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Overall thermal performance of ferrofluidic open loop pulsating heat pipes: An experimental approach

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ABSTRACT

Pulsating heat pipes (PHPs) are simple, cheap, and efficient heat transfer devices. They have applications in electronic cooling. In the present research, an experimental investigation is conducted on startup and steady thermal performances of open loop pulsating heat pipes (OLPHPs). Effects of working fluid, heat input, non-condensable gases (NCGs), ferrofluid concentration, magnets location, and inclination angle on the thermal performance of OLPHPs have been considered. Obtained results show that using ferrofluid can improve the thermal performance in steady state condition. Furthermore, applying a magnetic field enhances the heat transfer characteristics of ferrofluidic OLPHPs in both startup and steady state conditions. At 20 W heating power and startup condition, higher NCGs have the best performance in the presence of magnetic field. However, in the absence of magnetic field opposite trend is observable. In the case of steady thermal performance in both presence and absence of magnetic field, lower amounts of NCGs lead to better thermal performance. Best heat transfer capability is achieved at around 67.5° inclination angle relative to the horizontal axis for all of the working fluids. With the application of magnetic field in different locations of the OLPHPs, one can adjust their thermal performance to the desired value.

1. Introduction

Heat pipes (HPs) are efficient heat transfer devices and their considerable thermal performance is mainly due to their phase change heat transfer. New generation of HPs are pulsating heat pipes (PHPs) that are invented in 1990 by Akachi [1].

PHPs are more efficient than conventional HPs due to the following reasons:

(1) Unlike HPs, heat transfer in PHPs is a combination of latent and sensible heat transfer mechanisms [2].
(2) Due to the same direction of liquid and vapor flows in a PHP, these flows do not influence each other [3].
(3) There is no need to use wick structures in PHPs [4].

Basically, a PHP is formed by bending a capillary tube into several turns and is partially filled with a working fluid. PHPs are composed of three major parts: evaporator, condenser, and adiabatic section. The presence of adiabatic section is not mandatory and is only used when a distance between condenser and evaporator is needed [5].

Heat input to the evaporator is the driving force in PHPs. It results in the evaporation of the liquid film which surrounds the vapor bubbles [6]. Liquid temperature and pressure at the evaporator will be increased due to the boiling phenomenon while they decrease in the condenser due to condensation. So there is a pressure difference between the evaporating and condensing sections that results in the oscillation of working fluid and heat transfer between evaporator and condenser [5]. In addition, with the evaporation of working fluid and expansion of the vapor plugs, the liquid slugs will be pushed to the evaporator through the neighboring tube [6].

PHPs are classified in two types: open loop pulsating heat pipes (OLPHPs) and closed loop pulsating heat pipes (CLPHPs). Two ends of the tube are separated and sealed in OLPHPs while in the case of CLPHPs two ends are connected to each other. In CLPHPs the working fluid can be circulated in the tube [7].

At low heating powers, the movement of working fluid and the resulting heat transfer between evaporator and condenser occurs slowly. Therefore, introducing the PHP with the heat load, results in increment of temperature of evaporating section. This may affect the high temperature sensitive electronic equipments. As a result,

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improving the startup performance of PHPs has led to surveys in the literature.

Quan and Jia [8] performed experiments on a flat plate PHP. They studied the effects of working fluid, charging ratio, and inclination angle on the heat transfer characteristics of PHPs. They reported that after the PHP starts to work the temperature of the evaporating section reduces and the thermal resistance of the PHP decreases.

Xu and Zhang [9] studied startup and steady thermal oscillation of a CLPHP. They reported two kinds of startup process in their survey. They showed that pulsation of the flow at lower heating powers has random performance while at higher heating powers it has a relatively periodic nature.

Li and Yan [10] implementing a glass capillary tube CLPHP, observed the flow patterns of different flow regimes, such as startup, transition and steady state. Effects of charging ratio, and heat transfer rate have been considered in their survey. They mentioned that at top heating orientation annular flow is not observable. They reported 50% as the best charging ratio in their study.

Dispersion of nanometric particles in a base fluid results in higher thermal conductivity [11], and therefore heat transfer enhancement. So using nanofluid in HPs and PHPs is a reliable technique to enhance their thermal performance in comparison to conventional fluids like distilled water.

Tsai et al. [12] used gold nanofluid to study its effect on the heat transport capability of a HP. They found that gold nanofluid can improve the heat transfer characteristics of the HP. They showed that the thermal resistance can vary with the diameter of the gold nanoparticles.

Ma et al. [13] performed experiments on a CLPHP charged with diamond nanofluid and observed considerable enhancements in the thermal performance. They reported that heat transfer performance of the CLPHP depends on working temperature. They could reach thermal resistance of 0.03 °C/W at input power of 336 W.

