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Film boiling of magnetic nanofluids (MNFs) over a vertical plate in presence of a uniform variable-directional magnetic field

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ABSTRACT

External magnetic fields are able to tune the thermophysical properties of magnetic nanofluids (MNFs) and control the flow and heat transfer rate. Orientation and intensity of the external magnetic field would influence the thermal conductivity of MNFs and makes it anisotropic. The motivation behind this study is the need to examine the effects of anisotropic behavior of thermal conductivity on flow field and heat transfer characteristics at film boiling of MNFs over a vertical plate in the presence of a uniform variable-directional magnetic field. The modified Buongiorno model is employed for modeling the nanofluids to observe the effects of nanoparticle migration. The results have been obtained for different parameters, including Brownian motion to thermophoretic diffusion N_{BT}, saturation nanoparticle concentration ϕ_{sat}, Hartmann number Ha, magnetic field angle α, and normal temperature difference $\gamma = (T_w - T_{sat})/T_w$. A closed form expression for the distribution of nanoparticle volume fraction has been obtained and the effects of pertinent parameters on heat transfer rate have been investigated. It has been shown that the heat transfer rate is improved further when an external magnetic field exerts in the direction of the temperature gradient.

1. Introduction

Inclusion of nano-sized particles is a method to construct more efficient heat exchange equipment, because they improve thermal conductivity of regular cooling fluids such as water, oil, and ethylene-glycol. Nanoparticles have intentionally higher thermal conductivity relative to the working fluids and, due to their similar size to the molecules of the base fluids, they would not induce any significant problems (abrasion, clogging, fouling and additional pressure loss in heat exchangers) compared with larger particles. For magnetic nanoparticles, the magnetic nanofluid (MNF) introduces a different behavior that can be controlled by an external magnetic field. The possibility of controlling the flow and heat transfer characteristics makes MNFs ideal for several types of heat exchange equipment, particularly in developing magnetically controlled heat transfer in energy conversion systems, heat transfer enhancement for cooling of high powers, solar collectors, and miniature electronic devices like microelectromechanical systems (MEMSs). Magnetic nanoparticles are generally arranged in different sizes and shapes from metal (ferromagnetic materials) such as iron, cobalt, nickel and their oxides (ferrimagnetic materials) like magnetite (Fe_3O_4). Although magnetic nanoparticles have relatively low thermal conductivity rather than metallic and metallic oxide nanoparticles, their possibility of controlling the thermal conductivity and viscosity under an external magnetic field makes them an effective option for a suspension to enhance the heat transfer rate of equipment.

1.1. Magnetic field effects

Few investigations have so far been conducted on fluid flow and heat transfer characteristics of magnetic nanofluids. Jafari et al. [1] employed a two-phase mixture model to investigate natural convective heat transfer of kerosene-based MNFs under an external magnetic field. Their outcomes indicated that using a magnetic field normal to the temperature gradient increases the heat transfer rate further than that of using a parallel magnetic field. Wrobel et al. [2] conducted an experimental and numerical analysis on thermo-magnetic convective flow of paramagnetic fluid in vertical annular enclosures. They stated that a strong external magnetic field is able to control magnetic convection of paramagnetic fluid. The effects of space dependent magnetic field on free convection of Fe_3O_4–water nanofluid have been investigated by Sheikholeslami and Rashidi [3]. The control volume based finite element method (CVFEM) is employed to solve the governing equations to consider the combined ferrohydrodynamic and magnetohydrodynamic effects. They stated that heat transfer

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Nomenclature

c_p	specific heat (m^2/s^2 K)
D_B	Brownian diffusion coefficient
D_T	thermophoresis diffusion coefficient
Ha	Hartmann number
HTC	heat transfer coefficient
k	thermal conductivity (W/m K)
k_{BO}	Boltzmann constant (=1.3806488 × $10^{-23} m^2 kg/s^2 K$)
N_{BT}	ratio of the Brownian to thermophoretic diffusivity
q''_w	surface heat flux (W/m^2)
T	temperature (K)
u	axial velocity (m/s)
x, y	coordinate system

Greek symbols

δ	film thickness
ϕ	nanoparticle volume fraction
γ	normal temperature difference, $\gamma = (T_w - T_{sat})/T_w$
η	transverse direction
μ	dynamic viscosity (kg/m s)
ρ	density (kg/m^3)

