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Effect of nanoparticles on condensation of humid air in vertical channels

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In this paper, the effect of uniform surface injection of nanoparticles on humid air condensation, as a main type of vapor condensation in the presence of non-condensable gas (NCG), is numerically investigated. Various inlet conditions (velocity and relative humidity) of vertical CONAN type classical test section were modeled. Two mass concentrations of different nanoparticles were examined and the behavior of filmwise condensation was studied under different parameters of heat and mass transfer, such as: Reynolds number and mean Nusselt number of the condensed film, and local and mean Sherwood number. Finally, by using response surface methodology, the statistical interpretation (objective function) of the numerical results are provided for other inlet conditions. As shown in the results, an increase in the nanoparticles mass concentration has direct influence on condensate Reynolds number and Sherwood number of the humid air. At higher relative humidities (ω), using nanoparticles has more impact and the maximum improvement of the condensate Reynolds number (at the outlet), mean Nusselt number of the condensed film and mean Sherwood number are 11.4, 4.5 and 6%, respectively. It is observed that, under best conditions ($\omega = 100\%$, $U_{in} = 3$ m/s), 0.5% of nanoparticles mass concentration improves the total heat flux by more than 10.4%.

1. Introduction

The humid air condensation, as an example of condensation in the presence of NCG, is one of the most applicable methods of phase change which is observed in different industrial equipment such as Heating, Ventilating and Air Conditioning (HVAC) or coolant systems. For this purpose, various studies focused on filmwise condensation enhancement with multifarious passive or active methods. Undeniably, transformation to the era of nanotechnology has a strong potential for improvement of phase change performance. Therefore, using nano-material, as an additive to the main fluid, is considered and several investigators have tried to evaluate the effect of nano-materials on heat and mass transfer enhancement in heat exchangers [1–3]. Accordingly, a better understanding of the nano-particles/nano-fluids effects on heat and mass transfer, especially in the presence of phase change, and its influence on the mechanism of condensation/evaporation is needed as a key factor for more efficient equipment design.

1.1. Condensation of humid air

There are comprehensive studies in the area of filmwise condensation for pure vapor and air/vapor mixture, with several correlations for heat and mass transfer parameters for various geometrical conditions [4–6]. Desrayaud and Lauriat [7] demonstrated a new analogy of heat and mass transfer for condensation of humid air under laminar natural convection flow. Based on the thin film assumption, they reported new correlations for Sherwood number, latent and sensible Nusselt numbers. Rao et al. [8] performed an analytical model for laminar film condensation of vapor in the presence of air as a high concentration of NCG in a vertical tube. With the help of heat and mass balance equations at the interface, they estimated the gas-liquid interface temperature and reported the condensate Nusselt number, condensate Reynolds number and pressure drop for different inlet conditions, such as Reynolds number in the range of 1000–2000, and relative humidity up to 80%. In a similar study, Wu and Vierow [9] investigated the condensation of the vapor in the presence of NCG in a

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horizontal tube and compared the condensation heat transfer coefficient at the top and bottom of the tube. By comparing the centerline temperature profiles and the overall heat transfer rate, the global effect of NCG on the heat transfer rate was evaluated and the local effects of NCG on condensation process were reported.

Ambrosini et al. [10,11] attempted to compare the numerical simulation of several CFD commercial software with the experimental benchmark results of the CONAN typical classical test section. The experimental correlations of Nusselt number and Sherwood number for wall condensation of an external flow over a vertical flat plate was proposed by them. Vyskocil et al. [12] carried out air-steam condensation numerically and highlighted the simulation of wall condensation ignoring the effect of volume condensation. They compared their results with the benchmark data of CONAN experimental facility and predicted the condensation rate for different inlet conditions. Similarly, Zschaeck et al. [13] provided a new CFD model of the wall condensation of vapor in the presence of non-condensable multi components gas mixture in a vertical channel and compared the numerical results with experimental data of CONAN experimental facility [10]. A comprehensive review of vapor condensation in the presence of NCG was done by Huang et al. [14]. They categorized previous studies into dropwise and filmwise condensation and focused on semi-theoretical and theoretical models of condensation process in the presence of NCG. The effect of condensate thickness film, surface waves, interfacial shear strength and suction effects on filmwise condensation in the presence of NCG were evaluated by them. Saraireh et al. [15] used ANSYS FLUENT commercial CFD software with the aim of comparing the numerical results with well-established correlations of wall condensation parameters (condensation rate of vapor and heat flux) in the presence of air. Agrawal and Das [16] used in-house developed CFD code (HDS) and modeled unsteady form of wall film condensation under hydrogen distribution in an enclosure which is filled with mixture of vapor and air for a vertical injection of hydrogen from the bottom. They claimed that downward motion of the condensed film causes the concentration of hydrogen in lower parts of the enclosure. Szijarto et al. [17] utilized RELAP5, a thermal-hydraulic system code, to trace the wall condensation and provided the prediction of heat transfer process considering variation of temperature, pressure and void fraction of vapor along the horizontal pipe. In their study, based on three different regimes of condensation, they defined the significant role of stratification angle for transient condensation in a horizontal pipe. The numerical models of natural convection and wall condensation of humid air with time dependent wall temperature were defined by Sun et al. [18]. The thickness of the condensed film was discussed and it was claimed that the thickness reflects on the flow structures. The effect of geometrical parameters (such as aspect ratio of cavity) on wall condensation/evaporation was also addressed.