Qu et al. [14] explored the influence of using Al_2O_3 nanofluid on the heat transfer characteristics of a CLPHP. In addition, they studied the effects of charging ratio, heat input, and nanofluid concentration on the overall thermal performance and showed enhancements in thermal performance in comparison with the case of distilled water. They claimed that variation of surface condition as a result of nanoparticle settlement is the main reason for the enhancements on the thermal performance of Al_2O_3 nanofluid charged CLPHP.

Ji et al. [15] investigated the effects of particle shape on the thermal performance of CLPHPs. They used four different particle shapes of blade, platelet, cylinder and brick. They used a blend of ethylene glycol and deionized water as the base fluid. They showed that particle shape and volume fraction of nanoparticles have impacts on the thermal performance of CLPHPs. They reported cylindrical shape to have the best heat transport capability in the CLPHPs.

To the authors' best knowledge, there is no study on startup and steady thermal performances of ferrofluidic OLPHPs. So the main objective of this research is the implementation of ferrofluid in an OLPHP. The effects of heat input, NCGs, ferrofluid concentration, inclination angle, application of magnetic field as well as magnet location, on thermal performance are thoroughly discussed in this paper.

2. Description of the experiment

2.1. Experimental set-up

Initially a five turn OLPHP is fabricated by bending a copper tube into a serpentine shape. The internal and external diameters of the copper tube are chosen to be 1.75 and 3 mm, respectively. These dimensions ensure the slug–plug flow pattern of the working fluid [7]. Six K type thermocouples are used for temperature measurements, three at the evaporator (T_{e1}, T_{e2}, and T_{e3}) and the rest at the condenser (T_{c1}, T_{c2}, and T_{c3}). Nickel chrome electrical heater is wrapped around the copper tube at the evaporator and the cooling water flow is provided at the condenser. A DC power supply is used in order to supply desired power in electrical heater. A vacuum system including a high vacuum pump and related fittings are used in order to reduce the internal pressure of the OLPHP to desired amount.

OLPHP is divided in three parts: evaporator, condenser, and adiabatic section which are 70, 50, and 80 mm in dimensions, respectively. Evaporator and adiabatic section are insulated during the experiment in order to prevent heat loss. Fig. 1 shows the schematic of experimental set-up.

Three ceramic magnets are used for the application of magnetic field at the evaporator and adiabatic section. They have a magnetic flux density of 3700 G at their surface. The magnets are 50 mm × 100 mm × 25 mm in dimensions.

2.2. Preparation of ferrofluid

The ferrofluid used in this study is synthesized based on the method expressed by Bagheri et al. [16]. The important task which should be considered in all of the steps is to retain the prepared solution in the atmosphere of the N_2 gas. Since Fe_3O_4 nanoparticles tend to react with the oxygen and be converted to the Fe_2O_3. Occurrence of this reaction could be specified from the color of the nanoparticles. Fe_3O_4 nanoparticles are black while Fe_2O_3 nanoparticles are brown in color.

At first, a mixture of 0.85 mL concentrated HCl, 2 g $FeCl_2 \cdot 4H_2O$, and 5.2 g $FeCl_3 \cdot 6H_2O$ under the N_2 gas environment is prepared. Then 250 mL sodium hydroxide solution (1.5 M) is prepared in a container and degassed using N_2 gas. Afterward, the first solution is added slowly to the latter while the latter is fully stirred for about 30 min. Quality of adding the first solution is very important. To have fine and homogenous nanoparticles the addition rate should be drop wise. The resulting solution is the ferrofluid.

Diameter of the nanoparticles is measured using direct light scattering (DLS) technique. This technique is carried out with the use of NanoZS (red badge)-ZEN3600 light scatter from Malvern tool at 25 °C. The average diameter of the nanoparticles of ferrofluid is approximately 25 nm.

Ferrofluid has a large magnetism effect and under the application of magnetic field, nearly all of the nanoparticles are affected.

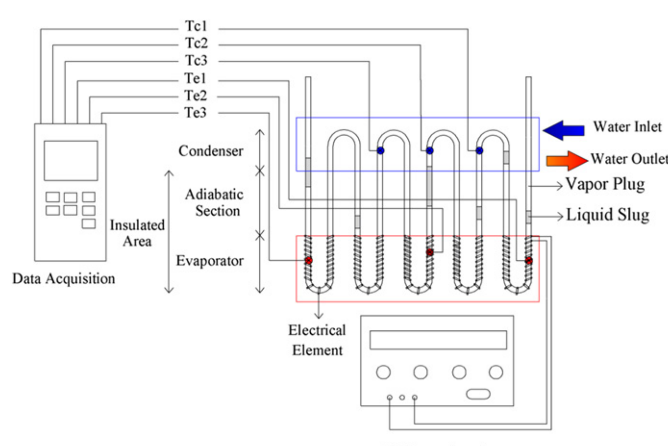

Fig. 1. Schematic diagram of experimental set-up.