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Effect of functionalized MWCNTs/water nanofluids on thermal resistance and pressure fluctuation characteristics in oscillating heat pipe ☆

Md. Riyad Tanshen [a,1], B. Munkhbayar [a,b,1], Md. J. Nine [a], Hanshik Chung [c], Hyomin Jeong [c,*]

[a] *Department of Energy and Mechanical Engineering, Gyeongsang National University, 445 Inpyeong Dong, Tongyeong, Gyeongnam 650-160, Republic of Korea*
[b] *School of Chemical Engineering, The University of Adelaide, SA 5005, Australia*
[c] *Department of Energy and Mechanical Engineering, Institute of Marine Industry, Gyeongsang National University, 445 Inpyeong Dong, Tongyeong, Gyeongnam 650-160, Republic of Korea*

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ABSTRACT

An influence of multi-walled carbon nanotube (MWCNT) based aqueous nanofluids with different concentrations on the heat transport and the relevant pressure distribution in oscillating heat pipe (OHP) has been investigated. The present paper describes the heat transfer phenomena in terms of thermal resistance, pressure and frequency of pressure fluctuation in multi-loop oscillating heat pipe (OHP) charged by aqueous nanofluids with MWCNT loadings of 0.05 wt.%, 0.1 wt.%, 0.2 wt.% and 0.3 wt.%. The multi-loop OHP with 3 mm inner diameter has been conducted in the experiment at 60% filling ratio. Experimental results show that thermal characteristics are significantly inter-related with pressure distribution and strongly depend upon the number of pressure fluctuations with time. The investigation shows that the 0.2 wt.% MWCNTs based aqueous nanofluids obtain maximum number of the fluctuation frequency and low thermal resistance at any evaporator power input. Based on the experimental results, we discuss the reasons for enhancement and decrement of thermal characteristics of the nanofluids.

1. Introduction

The applications of nanofluids are placed in most of the high efficient heat transfer devices since the innovation of this new heat transfer fluid by Choi in 1995 [1]. Oscillating and pulsating phenomena carry great role in the field of heat transfer to control thermal transport into micro cavity. The self exciting oscillation inside the OHP that is driven by the fluctuation of pressure waves occurs with greater and rapid heat transfer from one end to another. The pressure fluctuation occurs due to the nucleate boiling by evaporative section and condensation of the working fluid. The OHP can transfer heat in quick response in any orientations. The article describes the vertical orientation of multi-loop OHP.

Recently, many experiments have been studied in the field of the OHP because of its specific features. Extended investigations of the OHP have been investigated since the first OHP developed by Akachi in 1990 [2]. The mechanism that occurs in the OHP is the utilization of pressure change in volume expansion and contraction during phase change to excite the oscillating motion of liquid plugs and vapor bubbles between evaporator and condenser. Comparing to the OHP with other conventional heat pipes, the unique feature of OHP is that there is no wick structure to return the condensate to the evaporator and no countercurrent flow between the liquid and the vapor flows because both operates in the same direction [3] — (1) The thermally-driven oscillating flow inside the capillary tube effectively produces some free surfaces that significantly enhance evaporating and condensing heat transfer. (2) The oscillating motion in the capillary tube significantly enhances the forced convection in addition to the phase-change heat transfer. These significant characters of OHP make itself very special heat transfer device in modern application.

Past works on the OHP can be concluded within several features such as heat transfer characteristics and capability with different filling ratio, flow visualization inside the OHP, effects of length ratio and diameter on performance of OHP, nanofluids and other applicable fluids have been used as a working fluid for developing OHP performance.

Charoensawan et al. [4], Rittidech et al. [5] and Tong et al. [6] have discussed the effects of several parameters on thermal performance, such as internal diameter, number of turns, working fluid and inclination angle of the device. Wang and Nishio [7] investigated the effect of length ratio of heating section to cooling section on the ultimate heat transport capability of OHP. The influence of gravity on slug flow and influence of number of turns on spatial dynamic pressure affect the OHP performance. Besides the input heat is also a strong parameter that affects dynamic instability especially in density wave oscillation [8,9].

Saha et al. [10] conducted flow visualization for closed-loop PHP made from Teflon tube of 2 mm internal diameter and partially filled with R142b. The PHP consisted of 10 meandering turns and it is

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* Corresponding author.
E-mail addresses: muugii_3685@yahoo.com (B. Munkhbayar), hmjeong@gnu.ac.kr (H. Jeong).
[1] Authors are equally contributed: Md. Riyad Tanshen, B. Munkhbayar.

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Nomenclature

Bo	Bond number
$E\ddot{o}$	Etövös number
D	Tube diameter
g	Acceleration of gravity [m/s^2]
I	Input current [A]
N	Total number of Data
P_m	Mean pressure [Pa]
$\sqrt{\overline{p}^2}$	RMS value of pressure or pressure fluctuation [Pa]
Q	Heat load [W]
R	Thermal resistance [°C/W]
t	Time [s]
$\overline{T}_e$	Average OHP wall temperature in evaporator [°C]
$\overline{T}_c$	Average OHP wall temperature in condenser [°C]
wt	Weight concentration [%]
V	Input voltage [Volts]
ρ	Density[Kg/m^3]
σ	Surface tension [N/m]

Subscript

c	Condenser section
cri	Critical value
e	Evaporator section
i	Inner
liq	Liquid
vap	Vapor

400 mm from the evaporator to condenser. The evaporator was heated by a hot bath and the condenser was cooled by a cold bath. It was concluded that the highest thermal performance for the PHP is achieved when the FR is from 0.5 to 0.6.

