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Heat transfer in stable film boiling of a nanofluid over a vertical surface

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ABSTRACT

The paper focuses on modeling of heat, momentum and concentration transport in stable film boiling of a nanofluid over a vertical surface. An approximate analytical model of the transport processes in the vapor film was employed in simulations. The model takes into account effects of the Brownian and thermophoretic diffusion. The novelty of the model consists in pinpointing six major non-dimensional parameters, which describe effects of the nanoparticles on heat transfer and fluid flow in the vapor film. They include: (i) parameter A that accounts for the relation between the thermophoretic and Brownian diffusion; (ii) the nanoparticle concentration φ_∞ in the vapor; (iii and iv) the normalized densities of the nanoparticles R_{pv} and R_{pf}; (v) the relative thermal conductivity of the nanoparticles K; and (vi) parameter m that characterizes the viscosity of nanofluids. Novel analytical solutions resulting from this model characterize velocity profiles, the mass flow rate, the thickness of the vapor film and the Nusselt number as the functions of the aforementioned parameters. It was demonstrated that an increase in the nanoparticles concentration fosters the processes of momentum, mass and heat transfer.

1. Introduction

It is well known that nanoparticles added to a single phase fluid significantly enhance heat transfer as discussed in details in the reviews of Wenhua et al. [1], Kakaç and Pramuanjaroenkij [2] and Buschmann [3]. Keblinski et al. [4] paid special attention to the heat transfer mechanisms in suspensions of nanoparticles in nanofluids. Relatively recently, an interest arose to the study of the influence of nanoparticles on heat transfer with phase transitions. This interest is stipulated by a perspective to employ the nanofluids for nuclear applications elucidated by Bang et al. [5] and quenching processes discussed by Kim et al. [6]. A number of papers reported a significant increase in the HTC (or wall heat flux) at boiling of different nanofluids. Rohsenow [7] demonstrated experimentally that the HTC in boiling of water with an addition of TiO_2 and Al_2O_3 nanoparticles can exhibit a rise up to 4 to 5 times. Kim et al. [6] documented results of the modern research of the CHF in nanofluids. Addition of the TiO_2, SiO_2, CeO_2, Al_2O_3, Au and ZnO nanoparticles in water and ethylene glycol has abruptly, by 170–200%, increased the CHF. Similar trends in the variation of the HTC and the CHF in nanofluids were disclosed in the works of Ramesh and Prabhu [8], Das et al. [9], Wang and Mijumdar [10] and Bang and Chang [11].

Nevertheless, heat transfer augmentation was different in different studies. Experiments with a CuO-water nanofluid performed by Ramesh and Prabhu [8] revealed that in nucleate boiling the HTC and the CHF increase together with the mass concentration of nanoparticles. However, when the nanoparticle concentration reached 1%, the HTC attained its maximum; at larger nanoparticle concentrations, the heat transfer deteriorates. Bang and Chang [11] studied the CHF in boiling of a nanofluid Al_2O_3-water over a surface of 100 mm^2. With an increase in the nanoparticle concentration, the CHF exhibited a rise of 32% over a horizontal and 13% over a vertical flat surface. Although Das et al. [9], Wang and Mijumdar [10] and Lotfi and Shafii [12] observed heat transfer deterioration and CHF reduction at boiling in nanofluids. A boiling curve and the CHF in an Al_2O_3-water nanofluid in the pool at a nanoparticle concentration of 0–0.05 g/l was investigated by You et al. [13]. It was disclosed that the HTCs in the nanofluid and water were the same, and the heat transfer efficiency in nucleate boiling does not depend on the presence of nanoparticles.

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Nomenclature

A	parameter A, the relation between the mechanisms of the thermophoretic and Brownian diffusion, Eq. (18)
c_p	specific heat of the nanoparticles
D_B	Brownian diffusion coefficient
D_T	thermophoretic diffusion coefficient
g	acceleration of gravity
G	mass flow rate through the vapor film
k	thermal conductivity of the vapor with nanoparticles
K	normalized thermal conductivity of the nanoparticles, Eq. (20)
L_v	latent heat of vaporization
Nu	Nusselt number, Eq. (54)
Pr	Prandtl number
q_w	heat flux density at the wall
R	ratio of the densities of the nanoparticles and the fluid, Eq. (18)
T	temperature
u	streamwise velocity component
U	dimensionless velocity, Eq. (36)
x, y	Cartesian coordinates

