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Research Paper

Laminar filmwise condensation of nanofluids over a vertical plate considering nanoparticles migration

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HIGHLIGHTS

- An exact analytical solution for nanoparticle distribution inside the condensation film is obtained.
- Effects of nanoparticle migration on heat transfer enhancement in the film are studied.
- Thermophoresis and Brownian motion effects on the cooling performance are studied.
- It is shown that alumina nanoparticles reveal better performance than titanium.

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ABSTRACT

This is an investigation on developing the transport phenomenon of the nanofluids falling condensate film, taking into account the effects of nanoparticle migration. 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. Thus, Brownian motion and thermophoretic diffusivity have been considered by using the modified Buongiorno model to observe the effects of nanoparticle slip velocity relative to the base fluid. Our outcomes have been obtained for different parameters, including the ratio of Brownian motion to thermophoretic diffusivity N_{BT}, saturation nanoparticle volume fraction ϕ_{sat}, and normal temperature difference $\gamma = (T_{sat} - T_w)/T_w$. It is revealed that increasing ϕ_{sat} and decreasing γ enhance the heat transfer rate and the nanoparticle volume fraction inside the condensate film. In addition, as the nanoparticle diameter increases, its migration grows in the film, which intensifies the nanoparticle volume fraction on the cold wall. Further, inclusion of alumina nanoparticles signifies a better cooling performance than titania.

1. Introduction

Condensation is a crucial part of recent heat removal equipment and has several industrial applications. Heat transfer rates associated with condensation process are 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 are fully reviewed and presented in the literature, such as [2–7]. Shang [8] reviewed the theory of film 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. [9] investigated a model for the heat transfer of nanofluids condensate film near a vertical plate. Their model developed the Nusselt's classical model by including an equation for the nanoparticle concentration and a dependence of the nanofluid density on the nanoparticle concentration. In another study [10], the heat transfer rate at condensate film of moving vapor with nanoparticles over a flat surface was studied. They concluded that increasing the nanoparticle volume fraction enhances the momentum and heat transfer rate. Turkyilmazoglu [11] investigated the effect of considering the slip velocity of nanoparticles for the condensate film of nanofluids and indicated that slip mechanisms could be responsible for additional heat transfer enhancement. The proposed model also used to study the stable film boiling (the opposite behavior with respect to the film condensation) of nanofluids over vertical surfaces [12,13]. Then, Malvandi [14,15] considers the film boiling of magnetic nanofluids (MNFs) over a vertical plate and cylinder in the presence of a uniform

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variable-directional magnetic field. A completed review of the nanofluids film characteristics is conducted by Fang et al. [16].

Nanoparticle flux due to slip mechanisms in nanofluids is a key factor that enhances the thermal conductivity and heat transfer rate of nanofluids. According to Buongiorno [17], Brownian diffusion and thermophoresis are the only two important slip mechanisms in nanofluids. The effects of Brownian motion and thermophoresis on nanoparticle migration of nanofluids have been investigated by several researchers. For example, Yang et al. [18,19] 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. Malvandi et al. [20,21] conducted a numerical analysis on mixed convection of nanofluids in a vertical channel and concentric annulus. In another study, Malvandi and Ganji [22] investigated the effects of nanoparticle migration on alumina/water nanofluids in a parallel-plate channel. They demonstrated that nanoparticles move 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 takes control of the nanoparticle migration. Hedayati and Domairry [23,24] studied 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 [25] and Bahiraei and Hosseinalipour [26] considered the effect of particle migration on flow and heat transfer characteristics of magnetic nanoparticle suspensions and TiO_2–water nanofluid respectively. Malvandi and Ganji [27] examined the effects of nanoparticle migration on hydromagnetic mixed convection of alumina/water nanofluid in vertical channels with asymmetric heating. Ghalambaz et al. [28] investigated the effects of nanoparticles diameter and concentration on natural convection of the alumina–water nanofluids considering variable thermal conductivity around a vertical cone in porous media. Ahmed and Eslamian [29] considered the effects of flow inertia and external forces on heat transfer and fluid flow characteristics of nanofluid in a microchannel. Sheikholeslami et al. [30,31] studied the effects of magnetic fields on heat transfer characteristics of nanofluids in a semi annulus with and without taking into account the thermal radiation. In the case of free convection, Garoosi et al. [32] conducted a numerical simulation of natural convection of the nanofluid in heat exchangers using Buongiorno model. Parvin and Chamkha [33] investigated the free convection flow, heat transfer and entropy generation of nanofluids in an odd-shaped cavity. Sarkar et al. [34] examined a buoyancy driven convection of nanofluids in an infinitely long channel under the effect of a magnetic field. Sheremet and Pop [35] considered the free convection in a porous horizontal cylindrical annulus with a nanofluid using Buongiorno model. Their results show that inclusion of nanoparticles into pure water alters the flow structure at low Rayleigh number.

