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Analytical study of multiple evaporator heat pipe with nanofluid; A smart material for satellite equipment cooling application

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ABSTRACT

Thermal management of satellite equipment is one of the most significant issues in the space industries. Heat generated by electrical component should be dissipated to avoid damaging the satellite. Heat pipe with discrete heat sources is often used to remove heat flux from satellite heat dissipating equipment. In this work, a two-dimensional analysis is used to evaluate the thermal performance of a cylindrical heat pipe with multiple heat sources (evaporators) using nanofluid. Pure water and Al_2O_3–water mixture are used as working fluids. The effect of particle concentration level ($\varphi = 0$ (distilled water), 2, 4, and 8%) and head load ($Q = 30$, 60, and 90 W) on the wall temperature, pressure drop, velocity field, thermal resistance, thermal-hydraulic performance, and heat pipe size is investigated. A remarkable decrease in wall temperature is observed, especially on the heat sources. It is found that heat transfer coefficient increases as particle concentration increases while an existence of an optimal particle concentration level for the lowest pressure drop and thus best thermal-hydraulic performance is established. There is a significant reduction in the thermal resistance and size of heat pipe when nanofluid is used. Results also show that applying nanofluid for the higher heat loads, in which more heat removal is required, has a more pronounced effect on the heat transfer rate augmentation and temperature reduction of satellite equipment. This useful feature of Al_2O_3–water proved its potential as a smart material in satellite equipment cooling application.

1. Introduction

High-efficiency cooling systems are considered as key points in the design of satellites to solve growing problem of heat generated by electronic equipment. Heat pipes are often used as heat exchanger in space application because they transfer the heat with relatively smaller temperature gradient without using pump. In this regard, several studies have been carried out [1–3]. Park [1] investigated the operation of a cylindrical heat pipe with two heat sources, both numerically and experimentally, to optimize the heat distribution of satellite equipment. As another clear example, Kim et al. [3] suggested a new spacecraft thermal control hardware composed of heat pipe and solid–liquid phase change material for high heat dissipating component. Heat dissipating components in satellite such as high power amplifier, frequency converter, and power supply are inserted in a series on a heat pipe embedded in a honeycomb panel. Each of these components acts such a heat source which corresponds to an evaporator section in heat pipe [1]. Therefore heat pipe with multiple discrete heat sources (evaporators) has been widely used in satellite equipment cooling application rather than conventional heat pipe with only one evaporator. The limiting factor in heat pipe performance is the poor thermal properties of conventional working fluid such as water, ammonia, ethanol, and ethylene glycol. Loading nanoparticle with high thermal conductivity into basefluid can be considered as a remedy to overcome this limitation. This type of fluid is called "nanofluid" which was firstly introduced by Choi and Eastman [4]. Due to high thermal conductivity of nanofluids, several efforts have been made to engage it in a heat pipe [5–14]. Some of these studies are summarized by Alawi et al. [15], Bahrami et al. [16], and Liu and Li [17].

A two-dimensional modeling is applied by Shafahi et al. [5] to investigate the thermal performance of a cylindrical heat pipe using three of the most common nanofluid, namely Al_2O_3, CuO, and TiO_2. It was found that the presence of nanoparticles within

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Nomenclature

B_c	Boltzmann constant	
d	diameter	m
h	convective heat transfer coefficient	
h_{fg}	latent heat of the working fluid	KJ/Kg
I	modified Bessel function of first kind	
k	thermal conductivity	W/m K
K	modified Bessel function of second kind permeability of the wick	m^2
L	heat pipe length	m
l_{bf}	mean free path of the basefluid	m
p	pressure	Pa
Q	heat load	W
$\ddot{q}$	heat flux	W/m^2
R	radius m, heat pipe thermal resistance	K/W
r	cylindrical coordinates	m
T	temperature	m
U	local mean vapor velocity	m
u	axial velocity	m/s
v	radial velocity	m/s
x	cylindrical coordinates	m

Greek symbols

α	basefluid thermal diffusivity	m^2/s
ε	porosity of the wick	
η	thermal-hydraulic performance	
φ	Nanoparticle volume fraction	
μ	Dynamic viscosity	$N\,s/m^2$
ρ	Density	kg/m^3

