Advanced Powder Technology 27 (2016) 1539–1546

Contents lists available at ScienceDirect

Advanced Powder Technology

journal homepage: www.elsevier.com/locate/apt

Original Research Paper

Effects of magnetic field strength and direction on anisotropic thermal conductivity of ferrofluids (magnetic nanofluids) at filmwise condensation over a vertical cylinder

A. Malvandi [a,*], S. Heysiattalab [b], D.D. Ganji [c]

[a] Department of Mechanical Engineering, Neyshabur Branch, Islamic Azad University, Neyshabur, Iran
[b] Mechanical Engineering Department, Islamic Azad University of Qaemshahr, Qaemshahr, Iran
[c] Mechanical Engineering Department, Babol University of Technology, Babol, Iran

ARTICLE INFO

Article history:
Received 6 March 2016
Received in revised form 16 April 2016
Accepted 18 May 2016
Available online 31 May 2016

Keywords:
Filmwise condensation
Magnetic nanofluids
External magnetic field
Anisotropic thermal conductivity
Nanoparticle migration

ABSTRACT

Brownian diffusion and thermophoresis are two primary sources of nanoparticle migration in nanofluids which have considerable impact on thermophysical properties of ferrofluids (magnetic nanofluids). Furthermore, orientation and intensity of magnetic fields influence the thermal conductivity of ferrofluids and make them anisotropic. In this paper, a theoretical investigation on filmwise condensation of ferrofluids over a vertical cylinder in the presence of a uniform variable-directional magnetic field is investigated, taking into account the anisotropic effects of thermal conductivity. The modified Buongiorno's model is employed for the nanoparticle–fluid suspension to simulate the nanoparticle slip velocity relative to the base fluid originating from the thermophoresis (nanoparticle slip velocity due to temperature gradient) and Brownian motion (nanoparticle slip velocity due to concentration gradient). The distribution of nanoparticles inside a condensate film is analytically obtained and it is revealed that the heat transfer rate is improved further when the angle between the magnetic field and temperature gradient grows.

1. Introduction

The condensation process is a crucial part of recent heat removal equipment and has several industrial applications. Heat transfer rate associated with condensation process is more than an order of magnitude larger than those associated with conventional heat transfer methods like conduction and convection. Nusselt [1] was the first to present theoretical models to examine the filmwise condensation heat transfer of pure vapors over tubes and plates. Then, several publications were devoted to developing our understanding on film condensation which is fully reviewed in the literature such as [2–5]. Shang [6] reviewed the theory of filmwise condensation in a comprehensive study and introduced novel similarity solutions for a wide range of basic problems. Nonetheless, few studies have been conducted on the condensation of nanofluid vapor. Recently, Avramenko et al. [7] investigated a model for the heat transfer of nanofluids condensate film over a vertical plate. Their model developed the Nusselt's classical model by including an equation for the nanoparticle concentration (the dependency of the nanofluid density on the nanoparticle concentration is considered). Then, Turkyilmazoglu [8] investigated the effects of considering the slip velocity of nanoparticles for the condensate film of nanofluids and indicated that slip mechanisms are responsible for additional heat transfer enhancement. However, both studies [7,8] did not consider the effects of nanoparticle migration on fluid flow and heat transfer characteristics.

1.1. Nanoparticle migration due to slip mechanisms

Nanoparticle migration induced by slip mechanisms in nanofluids is a key factor that enhances the thermal conductivity and heat transfer rate of nanofluids. According to Buongiorno [9], Brownian diffusion and thermophoresis are two significant slip mechanisms in nanofluids. The effects of Brownian motion and thermophoresis on the nanoparticle migration of nanofluids have been investigated by several researchers. For example, Garoosi et al. [10] conducted a numerical simulation of natural convection of the nanofluid in heat exchangers using Buongiorno model. Ghalambaz et al. [11] investigated the effects of nanoparticles diameter and concentration on

* Corresponding author. Tel.: +98 21 65436416; fax: +98 21 65436660.
E-mail address: amirmalvandi@aut.ac.ir (A. Malvandi).

http://dx.doi.org/10.1016/j.apt.2016.05.015

Nomenclature

c_p	specific heat ($m^2\ s^{-2}\ K^{-1}$)
d_p	nanoparticle diameter (m)
D_B	Brownian diffusion coefficient
D_T	thermophoresis diffusion coefficient
g	gravity (m/s^2)
h_p	specific enthalpy of nanoparticles (J/kg)
HTC	heat transfer coefficient
J_p	nanoparticle mass flux ($kg/m^2\ s$)
H_a	Hartmann number
k	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
k_{BO}	Boltzmann constant ($= 1.3806488 \times 10^{-23}\ m^2\ kgs^{-2}\ K^{-1}$)
N_{BT}	ratio of the Brownian to thermophoretic diffusivity
q	energy flux relative to the nanofluid (W)
q''_w	surface heat flux ($W\ m^{-2}$)
T	temperature (K)
u	axial velocity ($m\ s^{-1}$)
x, r	coordinate system