Subscripts

bf	base fluid
p	nanoparticle
w	condition at the wall

Superscripts

*	dimensionless variable

enhancement reduces with an increase in the Rayleigh number. Goharkhah et al. [4] experimentally investigated the convective heat transfer and hydrodynamic characteristics of magnetic nanofluids under the effects of an alternating magnetic field. Their results indicated that the convective heat transfer coefficient is proportional to the Reynolds number as well as the nanoparticle volume fraction. Furthermore, they maintained that there is an optimum frequency for every single Reynolds number which grows as the Reynolds number increases. The effects of chain-like magnetic nanoparticles aggregates on thermal conductivity of MNFs under the external magnetic fields have been investigated by Nkurikiyimfura et al. [5]. The anisotropic feature of thermal conductivity was shown via an external magnetic field which induced chain-like nanoparticle aggregates. They stated that when a magnetic field is parallel to the temperature gradient, the thermal conductivity component in the direction of the magnetic field would be strongly enhanced because of the induced chain-like nanoparticles aggregates. More investigations on heat transfer performance of MNFs have been conducted by different researchers which can be found in open literature [6–12]. A complete review on magnetic field effects has been conducted by Bahiraei and Hangi [13].

1.2. Migration of nanoparticles

Nanoparticle migration is a basic phenomenon in nanoparticle–fluid mixtures that arises due to nanoparticle slip velocity relative to the base fluid, thereby significantly affecting the thermophysical properties of nanofluids. Nanoparticles migrate due to the slip mechanisms in nanofluids, a key aspect that enhances the thermal conductivity and heat transfer rate of nanofluids. According to Buongiorno [14], Brownian diffusion and thermophoresis are the dominant slip mechanisms in nanofluids. Their impacts on nanoparticle migration within nanofluids have been extensively studied [15–21]. Recently, Yang et al. [22] modified the Buongiorno model to consider the effects of nanoparticle migration on forced convective heat transfer of alumina–water and titania–water nanofluids in a circular annulus. Malvandi et al. [23], subsequently extended their study by considering the mutual effects of buoyancy and nanoparticle migration on mixed convection of nanofluids in vertical annular tubes. In another study, Malvandi and Ganji [24] examined the impacts of nanoparticle migration on alumina/water nanofluids in a parallel-plate channel. Their findings indicated that nanoparticles move from the adiabatic wall (nanoparticle depletion) to the cold wall (nanoparticle accumulation), which results in their non-uniform distribution. Hedayati and Domairry [25,26] investigated the effects of nanoparticle migration on titania/water nanofluids in horizontal and vertical channels. Their results indicated that nanoparticle migration has significant effects on heat transfer characteristics of nanofluids. Bahiraei [27] studied the effects of nanoparticle migration on flow and heat transfer characteristics of magnetic nanoparticle suspensions. More details on these phenomena can be found in other pertinent studies in this field [28–32].

1.3. Film boiling

Due to a large internal energy difference between the liquid and vapor states, boiling process releases a significant amount of heat. This makes it ideal for several heat exchange purposes such as evaporation and condensation in heat pipes, immersion and microchannel cooling of microelectronics, and crystal growth. The ability of nanoparticles to enhance the Critical Heat Flux (CHF) is one of the recently discovered and very intriguing features of nanofluids. You et al. [33] experimentally studied the effects of Cu nanoparticles on CHF of water in pool boiling heat transfer from a flat square heater. The authors reported that the enhancement of CHF is significant when nanofluid, rather than pure water, is used as a cooling liquid. Bang and Chang [34] investigated boiling heat transfer characteristics of alumina–water nanofluids. They stated that CHF was enhanced in not only horizontal but also vertical pool boiling. The quenching curves for small (~1 cm) metallic spheres exposed to pure water and water-based nanofluids with alumina, silica and diamond nanoparticles at low concentrations ($\leqslant$0.1 vol%) were acquired experimentally by Kim et al. [35]. Their findings indicated that the quenching behavior in nanofluids is nearly identical to that in the pure water. However, the authors also found that nanoparticles accumulate on the surface, leading to vapor film destabilization in subsequent tests, thus greatly accelerating the quenching process. Lotfi and Shafii [36] conducted an experimental study, aiming to investigate the boiling heat transfer characteristics of nanofluids for Ag and TiO_2 nanoparticles. They maintained that inclusion of nanoparticles into water diminishes the film boiling mode at lower temperatures, the value of which depends on the mixture concentration. In addition, the authors concluded that the heat transfer rates were lower than those in pure water. Recently, Avramenko et al. [37] proposed an approach based on Buongiorno model to study the film boiling of