International Journal of Heat and Mass Transfer 82 (2015) 316–324

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Heat transfer at film condensation of moving vapor with nanoparticles over a flat surface

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ARTICLE INFO

Article history:
Received 14 April 2014
Received in revised form 13 September 2014
Accepted 18 November 2014
Available online 6 December 2014

Keywords:
Heat transfer
Nanofluid
Condensation
Liquid film

ABSTRACT

Fluid mechanics, heat and mass transfer taking place at condensation of moving vapor with nanoparticles near a flat plate were simulated analytically. An approximate analytical model was employed for simulation of the transport phenomena in the film of condensate, which takes into consideration mechanisms of the Brownian and thermophoretic diffusion. An important novelty of this model is that it suggested five major dimensionless parameters, which are included in the functional dependence of the heat transfer and fluid flow parameters in the condensate film of the nanoparticle concentration and physical properties: (i) parameter A, i.e. the relation between the thermophoretic and Brownian diffusion; (ii) the nanoparticle concentration in the vapor φ_∞; (iii) the density R of the nanoparticles normalized by that of the fluid; (iv) the thermal conductivity of nanoparticles K normalized by that of the fluid; (v) and the parameter m describing the properties of the nanofluid viscosity. Consequently, novel analytical solutions were deduced for the velocity profiles, the mass flow rate, the thickness of the condensate film and the Nusselt number was obtained as a function of the aforementioned dimensionless parameters. It can be concluded that an increase in the nanoparticles concentration favors augmentation of the processes of momentum and heat transfer.

1. Introduction

Condensation phenomena take place quite often in biotechnology [1–3] and in food processing [4–6]. A request for augmentation of the heat and mass transfer processes and the overall efficiency of the technological processes is an actual task of researcher and practical engineers dealing with such processes.

The number of investigations into of heat transfer during condensation of the vapor with nanoparticles is rather limited. Authors of the work [7] conducted experiments on heat transfer at condensation of nanofluid vapor with iron oxide nanoparticles in a thermosyphon. They found out that an increase in the mean HTC is a function of the inclination angle γ of the condenser. At $\gamma = 30°$, the HTC increased by 9% at the nanoparticle concentration $\varphi = 2\%$, and 19% at $\varphi = 5.3\%$. For $\gamma = 45°$, the HTC increased by 6% at $\varphi = 2\%$, and by 14% at $\varphi = 5.3\%$. For $\gamma = 45°$ and 60°, the HTC grew by 8% at $\varphi = 2\%$, and by 15% at $\varphi = 5.3\%$. The angle $\gamma = 90°$ yields in the HTC enhancement of 7% at $\varphi = 2\%$, and 13% at $\varphi = 5.3\%$. Thus, heat transfer enhancement at due to the nanoparticles is independent of the inclination angle.

Experiments on heat transfer at the vapor condensation in the presence of copper oxide nanoparticles with the concentration $\varphi = 1.0\%$ at the pressure of 7.45 kPa in inclined and horizontal grooved heat pipes were performed in the study [8]. For a pure fluid, the HTC in inclined tubes went up by about 60–80% over the horizontal tube heat transfer rate and reached a maximum at the inclination angle of 75°. In the nanofluid, the HTC increased by approximately 60–100%, which means that the maximal HTC growth at the expense of nanoparticles did not exceed 20%. Authors of the work [8] stated that heat transfer enhancement occurred because on the wall a thin porous layer formed with high thermal conductivity.

Authors of the work [9] carried out 3D numerical simulations of heat transfer at condensation of the nanofluid vapor in thermosiphons. They demonstrated that the maximum HTC value attained 1740 W/m$^2 \cdot$ K for the vapor with iron oxide nanoparticles at $\varphi = 5.3\%$. The minimum HTC value was 1450 W/m$^2 \cdot$ K at $\varphi = 2\%$. The simulations agreed well with experiments performed in the work [7].