In 1998, Chandratilleke et al. [11] developed the cryogenic loop heat pipes. The development of cry cooler cooled superconducting magnet applications, where heat transport distance is large, and the heat conduction by a copper block will be constrained by its cross section transport capacity. Mo et al. [12,13] shows that the heat transport capacity of loop heat pipe with liquid nitrogen as working fluid is very low (26 W) when it operates in horizontal direction and its lowest thermal resistance reaches 1.3 K/W, which is too high for the most of cryogenic heat transport system.

Recently, it was found that the heat transport capability can be increased when nanoparticles [14] or microparticles were added into the base fluid in an OHP. The thermally-excited oscillating motion in the OHP can make the particles suspended in the base fluid. Although the nanoparticles added on the base fluid cannot largely increase the thermal conductivity [13], the oscillating motion of the particles in the fluids may have additional contribution to the heat transfer enhancement in addition to the thermal conductivity. Ma et al. [15] charged the nanofluids into OHP and found that the nanofluids significantly enhance the heat transport capability of OHP. The investigations show that OHP charged with diamond nanofluids can reach a thermal resistance of 0.03 °C/W at power input of 336 W. In 2010, Qu et al. [16] also conducted an investigation of the effect of spherical 56 nm Al_2O_3 particles on the heat transport capability in an OHP and found that the Al_2O_3 particles can enhance heat transfer and an optimal mass fraction exists; although these investigations have demonstrated that the particles can enhance heat transfer in the OHP. It is not well understood whether there exists an optimum particle size for a given type of the particles. Maezawa et al. [17] reported that the appearance and movement of bubbles are affected by surface tension and buoyancy in the channel. The relation of surface tension and buoyancy could be explained by the following dimensionless formula:

$$Bo = D_i \left[\frac{g\left(\rho_{liq} - \rho_{vap}\right)}{\sigma} \right]^{0.5} = \sqrt{E\ddot{o}}.$$

When Eö = 4, the bubble will get seized on both sides of the wall but not moving statically, and the liquid forms liquid slug flow, is calculated instead of getting the critical pipe diameter D_{cri} of OHP. The formula is:

$$D_i < D\Box\_cri \leq 2* \sqrt{\frac{\sigma}{\left(\rho_{lic} - \rho_{Vap}\right) g}}.$$

The tube inner diameter should be small enough to ensure the flow oscillations, i.e. smaller than a critical value. Lately, Nine et al. [18] has investigated a stable hybrid nanofluid combining Al_2O_3 nanoparticles with ground and non-ground type of the MWCNTs into water. They showed that a small inclusion of ground MWCNTs into Al_2O_3/water nanofluids can influence the thermal characteristics in a large scale where the stability of nanofluids does not deteriorate. The article concentrates on the pressure characteristics inside the OHP charged with different concentrations of the nanofluids. The present work explains the inside phenomena of the OHP in terms of pressure where previous works focused on some other necessary parameters. Pressure distribution and repeated fluctuation into the OHP using different concentrations of the nanofluids have been investigated under various evaporator power input. It is well known that the heat transfer by oscillating heat pipe occurs for quick fluctuation of pressure intensity. However, some works over pressure distribution inside the OHP can be hardly found.

2. Experimental setup

2.1. Experimental apparatus and procedure

The installation of multi-loop OHP is shown in Fig. 1 that consists of 100 mm evaporating section powered by a plate type heater and condensing section connected with a constant cooling bath where the middle section between evaporator and condenser is thermally insulated. The heat pipe is made by copper with an inner diameter of 3 mm and a total length of 6 m. The evaporative section is made by two aluminum plates which grooved the inner part precisely to set OHP like sandwich type and both parts are perfectly attached with a flat plate type of electric heater. The evaporative section covers a vertical length of 100 mm OHP where the working input power is maintained in the range of 50 W to 400 W. Similarly, 140 mm of upper loop section was inserted through the sealed condensing tank where the isothermal cooling unit is used to keep the condenser under 18 °C. The middle of this OHP with 200 mm adiabatic section is covered by 2 cm thick glass wool for the perfect thermal insulation. T-type thermocouple was soldered to the outer wall of the OHP in both condensing and evaporative sections to measure the wall temperature of OHP.

After running the system, it takes time approximately 15 to 20 min to get thermally stable. It occurs due to the electric heating that is not directly wrapped on the OHP. One piezoresistive absolute pressure sensor (Model-Kistler 4045A5 Kistler Instruments (Pte) Ltd. Singapore) is set with another small pass tube below the condensing section of the OHP to take the pressure characteristics inside the tube. The sensor is perfectly sealed and tested several times. Data acquisition rate was 100 data points/s and the duration of data was approximately 10 min. To find out the frequency distribution, FFT analysis is worked with 10,240 data. For the convenience of understanding, a part of real experimental setup has been shown just at the right side of Fig. 1.