1.1. Motivation

Condensation process releases a significant amount of heat because of a large internal energy difference between the liquid and vapor states. It is ideal for several heat exchange equipment in biotechnology, food processing, heat transfer enhancement for high-power cooling, and miniature electronic devices like microelectromechanical systems (MEMS). Basically, heat is transferred to condensate film merely by conduction, which depends on the thickness of the film and condensation rate of the vapor. Both the thickness of condensate film and the condensation rate of vapor depend on thermophysical properties, which can be tuned by the inclusion of nanoparticles. Inclusion of nanoparticle helps to construct more efficient heat exchange equipment, because it improves 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 [17,36].

1.2. Novel contributions of the paper

The current study has three aspects: (a) to develop a formula for nanoparticle migration inside the film condensation, (b) to consider the effect of nanoparticle migration on thermophysical properties of nanofluids and how it can influence the heat transfer rate, and (c) to compare different nanoparticle types and find the methods for intensifying the heat transfer rate. As a result, in this paper, the falling filmwise condensation of nanofluids over a vertical flat plate has been investigated theoretically considering the effects of nanoparticle migration. Modified Buongiorno's model is used for the nanofluids considering the dependency of Brownian motion and thermophoresis to temperature and nanoparticle concentration, respectively. To the best of the authors' knowledge, no study has been done on this concept so far, and our outcomes are novel and original.

2. Problem formulation and model development

Fig. 1 illustrates the physical geometry and the schematic formation of a continuous condensate film of nanofluids over a vertical plate in contact with a vapor, when the surface temperature (T_w) is cooled below the local vapor saturation temperature (T_{sat}). Under the influence of gravity, the formed condensate film at the top of the plate flows downward. A two-dimensional coordinate system is considered where the x-axis is aligned vertically and the y-axis is normal to the walls. The following assumptions are made hereinafter originating from the analysis of Nusselt [1]:

- Flow has been assumed to be laminar.
- The vapor temperature is constant such that the condensation is the only heat transfer mechanism at the liquid–vapor interface.

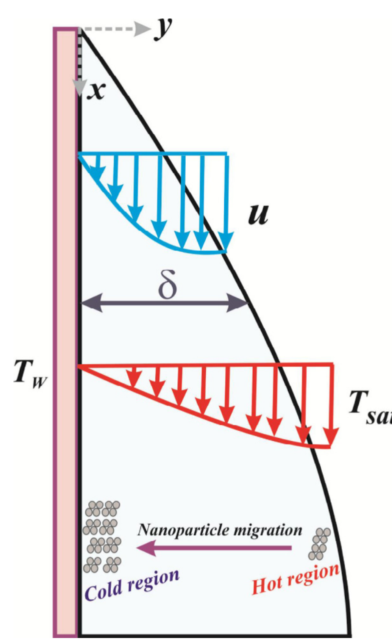

Fig. 1. The geometry of physical model and coordinate system.