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Research Paper

Visualization and thermal resistance measurements for a magnetic nanofluid pulsating heat pipe

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HIGHLIGHTS

- Magnetic field on the Fe_3O_4 nanofluid PHP enhanced the thermal performance.
- Performance of PHP was independent of the magnetic field at a higher heat input.
- Deposition of particles and enhancement in boiling was investigated.

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ABSTRACT

The use of a nanofluid as the working fluid in pulsating heat pipes (PHPs) is currently an attractive technique for heat transfer enhancement. Applying a magnetic field on a magnetic nanofluid-charged PHP enhances thermal performance. To study the mechanism of a magnetic field with magnetic nanofluid can help to reach startup faster in low heat input. A glass PHP with five turns as well as an internal diameter of 3 mm and external diameter of 6 mm was used in the study experiment. Heat input was applied at 20, 55, 90, 125, and 160 W. Deionized (DI) water and iron oxide nanofluid at concentrations of 90, 270, and 450 ppm were used as working fluids. The cooling water temperature was set at 25 °C. The experiment was conducted with and without a magnetic field. A video camera was set up to record the motion of the working fluid in the PHP, and temperatures were measured.

The results revealed that the addition of a magnetic nanofluid could improve the performance of the PHP, and in the magnetic field, thermal resistance decreased with an increase in heat input for all experimental parameters. When the heat input was increased from 20 to 55 W, a marked drop in thermal resistance was observed. In addition, the nanofluid particles were securely deposited on the wall under the influence of the magnetic field. Moreover, the nanofluid enhanced boiling by depositing a layer of nanoparticles on the boiling surface.

1. Introduction

Pulsating heat pipes (PHPs) or oscillating heat pipes work on the principle of a circulating flow of working fluids within a meandering capillary tube. A PHP is also called a meandering capillary tube heat pipe, a self-excited oscillation (pulsation) heat pipe, or Akachi pipe, named after Akachi [1]. When one end of the capillary tube (the evaporator) is heated, the working fluids evaporate and increase the vapor pressure, thus causing the bubbles in the evaporator zone to expand. This pushes the liquid toward the low-temperature end (the condenser). Cooling of the condenser results in a reduction of vapor pressure and condensation of bubbles in that section of the heat pipe. The expansion and collapse of the bubbles in the evaporator and condenser sections, respectively, result in an oscillating motion within the tube. Heat is transferred through latent heat in the vapor and through sensible heat transferred by the liquid slugs [2]. The operational mechanism and heat transfer characteristics of PHPs have been extensively investigated since PHP was proposed [3–6].

Nanofluids have been reported to substantially improve the performance of PHPs. A higher thermal conductivity level and stronger oscillating motion of nanoparticles might be the primary enhancement factors. Theoretically, although nanofluids have a higher heat conduction coefficient that enables them to dissipate more heat, a higher concentration of nanofluids results in higher viscosity. Furthermore, the higher viscosity renders bubble formation difficult, and the friction force intensifies the obstruction between the liquid slug and the tube wall. Thus, obstruction is relatively high when the bubble is promoted and influences the heat

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Nomenclature

q	heat input (W)	$\overline{Te}$	average temperature of evaporator (°C)
R_s	thermal resistance of PHP (°C/W)	$\overline{Tc}$	average temperature of condenser (°C)

transfer efficiency, consequently engendering an optimal concentration. In addition, a thin layer of porous sediments on the wall of the PHP strongly affects the thermal transport capability [7–11].

Ferrofluids (magnetic nanofluids) are promising working fluids exhibiting a high thermal conductivity that may enhance heat transfer. In addition, the thermal performance of ferrofluid-charged PHPs can be influenced by applying a magnetic field. Mohammadi et al. [12] performed an experimental study to explore the effects of working fluids (water and ferrofluid), charging ratio (40% and 70%), heat input (35, 45, 55, 65, 75, and 85 W), orientation (horizontal and vertical heat mode), ferrofluid volumetric concentration (2.5% and 7%), and magnetic field on the thermal performance of PHPs. The PHP was fabricated from a copper tube with an inner diameter of 2.2 mm. A magnetic field was applied using three ceramic magnets placed at a distance of 8 mm from the PHP. These magnets covered 50 mm of the lower part of the evaporator. The magnets measured 100 mm × 50 mm × 20 mm and had a magnetic flux density of 0.055 T on their surface. Experimental results revealed that the magnetic field reduced the thermal resistance of the PHP filled with ferrofluid. In the presence of the magnetic field, the best thermal performance was achieved at a high charging ratio (70%) in all orientations. Ferrofluidic PHPs had a favorable thermal performance in the horizontal mode because of the magnetic force exerted on the ferrofluids. They also found that in the absence of a magnetic field, the thermal resistance associated with 2.5% ferrofluid concentration was lower than that associated with 7% concentration because of the low viscosity. However, in the presence of a magnetic field, the 7% concentration was associated with better thermal performance because of magnetism.

