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Heat transfer at film condensation of stationary vapor with nanoparticles near a vertical plate

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HIGHLIGHTS

- A model is presented for heat transfer at film of nanofluid near a vertical plate.
- Expressions were obtained for mass flow rate and the Nusselt number in the film.
- Fluid flow and heat transfer are influenced by three non-dimensional parameters.
- An increase in each of these parameters leads to heat transfer enhancement.

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ABSTRACT

Processes of momentum, heat and mass transfer at the condensation of the stationary vapor with nanoparticles near a vertical plate were investigated using an approximate analytical model. This model extends the classical model of Nusselt by way of the inclusion of an equation for the nanoparticle concentration and a dependence of the nanofliud density on the nanoparticles concentration. Thus, mechanisms of the Brownian and thermophoretic diffusion are incorporated. The essential novelty lies in the identification of three main dimensionless parameters, which describe the influence of nanoparticles on heat transfer and fluid flow. They are (i) the parameter A that denotes the relation between the mechanisms of the thermophoretic and Brownian diffusion, (ii) the concentration ϕ_∞ of nanoparticles in the vapor, and (iii) the ratio R of the densities of the nanoparticles and the fluid. Novel analytical solutions were derived that describe velocity profiles, the mass flow rate and the thickness of the film as the functions of the parameters A, ϕ_∞ and R. Finally, a novel analytical solution for the normalized Nusselt number was obtained as a function of the aforementioned three dimensionless parameters. An increase in each of these parameters causes an increase in the normalized Nusselt number.

1. Introduction

Condensation processes are quite common in biotechnology [1–3] and in food processing technologies [4–6], which inevitably entails a request for augmentation of the heat and mass transfer processes and consequently for an increase in the overall efficiency of the technological processes.

The number of publications devoted to the study of heat transfer during condensation in the presence of nanoparticles is quite limited. An experimental study of heat transfer at condensation of nanofluid vapor with iron oxide nanoparticles in a two-phase closed thermosyphon has been performed in the work [7]. It was revealed that an increase in the mean HTC in the presence of nanoparticles (as compared to an ordinary fluid) depends on the inclination angle of the condenser. Given an inclination angle of 30°, the increase in the HTC reached 9% at the nanoparticle concentration of 2%, and 19% at the nanoparticle concentration of 5.3%. For the inclination angle of 45°, the HTC grew by 6% at the nanoparticle concentration of 2%, and by 14% at the nanoparticle concentration of 5.3%. For the angle of inclination of 60°, the HTC went up by 8% at the nanoparticle concentration 2%, and by 15% at the nanoparticle concentration of 5.3%. The inclination angle of 90° resulted in the heat transfer enhancement of 7% at the particle concentration of 2%, and 13% at the particle concentration of 5.3%. As it seen from here, heat transfer augmentation at the expense of the nanoparticle addition is not affected by the inclination angle. An experimental study of heat transfer at condensation of vapor

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Nomenclature

A	parameter A, the relation between the mechanisms of the thermophoretic and Brownian diffusion, Eq. (12)
D_B	Brownian diffusion coefficient, m^2 s^{-1}
D_T	thermophoretic diffusion coefficient, m^2 s^{-1}
g	gravity, m s^{-2}
G	mass flow rate, kg m^{-1} s^{-1}
Ga	Galilei number, Eq. (29)
k	thermal conductivity, W K^{-1} m^{-1}
K	phase transition number, Eq. (30)
Pr	Prandtl number
q_w	heat flux density at the wall, W m^{-2}
r	latent heat of vaporization, J kg^{-1}
R	ratio of the densities of the nanoparticles and the fluid, Eq. (18)
T	temperature, K
u	streamwise velocity component, m s^{-1}
U	dimensionless velocity
x, y	Cartesian coordinates, m

Greek symbols

δ	condensate film thickness, m
η	dimensionless coordinate
Θ	dimensionless temperature
μ	dynamic viscosity, Pa s
ρ	density, kg m^{-3}
ϕ	nanoparticle concentration

