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Effects of graphene oxide nanofluids on heat pipe performance and capillary limits

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ABSTRACT

In the present study, thermal performances of water-filled and 0.01 and 0.03 vol% graphene oxide (GO)/water nanofluids-filled heat pipes with a screen mesh wick were studied in order to investigate the effects of nanofluids on the heat pipe operation. The wall temperatures of the GO/water nanofluids-filled heat pipes were found to be lower than those of the water heat pipe. Also, the heat pipes charged with GO/water nanofluids showed lower evaporator thermal resistances by about 25% compared with the water-filled heat pipe, although the condenser thermal resistances were similar in both cases. The 0.01 vol% GO/water nanofluid-filled heat pipe showed better boiling heat transfer than 0.03 vol% GO/water nanofluid because of the different structures of the deposited nanoparticle layers on the wicks. The capillary limit of the heat pipes containing GO/water nanofluids was higher than for the water heat pipe, because the nanoparticles-coated layer modified the effective capillary radius and meniscus, resulting in an increase of the maximum liquid flow rate through the wick structure. The SEM images and wetting properties for wicks of the heat pipes with nanoparticles-coated layers support the thermal performance characteristics of the heat pipes obtained in the study.

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1. Introduction

A heat pipe is a device that transfers heat from the hot interface (evaporator) to the cold one (condenser) by phase change and capillary action of the working fluid. The utilization of the evaporation and condensation of the working fluid accompanied by convection through the wick structure, which is a porous medium inducing capillary pumping pressure between the evaporator and condenser sections of the heat pipe, results in a high thermal effectiveness [1]. Also, the heat pipe is a passive heat-transfer device, which does not require any external power source to operate. Thus, it has been widely used as a passive heat transfer device for various purposes, such as solar collectors, CPU cooling devices, and air conditioning systems.

The cooling devices are required to have high heat transfer capability because the development of electronic devices and thermal-controlled power production systems has resulted in high localized heat fluxes. Thus, the enhancement of the thermal performance of heat pipes has been studied extensively using nanofluids, self-rewetting fluids, composite wicks, and annular-type geometry of the test section. The most active research on the enhancement of heat pipe thermal performance is the use of nanofluids. Nanofluids are a new class of nanotechnology-based heat-transfer fluids, engineered by dispersing nanoparticles into conventional heat-transfer fluids with the expectation of improved thermal properties compared with conventional fluids, such as water, ethylene glycol, and oils. The phase change of the working fluid is the main heat transfer mechanism of the heat pipe showing high heat removal capacity. Thus, various nanofluids have been studied as alternatives to the typical working fluids in heat pipes because of their good thermal performances in boiling heat transfer [2–17].

Torri and Tung [2] studied the effect of 0.1, 1.0, 5.0 vol% diamond/water nanofluids on a heat pipe with the aim of developing a multi-heat-pipe cooling device. They found that the heat pipes filled with diamond/water nanofluids show lower evaporator thermal resistances than a water-filled heat pipe, and the reduction of the thermal resistance was amplified as the concentration of nanofluid increased. Chen [3] conducted experiments with 5, 50, 100 ppm silver/water nanofluids in a flat heat pipe. The flat heat

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Nomenclature

A	area [m^2]
C	correlation coefficient
f	friction factor
g	gravity [m/s^2]
K	permeability [m^2]
L	length [m]
M	number of wires per inch
Q	heat input, power [W]
q''	heat flux [kW/m^2]
r	radius [m]
R	thermal resistance [°C/W]
Re	Reynolds number
t	temperature difference between evaporator section and condenser section [°C]
T	temperature [°C]

Greek symbols

ε	porosity
ρ	density [kg/m^3]
σ	surface tension [N/m]
μ	dynamic viscosity [Pa·s]
λ	latent heat of vaporization [kJ/kg]
ψ	tilt angle
δ	thickness [mm]