Nusselt [10] has analytically investigated the heat transfer and fluid flow at the film condensation of the moving vapor. His model enabled finding out expression for the velocity and temperature

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.11.059
0017-9310/

Nomenclature

A	parameter A, the relation between the mechanisms of the thermophoretic and Brownian diffusion, Eq. (15)
c_p	specific heat capacity of the nanoparticles
D_B	Brownian diffusion coefficient
D_T	thermophoretic diffusion coefficient
G	mass flow rate
k	thermal conductivity
K	normalized thermal conductivity of the nanoparticles, Eq. (17)
q_w	heat flux density at the wall
r	latent heat of vaporization
R	ratio of the densities of the nanoparticles and the fluid, Eq. (36)
T	temperature
u	streamwise velocity component (x-component)
U	dimensionless velocity, Eq. (29)
x, y	Cartesian coordinates

Greek symbols

δ	condensate film thickness
ΔT	temperature difference across the film
η	dimensionless coordinate
Θ	dimensionless temperature, Eq. (13)
μ	dynamic viscosity
ρ	density
τ	shear stress, Eq. (8)
φ	nanoparticle concentration (volume fraction)

Subscripts

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

Acronyms

HTC	heat transfer coefficient

profiles in the film of the condensate, flow rate through the film and the Nusselt number. The model of Nusselt [10] has proved to be an adequate and physically justifiable mathematical description of the film condensation of the moving vapor.

Nanofluids possess unique properties, which motivate scientific community and industry to keep on intensive research of their fundamental aspects and practical applications. The most important properties of nanofluids are high thermal conductivity and low susceptibility of to sedimentation, fouling, erosion and clogging as compared to ordinary fluids with microparticles [11]. This inspired many promising applications of nanofluids, like those in nuclear energy, thermal management of systems with high dissipation rates of energy, cooling systems of electronic and optical devices, heat pipes and thermosyphons, as well as nanostructured materials and complex fluids [11–14].

It has been revealed that there is a slip between nanoparticles and the base fluid; however, in many cases nanofluids are modeled as uniform homogenous mixtures [14–25].

The works [17,26,27] demonstrated however that models employing the homogeneous (single-phase) flow approaches lead to underprediction of heat transfer rates between the nanofluids and solid bodies. Non-uniformity in nanofluids arises due to nanoparticle migration at the expense of the temperature and velocity gradients. As confirmed by experiments [18], the concentration gradient is also present in nanofluids. Works [19,20] provide more insight into theoretical aspects of non-uniformity in nanofluids.

Self-similar analysis known as a powerful tool of theoretical investigations was used to model laminar and turbulent boundary layer flows of nanofluids in the works [26–30]. Properties of a nanofluid as functions of the nanoparticle concentration and temperature were modeled in the works [27,28] in order to investigate fluid flow, heat and mass transfer in a boundary layer over a flat plate. Symmetry analysis (Lie groups) enabled finding proper self-similar variables and functions specific for the problems studied in [26,27]. Work [28] represents a study of a natural convection flow of a nanofluid over a vertical plate. The authors [29] theoretically studied onset of convection in a horizontal nanofluid layer of finite depth. The laminar boundary layer, with the surface velocity set to be a function of the streamwise coordinate and all fluid properties being independent of the concentration of nanoparticles, was investigated in the work [30]. As demonstrated in these theoretical works, an increase in the nanoparticle concentration causes enhancement of heat and mass transfer processes in nanofluids.

As mentioned above, the number of the works devoted to the experimental study of the condensation heat transfer in the presence of nanoparticles is limited by the publications [7–9]. A theoretical insight into this problem is given by the authors in the recent investigation [31]. However, these studies examined the condensation of the stationary vapor.

The present paper focuses on convective heat transfer in laminar flow of a film of a nanofluid over a flat surface under complicated velocity condition at the outer boundary of the film. The flow of the nanofluid results from condensation of a vapor of the same nanofluid that moves along the plate in the same direction as the nanofluid does. The plate is colder than the saturation temperature of the nanofluid vapor. To our knowledge, the stated problem has never been previously studied theoretically or experimentally.

This paper deals with an investigation of the effect of nanoparticles on the velocity profiles and HTC in the nanofluid. While considering heat transfer problems, effect of the nanoparticle concentration on all thermophysical properties must be taken into account, since the HTC is affected not only by thermal conductivity, but also by flow structure, thickness of the condensation layer and other flow characteristics. We employ here the known relations between thermophysical properties and the nanoparticle concentration.

The model proposed in the present work develops classical model of Nusselt [10] characterized above. The novelty of the present model lies in the inclusion of an equation for the nanoparticle concentration, which simulates heat transfer enhancement due to the addition of the nanoparticles and mass transfer effects. This novel model enabled deriving dimensionless parameters characterizing the effects of nanoparticles on fluid flow, heat and mass transfer processes. The model resulted also in the relations for the velocity profiles, condensate film thickness, mass flow rate through the film, as well as for the Nusselt number.

The major influence of nanoparticles is incorporated via an additional equation for the nanoparticle concentration and functional dependence of the nanofluid viscosity, thermal conductivity and density on the nanoparticle concentration like in the work [32].