Greek symbols

δ	thickness of the vapor film
ΔT	temperature difference, Eq. (16)
η	dimensionless coordinate, Eq. (16)
Θ	dimensionless temperature, Eq. (16)
μ	dynamic viscosity of the vapor with nanoparticles
ρ	density of the vapor with nanoparticles
φ	nanoparticle concentration (volume fraction)

Subscripts

f	fluid
p	properties of nanoparticles
v	properties of the pure vapor
w	wall
∞	outer boundary of the condensation film

Superscripts/Subscripts

(6) (7)	valid for boundary conditions (6) and (7)
(9) (10)	valid for boundary conditions (9) and (10)

Acronyms

HTC	heat transfer coefficient
CHF	critical heat flux
3D	three-dimensional

Bang et al. [5] explained the differences in the behavior of the boiling curves by the appearance of a layer of nanoparticles on the surface of the heater, whose thickness is up to several microns. This layer may change the contact angle (which quantifies the wettability of a solid surface by a liquid) and the number of the bubble-producing cites. In addition, the formation of a layer of nanoparticles fosters an increment in the radial heat conduction on the heating surface. Kim et al. [6] and Lotfi and Shafii [12] incorporate results of an investigation into quenching of steel and Zircaloy spheres in water and nanofluids with additions of aluminum, silicon and diamond nanoparticles. The measurements demonstrated that the film boiling did not set on, because nanoparticles are accumulated on the surface of a sphere. This entails destabilization of the vapor film and essentially accelerates the hardening process. All the data described above relate to the nucleate boiling. There is virtually no data on the influence of nanoparticles on laminar film boiling.

Intensive experimental investigations of the boiling processes in nanofluids have been undertaken during the last several years. An experimental study to investigate the pool boiling heat transfer characteristics of functionalized nanofluid at atmospheric and sub-atmospheric pressures has been carried out by Yang and Liu [14]. It was found that functionalized nanofluid can enhance the HTC comparing with the water case, but has nearly no effect on the CHF. Wen et al. [15] studied nucleate boiling heat transfer with aqueous alumina nanofluids on two specially designed surfaces. They showed that for the smooth surface, the deposition of particles onto the heating surface increases the surface roughness contributing to the increase in nucleate boiling heat transfer, while for the rough surface, no obvious change in the surface geometry is observed that results in a similar boiling curve.

Sheikhbahai et al. [16] investigated nucleate boiling and critical heat flux (CHF) of Fe_3O_4/ethylene glycolewater nanofluid at atmospheric pressure on a horizontal thin NiCr wire. Experiments showed that boiling heat transfer coefficients deteriorate by increasing nano-particle concentration in a nanofluid. Khoshmehr et al. [17] conducted experiments using two samples with rough and smooth surfaces at four different nanoparticle concentrations. They found that CHF values are lower in nanofluids of any nanoparticle mass concentration than in water and decrease with increasing mass concentration. Abedini et al. [18] have numerically investigated sub-cooled flow boiling of a nanofluid. Increasing the nanoparticle concentration enhances the heat transfer. It is shown that the low concentration of nanoparticles (about 1–2%) would be more effective than the higher concentration (about 4%). Li et al. [19] have tried developing a mechanistic model of nucleate boiling of nanofluids for nuclear applications. Park et al. [20] studied heat transfer at film boiling of Al_2O_3 nanofluids over a small steel sphere with the diameter of 10 mm. They found that presence of nanoparticles enhances vaporization process during the film boiling and decreases heat fluxes. However, there is virtually no data on the influence of nanoparticles on laminar film boiling over a vertical flat plate, which may occur in biotechnology and food processing industry.

Numerous theoretical investigations into heat transfer in nanofluids have been performed during the last years. The boundary layer flow of a nanofluid was modeled using the Buongiorno-Darcy model and a finite-difference scheme by Thama et al. [21]. Effects of thermophoresis were modeled theoretically in detail by Eslamian and Saghir [22]. Hassan and Harmand [23] developed a 3D transient model of a vapor chamber and investigated effects of the nanofluids on its performance. An exhaustive critical analysis to the predictive models currently available for thermal conductivity of carbon nanotubes based nanofluids was performed by Lamas et al. [24]. A numerical investigation of the steady state developing flow and heat transfer in spiral tube coils using the FLUENT software has been undertaken by Altaç and Altun [25].

Among other analytical mathematical techniques, self-similar analysis is currently relatively widely employed to simulate laminar and turbulent boundary layer emerging in nanofluid flow over flat surfaces. Thermophysical properties of a nanofluid depending on both the nanoparticle concentration and temperature were incorporated as a part of the model of Avramenko et al.