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Thermophoresis and Brownian motion effects on heat transfer enhancement at film boiling of nanofluids over a vertical cylinder

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ABSTRACT

Thermophoresis and Brownian motion are two important sources of nanoparticle migration in nanofluids, which have considerable effects on the thermophysical properties of nanofluids. In the present study, a theoretical investigation on the impact of nanoparticle migration on the heat transfer enhancement at film boiling of nanofluids over a vertical cylinder has been conducted. Alumina-water and titania-water nanofluids have been considered to examine the impacts of different nanoparticle types and the modified Buongiorno model is employed for modeling the nanoparticle migration in nanofluids. The results are obtained for different parameters, including the Brownian motion to thermophoretic diffusion N_{BT}, saturation nanoparticle concentration ϕ_{sat}, 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 nanoparticle migration considerably affects the flow fields and heat transfer rate. It is shown that the smaller nanoparticles are able to accumulate at the heated wall and enhance the heat transfer rate. For larger nanoparticles, however, nanoparticle depletion at the heated walls prevents considerable enhancement in the heat transfer rate. Furthermore, inclusion of alumina nanoparticles signifies a better cooling performance compared to titania nanoparticles.

1. Introduction

Because of a large internal energy difference between the liquid and vapor states, boiling process releases an important 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 nanoparticles helps construct more efficient heat exchange equipments since they improve the 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.

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 is used as a cooling liquid instead of pure water. Bang and Chang [2] 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 (≤0.1 vol%) were acquired experimentally by Kim et al. [3]. They indicated that the quenching behavior in nanofluids is 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 inclusion of nanoparticles to water diminishes the film boiling mode at lower temperatures depending on the mixture concentration. Also, they concluded that the heat transfer rates were lower than those in 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. Then, Malvandi [6] studied the film boiling of magnetic nanofluids over a vertical plate in presence of a uniform

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Nomenclature

c_p	specific heat (m^2/s^2 K)
D_B	Brownian diffusion coefficient
D_T	thermophoresis diffusion coefficient
HTE	heat transfer enhancement
k	thermal conductivity (W/m·K)
k_{BO}	Boltzmann constant ($=1.380648810^{-23}$ 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, r	coordinate system

Greek symbols

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

variable-directional magnetic field. A complete review on this subject was investigated by Fang et al. [7].

1.2. Nanoparticle migration

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 [8], Brownian diffusion and thermophoresis are the dominant slip mechanisms in nanofluids. The impacts of Brownian motion and thermophoresis on nanoparticle migration of nanofluids have been attracted several attentions. For example, Yang et al. [9] 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. [10], then, extended their study to consider the mutual effects of buoyancy and nanoparticle migration for mixed convection of nanofluids in a vertical annular tubes. In another study, Malvandi and Ganji [11] 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 construction a non-uniform nanoparticle distribution. Moreover, as the Brownian motion takes control of the nanoparticle migration, the anomalous heat transfer rate occurs. Hedayati and Domairry [12,13] 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 [14] 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 [15–30].

1.3. Motivation and the novel contributions

The intensity and c able to tune the thermophysical properties of nanofluids, as well as control the flow and heat transfer, to improve the cooling performance. Migration of nanoparticle and its effect on heat transfer enhancement at film boiling of nanofluids has not been a subject of a study yet. Thus, in the present study, the film boiling of nanofluids over a vertical cylinder has been investigated theoretically considering the effects of nanoparticle migration. The motivation behind this study has three aspects: a) to model the film boiling of nanofluids via developing a formula for nanoparticle migration inside the film boiling and b) considering the effects of nanoparticle migration on the flow fields including velocity, temperature, and nanoparticle volume fraction profiles as well as how the migration of nanoparticles affects the heat transfer rate and c) comparing different nanoparticle type and find the methods for intensifying the heat transfer rate. To do this, the modified Buongiorno's model is used for the nanofluids considering the two important sources of nanoparticle migration, namely thermophoresis and Brownian motion. Two different types of nanoparticles (titania and alumina) have been considered to examine the effects of thermophysical properties. To the best of the author's knowledge, no study has been done on this concept so far and our outcomes are novel and original.

2. Problem formulation

Fig. 1 illustrates the physical geometry and the schematic formation of a continuous boiling vapor film of nanofluids flowing steadily upwards on a vertical cylinder in contact with a fluid, when the surface temperature (T_w) is heated above the local saturation temperature at

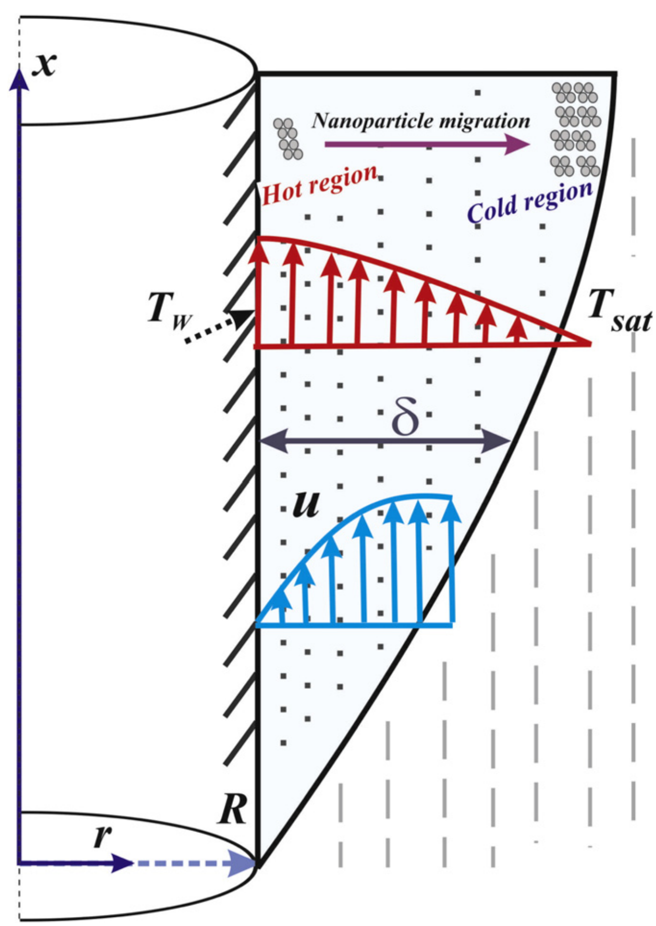

Fig. 1. The geometry of physical model and coordinate system.