Zhao et al. [13] investigated the magnetic field effect on the oscillating motion and heat transfer in a PHP containing magnetic nanofluids. They applied water-based dysprosium (III) oxide nanofluids at different mass ratios of 0.1%, 0.05%, and 0.01%. The dysprosium (III) oxide nanoparticles measured less than 100 nm. The PHP was fabricated from a copper tube with an inner diameter of 1.7 mm. A magnetic field was applied to the evaporator section of the PHP by using a permanent magnet. The effects of orientation and input power ranging from 50 to 250 W on the heat transfer capability of the heat pipe were investigated. Results revealed that the magnetic field could affect the oscillating motions and enhance the heat transfer performance of the magnetic nanofluid PHP. The magnetic nanoparticles in a magnetic field can reduce the start-up power of the oscillating motion and enhance the heat transfer performance at a low input power.

Understanding the role of nanofluids in PHP operation requires comprehensive knowledge of various mechanisms and the hydrodynamic and thermodynamic complex coupling effect. The magnetic field effects further increase the complexities. Notably, limited visualization studies have been performed using magnetic nanofluids in PHPs. Therefore, the present study experimentally investigated the thermal performance of a PHP by using DI water and water-based magnetic nanofluids. In addition, a visualization study was performed, the findings of which can be helpful for further elucidating the operational behavior of the magnetic nanofluid-charged PHP. Moreover, the characterization of the inner surface condition at the evaporator section because of the nanoparticle deposition was studied. The results of the present study are expected to facilitate understanding and designing more efficient magnetic nanofluid-charged PHPs.

2. Experiment

2.1. Experimental setup

The experiment was conducted using a closed-loop pulsating heat pipe (CLPHP) built by bending a glass tube into five turns with an internal diameter of 3 mm and external diameter of 6 mm. Fig. 1 presents the schematic of the experimental setup and location of the magnet. Heat input was applied on the evaporator by using a DC power supply (Chroma Model 62024 P-80-60) and Ni–Cr heating coils with an electrical resistance of 22.2 Ω/m. The condenser was cooled using a circulator and a thermostatic water bath with a flow rate 0.05 L/min maintained at 25 °C. Fourteen type-T thermocouples were installed along the PHP, and all temperature outputs

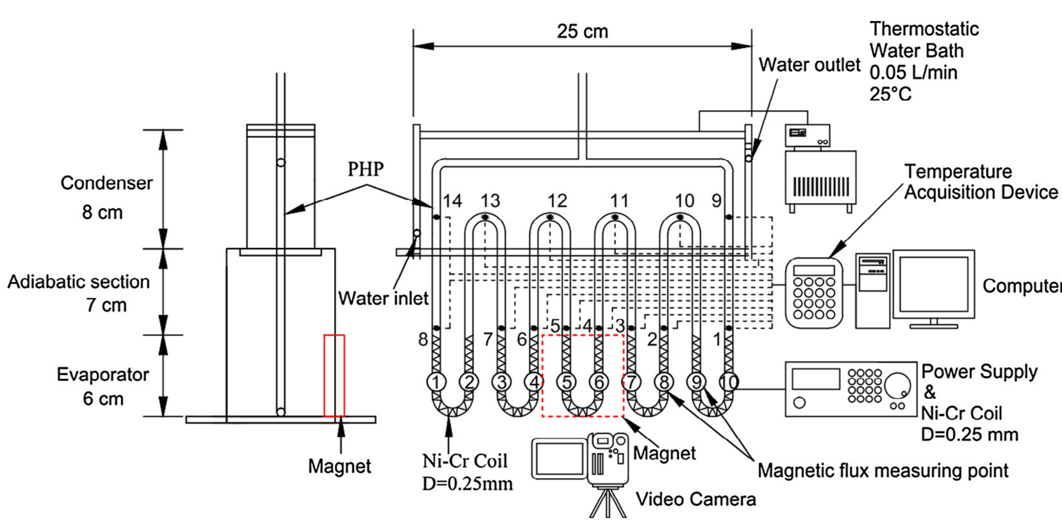

Fig. 1. Schematic of the experimental setup.