Subscripts

a	adiabatic
bf	basefluid
c	condenser
e	evaporator
l	liquid
nf	nanofluid
np	nanoparticle
o	outer surface of heat pipe
v	vapor, wick–vapor interface
w	wall, wall–wick interface

the liquid improves the thermal performance of the heat pipe by decreasing the thermal resistance and there is an optimum mass concentration for nanoparticles in maximizing the heat transfer limitation. These authors [6] also used analytical models to evaluate the thermal performance of rectangular and disk-shaped heat pipes using nanofluids and reported similar results to their previous study. Alizad et al. [7] investigated thermal performance, transient behavior and operational start-up features of flat-shaped heat pipe using nanofluid and showed an enhancement in the heat pipe performance for both flat-plate and disk shape heat pipes during the transient process. Tsai et al. [8] showed that the thermal resistance of heat pipe can be decreased between 20% and 37% when gold–water nanofluid is used. Kang et al. [9] investigated experimentally the application of water-based silver nanofluid for a conventional 1 mm wick-thickness sintered circular heat pipe and reported that the addition of nanoparticles into basefluid can decrease the temperature difference between condenser and evaporator 0.56–0.65 °C compared to pure water at an input power of 30–50 W. Putra et al. [10] conducted an experimental investigation to determine the effect of concentration and type of the nanofluid (Al_2O_3–water, Al_2O_3–ethylene glycol, TiO_2–water, TiO_2–ethylene glycol and ZnO–ethylene glycol) on the enhancement of thermal performance within a straight copper heat pipe. The best performance was the one with Al_2O_3–water with 5% volume concentration. The experiments showed that using nanofluids in the heat pipe forms coatings on the screen mesh surface which is resulted from the nanoparticles in the fluid. Kumaresan et al. [11] studied a copper sintered wick heat pipe using CuO nanoparticles dispersed in DI water. The experimental results demonstrated a reduction in the thermal resistance of 66.1% and enhancement in the heat transfer coefficient and thermal conductivity of 29.4% and 63.5% is respectively, observed for 1.0 wt.% of CuO/water nanofluid at 45° tilt angle compared with heat pipe kept at horizontal position. Chen et al. [12] conducted experiments for applying water, ethanol and nanofluids as working fluids in a new type of copper wire-bonded flat heat pipe. They reported that the best heat transfer performance of heat pipe is achieved at the concentration of 1.0 wt.%. An experimental study was performed by Hung et al. [13] to investigate the application of the aqueous suspension of Alumina nanoparticle in a cylindrical heat pipe. The heat pipe was a straight copper tube with an outer diameter of 9.52 mm and different lengths of 0.3 m, 0.45 m, and 0.6 m. The results showed that at a heating power of 40 W, the optimal thermal performance for Al_2O_3/water nanofluid heat pipes measuring 0.3 m, 0.45 m, and 0.6 m was 22.7%, 56.3%, and 35.1%, respectively, better than that of pipes using distilled water as the working fluid. An experimental investigation was recently carried out by Kumaresan et al. [12] to compare the enhancement in the thermal performance of sintered and mesh wick heat pipes by varying the working fluid, inclination angle and heat input. The results revealed that the maximum reduction in surface temperature is obtained for sintered wick heat pipe at 45° tilt angle and 60° for mesh wick heat pipe with CuO/DI water nanofluid concentration at 1.0 wt.% for both the cases.

Although no study was conducted to investigate the application of nanofluid in a heat pipe with multiple heat sources, some research groups [1,18,19] studied the performance of cylindrical heat pipe with discrete heat sources using water as working fluid. Lefevre and Lallemand [18] presented an analytical solution for both the liquid and vapor flows inside a flat micro heat pipe (MHP) coupled to an analytical solution for the temperature inside the MHP wall. A two-dimensional analysis was used by Shabgard and Faghri [19] for cylindrical heat pipes subject to multiple uniform heat sources and a constant heat flux or convective cooling condenser. They compared their results with those of numerical simulation and observed a very good agreement.

Respecting our problem which is the application of nanofluid for cylindrical heat pipe with multiple heat sources, there are a few works [20–22] in the literature concerning the application of nanofluid forced concentration for discrete heat sources cooling. Mashaei et al. [20] investigated the flow and heat transfer characteristics of nanofluid in a parallel plate channel with discrete heat sources. The heat sources were placed on the bottom wall at a constant heat flux, and remaining channel surfaces were considered adiabatic. It is found that the use of nanofluid can produce an asymmetric velocity along the height of the channel and the wall temperature decreases remarkably as Reynolds number and volume fraction increase. They [21,22] also reported that applying nanofluid for multiple heat sources cooling in a parallel plates (two-dimensional) channel has more remarkable effect compared to a three-dimensional one and nanofluid can be used as smart fluid. More recently, a numerical simulation was carried out by Mashaei et al. [23] to investigate the laminar forced convection