Subscript

avg	average
b	bare
c	condenser
cap	capillary
ce	effective capillary
e	evaporator
eff	effective
h	hydraulic
l	liquid
n	nanoparticle
max	maximum
sat	saturation
tot	total
v	vapor
w	wick

pipes containing silver/water nanofluids had lower thermal resistances than a heat pipe using water as the working fluid with a maximum reduction of 71%. They concluded that the thermal performance of a heat pipe does not strongly depend on the thermal conductivity of the working fluid, and the higher wettability of the nanofluids-filled heat pipes contributes to the flattening of temperature distribution and the reduction of thermal resistance. Sarafraz et al. [4] investigated the effect of TiO_2/water nanofluids on the heat transfer of a heat pipe at initial steady states and a long operation time. They confirmed that the increased number of nucleation sites caused the reduced thermal resistance, and the effect became large as the concentration of nanofluid increased at initial steady states. However, the long operation time resulted in blocking of small cavities formed on the wick structure by fouled nanoparticles. The fouling effect increased the thermal resistance after a certain operation time. Hajian et al. [5] experimentally studied the response time and thermal performance of 50, 200, 600 ppm silver/water nanofluids-filled heat pipes. The response time, which is the time to steady state, and thermal resistance were decreased for 50 ppm silver/water nanofluid-charged heat pipe. Although the thermal performance was enhanced at low concentration, the nanofluids with higher concentration caused reverse effects by agglomeration and instability of the nanofluid. Venkatachalapathy et al. [6] analysed the thermal performance of a copper mesh wick heat pipe using water based CuO nanofluids. The thermal resistance of the heat pipe was reduced with increasing CuO nanoparticles concentration. They concluded that the addition of CuO nanoparticles provides more area for liquid boiling at the evaporator section and thus enhances the thermal performance of a heat pipe. Do et al. [7] carried out experiments to observe the effect of Al_2O_3/water nanofluids on the thermal performance of a heat pipe. A 40% reduction of the thermal resistance at the evaporator-adiabatic section of the heat pipe was observed. They concluded that the thin porous coating layer, which consisted of Al_2O_3 nanoparticles at the evaporator section, improved surface wettability and capillary wicking performance reducing the thermal resistance of the heat pipe. Kole et al. [8] studied the effect of 0.5 wt% copper/water nanofluids on the heat transfer of a vertically mounted heat pipe. The thermal resistance was reduced by 27% compared with a water heat pipe, because the nanoparticle-coated layer enhanced the surface wettability, surface roughness, and capillarity. Solomon et al. [9] investigated the heat transfer characteristics of a copper heat pipe with copper oxide nanoparticles deposited on a screen wire mesh wick. They reported that the heat pipe containing the wick that was coated with copper oxide nanoparticles showed the maximum reduction in the thermal resistance of 40% because of the increased number of nucleation sites. Septiadi et al. [10] studied the effect of Al_2O_3/water and TiO_2/water nanofluids on the thermal performance of heat pipes and found that 5% volume concentration of these nanofluids reduced the temperature at the evaporator by as much as 23.7% and 20.2%, respectively, compared with water. They suggested that the enhanced thermal performance resulted from the increased Brownian motion of the nanofluids and the reduced pore size of the mesh wick due to the nanoparticles coating. Wang et al. [11] investigated the thermal performance of a mesh heat pipe using a CuO nanofluid as the working fluid. The total thermal resistance of the nanofluid heat pipe was reduced to about half of that of a water heat pipe with the 40% increased maximum heat removal.

Many other studies have also examined the thermal performance of heat pipes using various nanofluids [12–18]. Brownian motion, increased bubble departure frequency, improved wettability, and increased number of nucleation sites due to nanoparticle deposition on the wick structures were found to be the reasons for enhanced thermal performances of nanofluids-filled heat pipes. Table 1 summarizes the literatures on the heat pipes using nanofluids. Graphene oxide (GO)/water nanofluids were studied in pool boiling conditions to observe the effects of nanofluids in terms of boiling heat transfer coefficients and critical heat flux [19–21]. GO/water nanofluids showed an enhanced boiling heat transfer and critical heat flux simultaneously, although some nanofluids reported deteriorated boiling heat transfer and enhanced critical heat flux [22–28].

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