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Original Research Paper

Effects of nanoparticles migration on heat transfer enhancement at film condensation of nanofluids over a vertical cylinder

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ABSTRACT

The change in concentration and direction of nanoparticle migration can control the thermophysical properties of nanofluids. This dynamic is useful since it is able to improve the cooling performance by tuning the flow and heat transfer rate. In the current study, a theoretical investigation on the impact of nanoparticle migration on heat transfer enhancement of nanofluids condensate film over a vertical cylinder has been conducted. The Brownian motion and thermophoretic diffusivity have been considered by using the modified Buongiorno model which can take into account the effect of nanoparticle slip velocity. The results have been obtained for different parameters, including the Brownian motion to thermophoretic diffusivities N_{BT}, the saturation nanoparticle volume fraction ϕ_{sat}, and the normal temperature difference $\gamma = (T_{sat} - T_w)/T_w$. It is shown that nanoparticle migration has significant impact on the flow and thermal fields and considerably affects the heat transfer rate. Furthermore, heat transfer enhancement in film condensation is strongly depended on the thermophysical properties of nanoparticles such that alumina-water nanofluid exhibits higher cooling performance than titania-water.

1. Introduction

The condensation process is the change of the physical state of matter from gas to liquid phase. It usually releases a significant amount of heat due to large internal energy differences between the liquid and vapor states. Thus, it is ideal for several heat exchange equipments, especially in heat transfer enhancement for high-power cooling, food processing, biotechnology, and miniature electronic devices like microelectromechanical systems (MEMS) [1,2]. In addition, thermal performance of solar systems will be enhanced with the inclusion of nanoparticles to the working fluid. Consequently, it can be stated that nanofluids are able to participate in considerable reduction of carbon emissions. Generally, the heat will transfer inside the condensate film merely by conduction depending on the thickness of the film and the condensation rate. Either the thickness of the condensate film or the condensation rate of vapor depends on thermophysical properties which can be tuned by nanoparticle inclusion. Inclusion of nanoparticle improves the heat exchangers performance since it improves the thermal conductivity of regular cooling fluids such as water, oil, ethylene-glycol, and power-law fluid [3]. Notably, nanoparticles have higher thermal conductivity relative to the working fluids and due to their similar size to the molecules of the base fluid, they would not induce any significant problems (abrasion, clogging, fouling and additional pressure loss in heat exchangers) relative to larger particles. However, the stability of nanofluids is an extreme challenge in front of scientists and researchers. The stability of nanofluids is commonly depended to the method of nanoparticle preparation. Nevertheless, inclusion of surfactants is a useful technique to avoid aggregation of nanoparticles and to improve the stability. Their impact on the environment is another concern of using nanofluids that we have to face with. Public concerns about their safety forced the engineers to be prudent to produce green nanofluids by biodegradable and nontoxic nanoparticles.

1.1. Film condensation

Nusselt [1] originally presents a theoretical model for the film condensation of pure vapors over tubes and plates. Then, several

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Nomenclature

c_p	specific heat (m^2/s^2 K)
dp	nanoparticle diameter (m)
C_B	reduced Brownian diffusion coefficient (1/K), $C_B = D_B/T$
C_T	reduced thermophoretic diffusion coefficient, $C_T = D_T/\phi$
D_B	Brownian diffusion coefficient
D_T	thermophoretic diffusion coefficient
g	gravity (m/s^2)
hp	specific enthalpy of nanoparticles (J/Kg)
HTE	heat transfer enhancement
Jp	nanoparticle mass flux (kg/m^2 s)
k	thermal conductivity (W/m K)
k_B	Boltzmann constant (=$1.3806488 \times 10^{-23}$ m^2 kg/s^2 K)
N_{BT}	ratio of the Brownian to thermophoretic diffusivities
$\mathbf{q}$	energy flux relative to the nanofluid (W)
q''_w	surface heat flux (W/m^2)
R	cylinder radius (m)
T	temperature (K)
u	axial velocity (m/s)
x, r	coordinate system

Greek symbols

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 s)
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

publications are devoted to develop our understanding on film condensation which are fully reviewed and presented in literature such as [4–9]. Furthermore, Shang [10] conducted a comprehensive study of theory of film condensation and introduced novel similarity solutions for a wide range of basic problems. Nevertheless, few studies have been conducted for the condensation of nanofluid vapor.

Recently, Avramenko et al. [11] introduced a model for the heat transfer of nanofluids condensate film near a vertical plate. Their model developed the classical model of Nusselt by adding an equation for the nanoparticle concentration and a dependence of the nanofluid density on the nanoparticle concentration. In another study [12], they studied the heat transfer rate at condensate film of moving vapor with nanoparticles over a flat surface. They concluded that increasing the nanoparticle volume fraction enhances the processes of momentum and heat transfer. They also employed their model to study the stable film boiling of nanofluids over vertical surfaces [13]. Malvandi et al. [14] considered the laminar film condensation of nanofluids over a vertical flat plate considering nanoparticles migration. Turkyilmazoglu [15] investigated the effects of considering the slip velocity of nanoparticles for the condensate film of nanofluids and indicated that slip mechanisms can be responsible for additional heat transfer enhancement. It should be noted that study of the film condensation of nanofluids is important due to the wide range of applications in nanoparticle synthesis, thermosyphons cooling, and heat transfer in nano and micro heat exchangers [16].

1.2. Migration of nanoparticles

There are several papers in literature deal with the steady or unsteady motion of particles in regular fluids [17,18]. However, for nanofluids, nanoparticles migrate because of nano-scale slip mechanisms that intensify the thermal conductivity and heat transfer rate of nanofluids. According to Buongiorno [19], Brownian diffusion and thermophoresis are merely two important 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, Yang et al. [20,21] consider 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. Malvandi et al. [22] conducted a numerical analysis on mixed convection of nanofluids in a vertical concentric annulus. In another study, Malvandi and Ganji [23] investigated the effects of the nanoparticle migration on alumina/water nanofluids in a parallel-plate channel. They demonstrated that nanoparticles move from the adiabatic wall (nanoparticles depletion) toward the cold wall (nanoparticles accumulation) and construct a non-uniform nanoparticle distribution. In addition, the anomalous heat transfer rate occurs when the Brownian motion takes control of the nanoparticle migration. Hedayati and Domairry [24,25] studied the effects of nanoparticle migration on titania/water nanofluids in horizontal and vertical channels. They indicated that nanoparticles migration has significant effects on heat transfer characteristics of nanofluids. More details can be found in different scientific researches, for example [26–33].

1.3. Motivation

Recently, the thermophysical behaviors of film condensation of ferrofluids (magnetic nanofluids) as a class of metallic nanofluids in the presence of variable-directional magnetic field have been considered theoretically [34,35]. Their results indicated that anisotropic behaviors of thermophysical properties of ferrofluids in the presence of magnetic field are able to control the heat transfer behavior. However, film condensation of non-magnetic (regular) nanofluids (simply nanofluids) over a vertical cylinder has not been a subject of a study yet. Consequently, there is a need to consider the different behavior of heat transfer rate at film condensation