Greek symbols

α	magnetic field angle
β	proportionality factor
δ	condensate film thickness
ε	ratio of condensate film thickness to cylinder radius $\varepsilon = \delta/R$
ϕ	nanoparticle volume fraction
γ	normal temperature difference, $\gamma = (T_{sat} - T_w)/T_w$
η	transverse direction
μ	dynamic viscosity ($kg\ m^{-1}\ s^{-1}$)
ρ	density ($kg\ m^{-3}$)
τ	shear stress (Pa)

Subscripts

B	Brownian index
BT	ratio of Brownian to thermophoretic index
bf	base fluid
k	thermal conductivity index
p	nanoparticle
sat	saturation condition
t	time index
T	thermophoresis index
w	condition at the wall
μ	dynamic viscosity index
ρ	density index

Superscripts

t	transpose of a matrix
$*$	dimensionless variable

natural convection of the alumina–water nanofluids considering variable thermal conductivity around a vertical cone in porous media. Then, Yang et al. [12] considered the effects of nanoparticle migration on forced convective heat transfer of alumina/water and titania/water nanofluids in circular, parallel plate, and tube-in-tube channels and introduced the modified Buongiorno model. In the modified Buongiorno model, the viscosity and thermal conductivity of nanofluids are both depended on the nanoparticle volume fraction. On the other hand, the nanoparticle volume fraction is non-uniformly distributed by the ratio of Brownian motion and thermophoresis. Thus, it can be stated the modified Buongiorno model is able to consider the effect of nanoparticle volume fraction distribution. Next, Malvandi et al. [13] employed the modified Buongiorno model and conducted a numerical analysis on mixed convection of nanofluids in a vertical concentric annulus. In another study, Malvandi and Ganji [14] investigated the effects of nanoparticle migration on alumina/water nanofluids in a parallel-plate channel. They demonstrated that nanoparticles migrate from the adiabatic wall (nanoparticle depletion) toward the cold wall (nanoparticle accumulation) and construct a non-uniform nanoparticle distribution. In addition, the anomalous heat transfer rate occurs when the Brownian motion is significant. Bahiraei and Vasefi [15] presented a novel thermal dispersion model to improve the prediction of nanofluid convective heat transfer. Then Bahiraei [16] studied the effective factors on the nanoparticle migration for the laminar flow in a circular tube. Hedayati and Domairry [17] studied the effects of nanoparticle migration on titania/water nanofluids in a vertical channel. Then, Malvandi [18] studied the film boiling of magnetic nanofluids over a vertical plate in the presence of a uniform variable-directional magnetic field. They indicated that the nanoparticle migration has significant effects on heat transfer characteristics of nanofluids. In another study, Malvandi et al. [19] studied the transport phenomenon of the nanofluids falling condensate film, taking into account the effects of the nanoparticle migration. They indicated that the intensity and direction of nanoparticle migration are able to manage the thermophysical properties of nanofluids, as well as the control of flow, heat transfer, and mass transfer, in order to improve the cooling performance. More details can be found in different scientific researches, for example [20–25].

1.2. Magnetic nanofluids

Magnetic nanoparticles are generally arranged in different sizes and shapes of metal (ferromagnetic materials) such as iron, cobalt, nickel and their oxides (ferrimagnetic materials) like magnetite (Fe_3O_4). Although magnetic nanoparticles, with respect to metallic and metallic-oxide nanoparticles, have relatively low thermal conductivity, their possibility of controlling the thermal conductivity and viscosity under an external magnetic field makes them as an efficient option to intensify the heat transfer rate of equipment. Few investigations have so far been conducted on fluid flow and heat transfer characteristics of magnetic nanofluids. Jafari et al. [26] employed a two-phase mixture model to investigate natural convective heat transfer of kerosene-based Ferrofluids under an external magnetic field. Their results show that employing an external magnetic field perpendicular to the temperature gradient enhances the heat transfer rate further than that of using a parallel magnetic field. Wrobel et al. [27] conducted an experimental and numerical analysis on thermo-magnetic convective flow of paramagnetic fluid in vertical annular enclosures. They concluded that a strong magnetic field is able to tune the magnetic convection of paramagnetic fluid. The impact of space dependent magnetic field on natural convective heat transfer of Fe_3O_4–water nanofluid was studied by Sheikholeslami and Rashidi [28]. Their results show that the heat transfer rate decreases as Rayleigh number increases. Malvandi et al. [29,30] considered the effects of nanoparticle migration on hydromagnetic convective heat transfer of alumina/water nanofluid inside horizontal and vertical microchannels. They indicated that while the nanoparticle volume fraction was smaller than 0.1, the maximum increase in the values of heat transfer rate was 37% for small nanoparticles which dropped to 14% for larger nanoparticles. Sheikholeslami et al. [31,32] studied the effects of magnetic field on heat transfer characteristics of nanofluids in a