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Anisotropic behavior of magnetic nanofluids (MNFs) at film boiling over a vertical cylinder in the presence of a uniform variable-directional magnetic field

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ABSTRACT

Brownian motion and thermophoresis are two primary sources of nanoparticle migration in nanofluids which have substantial impacts on thermophysical properties of nanofluids. In addition, orientation and intensity of an external magnetic field influence the thermal conductivity of MNFs and make them anisotropic. An external magnetic field is also able to amend the thermophyscial properties of magnetic nanofluids (MNFs) to improve the thermal performance. The motivation behind this study is the need to examine the anisotropic behavior of thermal conductivity and its effects on flow field and heat transfer characteristics at film boiling of MNFs over a vertical cylinder in the presence of a uniform variable-directional magnetic field. The results have been obtained for different parameters, including the Brownian motion to thermophoretic diffusion N_{BT}, saturation nanoparticle concentration ϕ_{sat}, Hartmann number Ha, magnetic field angle α, ratio of film thickness to cylinder radius ε, and normal temperature difference $\gamma = (T_w - T_{sat})/T_w$. A closed form solution for the nanoparticle distribution is obtained and it has been indicated that the heat transfer rate is improved further when an external magnetic field is aligned in the direction of the temperature gradient. Furthermore, it is shown that the larger nanoparticles intensify the nanoparticle migration and enhance the heat transfer rate.

1. Introduction

Due to a large internal energy difference between the liquid and vapor states, boiling process releases a considerable 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 (MEMs), and crystal growth. On the other hand, the ability of nanoparticles to enhance the Critical Heat Flux (CHF) is one of the most recent intriguing features of nanofluids. 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 system, heat transfer enhancement for cooling of high powers, solar collectors, and miniature electronic devices like microelectromechanical system.

1.1. Film boiling

You et al. [1] experimentally studied the effects of Cu nanoparticles on CHF of water in pool boiling heat transfer from a flat square heater. They indicated that the enhancement of CHF is significant when nanofluid, instead of pure water, is used as a cooling liquid. Bang and Chang [2] investigated the 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 (⩽0.1 vol%) were acquired experimentally by Kim et al. [3]. They indicated that the quenching behavior in nanofluids was nearly identical to that in the pure water. But, it was found that nanoparticles accumulate on the surface, leading to destabilization of the vapor film in subsequent tests, thus greatly accelerating the quenching process. Lotfi and Shafii [4] conducted an experimental study to investigate the boiling heat transfer characteristics of nanofluids for Ag and TiO_2 nanoparticles. They maintained that

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Nomenclature

c_p	specific heat (m^2/s^2 K)
D_B	Brownian diffusion coefficient
D_T	thermophoresis diffusion coefficient
HTC	heat transfer coefficient
Ha	Hartmann number
k	thermal conductivity (W/m·K)
k_{BO}	Boltzmann constant ($=1.3806488\times10^{-23}$ m^2 kg/s^2 K)
N_{BT}	ratio of the Brownian to thermophoretic diffusivity
$\ddot{q}_w$	surface heat flux (W/m^2)
T	temperature (K)
u	axial velocity (m/s)
x, r	coordinate system

Greek symbols

α	magnetic field angle
ε	ratio of film thickness to cylinder radius $\varepsilon=\delta/R$
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

inclusion of nanoparticles to water diminishes the film boiling mode at the lower temperatures depending on the mixture concentration. Also, they concluded that the heat transfer rates were lower than those in the pure water. Recently, Avramenko et al. [5] proposed a model based on Buongiorno model to study the film boiling of nanofluids over a vertical flat plate. Their model takes into consideration the Brownian and thermophoretic diffusion mechanisms, together with the nanoparticle concentration effects on the fluid properties. A complete review on this subject was investigated by Fang et al. [6].

1.2. Nanoparticle migration

Nanoparticles migrate due to slip mechanism in nanofluids, a key aspect that enhances the thermal conductivity and heat transfer rate of nanofluids. According to Buongiorno [7], Brownian diffusion and thermophoresis are the dominant slip mechanisms in nanofluids. Brownian motion pushes the nanoparticles in the opposite direction of the concentration gradient and tries to make the nanofluid more homogeneous. Thermophoresis induces the nanoparticle migration in the opposite direction of the temperature gradient (from a warmer to a colder region), causing a non-uniform nanoparticle distribution. In fact, once the nanoparticle concentration gradient is extended by the thermophoretic force, Brownian force tends to counterbalance the former effect. The impacts of Brownian motion and thermophoresis on nanoparticle migration of nanofluids have attracted several attentions. For example, Yang et al. [8] 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. [9], then, extended their study to consider the mutual effects of buoyancy and nanoparticle migration for mixed convection of nanofluids in a vertical annular tube. In another study, Malvandi and Ganji [10] studied the impacts of nanoparticle migration on alumina/water nanofluids in a parallel-plate channel. They indicated that the motion of nanoparticles is from the adiabatic wall (nanoparticle depletion) to the cold wall (nanoparticle accumulation) which it leads to constructing a non-uniform nanoparticle distribution. Moshizi et al. [11] theoretically investigated the convective heat transfer and pressure drop characteristics of Al_2O_3–water nanofluid inside a concentric pipe in the presence of heat generation/absorption. Their results indicated that the changes of the heat transfer coefficient enhancement in the case of heat generation are much more than in the case of heat absorption. Then, Moshizi [12] studied the convective heat and mass transfer characteristics of Cu–water nanofluid inside a porous microchannel in the presence of a uniform magnetic field. He concluded that the inclusion of Cu-nanoparticles to the fluid has a significant influence on decreasing the nanoparticle concentration and temperature distribution at the both walls as well as the velocity profile along the microchannel. Hedayati and Domairry [13,14] investigated the effects of nanoparticle migration on titania/water nanofluids in horizontal and vertical channels. They indicated that nanoparticle migration has significant effects on heat transfer characteristics of nanofluids. Bahiraei [15] studied the effects of nanoparticle migration on flow and heat transfer characteristics of magnetic nanoparticle suspensions. More details can be found in different scientific researches, for example [16–28].

1.3. Magnetic nanofluids

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 as an effective option for a suspension to enhance 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. [29] 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. [30] 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 [31]. They stated that heat transfer enhancement reduces with an increase of Rayleigh number. Goharkhah et al. [32] 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. The effects of chain-like magnetic nanoparticle aggregates on thermal conductivity of MNFs under the external magnetic fields have been investigated by Nkurikiyimfura et al. [33]. The anisotropic feature of thermal conductivity was shown via an external magnetic field which induced chain-like nanoparticle aggregates. More investigations on heat transfer performance of MNFs have been conducted by different researchers which can be found in open literature [34–46].

1.4. Motivation and the novel contributions

The intensity and direction of an external magnetic field is able to tune the thermophysical properties of nanofluids, as well as control the flow and heat transfer, to improve the cooling performance. Further,