condenser and the adiabatic section were 10 cm, 15 cm and 20 cm, respectively. For the Pyrex PHP, lengths of the evaporator, condenser and adiabatic section are 12 cm, 12 cm and 20 cm, respectively.

In order to observe the flow regime in the copper heat pipe, a small piece of Pyrex was used in the adiabatic section and silicone glue was used for joint sealing (Fig. 2b). A direct current power supply and a nickel-chrome wire element were used to supply heat power in the evaporator. To reduce contact resistance, tubular wire was tightly wrapped around the tube. The element wrapped around the pipe develops a magnetic field due to having electric current. To neutralize this field, two coils were wrapped around the pipe in opposite direction beside each other. Moreover, two layers of electrical insulation cover were used to avoid electrical current transfer to the heat pipe so that it did not affect the nanofluid. A $16 * 10 * 5\ cm^3$ box was used to dissipate heat from the condenser. Cold water at the temperature of (±18 °C) entered the condenser reservoir and in order to fill or empty the heat pipe, an input pipe was used in the adiabatic section. Fig. 2-c shows a photo of the whole setup.

In order to measure the temperature, K-type thermocouples with an accuracy of ±0.5 °C were used. 3 and 2 thermocouples were used in the evaporator and condenser sections, respectively. The thermocouple's tip was covered by silicone paste to provide a bet-

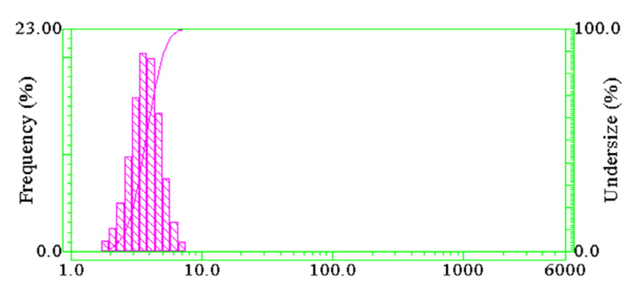

Fig. 1. Particle Size Analysis (PSA) of ferro particles.