Subscripts

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

Acronyms

HTC	heat transfer coefficient

containing copper oxide nanoparticles with the concentration of 1.0% at the operating pressure of 7.45 KPa in inclined and horizontal grooved heat pipes was carried out in the work [8]. It was found out that at the absence of nanoparticles the HTC of inclined tubes increased by about 60–80% as compared to the horizontal tubes and exhibited a maximum at the inclination angle of 75°. The presence of nanoparticles entails an increase in the HTC by approximately 60–100%, i.e. the maximal heat transfer augmentation due to the nanoparticles did not go beyond 20%. Authors of the work [8] believe that one of the reasons of the heat transfer augmentation is the formation of a thin porous layer over the surface, which has high thermal conductivity. 3D numerical modeling of heat transfer at condensation of the vapor with nanoparticles in thermosiphons was performed in the work [9]. It was revealed that the maximum value of the HTC reached 1740 W/m^2 K at condensation of the vapor with the iron oxide nanoparticles, whose concentration was 5.3%. The minimum value of HTC was 1450 W/m^2 K at the nanoparticle concentration of 2%. The simulations correlate overall well with the experimental results [7].

Unique properties of nanofluids keep on inspiring high interest to them both from scientific community and industry. These properties are high thermal conductivity and low susceptibility of nanofluids to sedimentation, erosion, fouling, and clogging in comparison to fluids with microparticles [10]. Therefore nanofluids have many promising applications, for instance in nuclear energy, thermal management of systems with high energy dissipation rates, thermosyphons and heat pipes, cooling systems for new generations of electronic and optical devices, as well as production of nanostructured materials and complex fluids [10–13]. For instance, analysis of the experimental results [14] for alumina nanofluid used as coolant in a corrugated plate heat exchanger for a nanofluid concentration of 4% revealed an increase in HTC is up to 13% with the maximum increase in the pressure drop of 45%.

Although it has been recognized that there is a slip between nanoparticles and the base fluid, in many modeling approaches nanofluids are simulated as uniform homogenous mixtures [13,15–25]. However, as shown in the works [17,26,27], modeling approaches employing the homogeneous (single-phase) flow models result in underprediction of the HTC in nanofluids. Non-uniformity in nanofluids result from nanoparticle migration induced by the velocity and temperature gradients. Experimental data [18] testify in favor of presence of the concentration gradient in nanofluids. Theoretical aspects of non-uniformity in nanofluids are elucidated in the works [19,20].

Authors of the works [26–30] investigated laminar and turbulent boundary layer flows of nanofluids with the help of a self-similar analysis. Avramenko et al. [26,27] studied fluid flow, heat, and mass transfer in a boundary layer over a flat plate and specified transport coefficients and fluid properties as functions of the nanoparticle concentration and temperature. Self-similar variables and functions used for this analysis were derived with the help of the symmetry analysis (Lie groups). Natural convection flow of a nanofluid over a vertical plate was studied in the work [28]. Onset of convection in a horizontal nanofluid layer of finite depth was theoretically studied by the authors [29]. Yacob et al. [30] investigated flow in a laminar boundary layer with the boundary surface velocity being a function of the streamwise coordinate; here all fluid properties were independent of the concentration of nanoparticles. All the aforementioned theoretical works revealed that an increase in the concentration of nanoparticles lead to the enhancement of heat and mass transfer processes.

The work [31] dealt with analytical optimization of a rectangular microchannel heat sink using aqueous carbon nanotubes based nanofluid. The effects of the temperature, aspect ratio, and other parameters on heat transfer and hydrodynamic resistance were studied. Nanofluid as a coolant essentially enhances thermal performance at high temperatures. A semi-empirical model developed in the works [32,33] was used to evaluate the heat transfer and flow characteristics of a nanofluid heat sink. In the paper [34], a micro pin fin heat sink was investigated numerically, where a nanofluid served as a cooling agent, with two types of nanofluids used (Diamond-water and Al_2O_3-water) together with the pure water. Simulations demonstrated that the use of a nanofluid instead of ordinary fluid augments heat transfer together with the pressure drop regardless of the pin fin shapes.

The present paper focuses on convective heat transfer in gravitation induced laminar flow of a nanofluid over a flat vertical plate. The fluid flow results from condensation of a stationary vapor of the same nanofluid on the vertical plate, which is colder that the saturation temperature of the vapor. To the knowledge of the authors, such a problem has never been previously studied theoretically. Investigation undertaken in this paper deals with the effect of nanoparticles on the velocity profiles in the fluid, as well as on the HTC, while effects of nanoparticles on thermal conductivity,