1.2. Nanoparticles application in convection heat transfer

Modeling of the particles behavior in gaseous phase is important for several processes and there are many works in the literature focused on investigation of particle deposition and suspended particle effects on heat transfer. Hudson [19] studied numerically the effect of copper nanoparticles on the enhancement of laminar natural/forced convection regime in a tube and an enclosure with different aspect ratios. Different particles tracking methods for various enclosures, with aspect ratio between 1 and 5, were examined and finally it was concluded that nanoparticles has a tendency to stay near the borders of an enclosure. Brereton [20] developed a Eulerian model for prediction of particle transport in an internal turbulent flow with thermophoretic term, as an eddy-viscosity-scaled multiple of the corresponding mean thermophoretic term, which is applicable for low inertia particles. Walsh et al. [21] developed an investigation of thermophoretic deposition of aerosol particles on relatively cool cylindrical tube. Based on the solution of aerosol population, they compared particles deposition in downward/upward flow through a vertical pipe and found that the free convection effects could be ignored for lower bulk Richardson number ($Ri < 1$). A two phase Euler-Euler model for prediction of conduction, convection and radiation heat transfer in dense gas-particle domains on the open-source code OpenFOAM for high temperature solar power applications was provided by Marti et al. [22]. In case of a moderate rise in the wall temperature (581 K) and particle diameter of 64 μm, they highlighted that the solid conduction accounts for about 97% of the wall to suspension heat flux. The increase of radiation heat flux portion up to 10% of the total wall to suspension heat flux is reported by them.

In order to evaluate particles force balance, Akbar et al. [23] studied the transport of particles in a square enclosure for laminar free convection regime using Eulerian-Lagrangian method at ANSYS FLUENT commercial CFD software. They investigated different motion mechanisms, including gravity, drag and lift forces, and thermophoresis and Brownian dispersions, for different Rayleigh numbers ranging from 100 to 800,000 and found that most of the particles dispersed towards the walls, while a portion of the particles were collected in a quasi-steady recirculation zone. Garoosi et al. [24], used Eulerian-Lagrangian hybrid method, to model deposition of solid particles in natural convection regime of an insulated square cavity with different replacement of cooler and heater elements. Tracking of 6000 discrete particles within a range of Rayleigh numbers ($10^4 \leq Ra \leq 10^7$) showed that thermophoresis force could be effective at lower Rayleigh numbers. For the case which were studied, at lower Rayleigh numbers and non-uniform distribution of particles; using more coolers and splitting elements into smaller segments causes a significant change in deposition rate of particles and heat transfer rate. Afshar et al. [25] solved the Navier-Stokes and energy equations for slip flow regime in microchannel analytically and evaluated dispersion of particles due to the mentioned effective parameters. In their analysis, it was shown that the control of entrance location of nanoparticles leads to a heat transfer enhancement. Additionally, a decrease in the particle diameter causes an increase in the surface to volume fraction, which is affects, the heat transfer in microchannels. In order to compare Eulerian and Lagrangian approaches, Saidi et al. [26] compared the motion of particles for the same problem using the two cited approaches. Their overall results showed that for low particles concentration, approximately $10^5\ m^{-2}$, the Eulerian approach diverges considerably and cannot be applicable for low particles concentration unless employing a long time scale. Using numerical solution of similarity transformations, Alam et al. [27] investigated unsteady forced convection heat and mass transfer equations for thermophoretic deposition of micro-particles driven by a rotating disk. Axial thermophoretic velocity, thermophoretic deposition flux and concentration profiles of particles were evaluated at different Schmidt number and it was concluded that, for larger Lewis numbers, the increasing trend of thermophoretic velocity could be affected by thermophoretic coefficient and thermophoresis parameter.

Based on general exact solution of particle transport [28], Bertoli et al. [29] obtained several limiting solutions for heat transfer in multi-particles systems, single particle and single phase flow. The effect of magneto hydrodynamic (MHD) on transportation and deposition of micro- and nano-sized particles (particle diameter in the range of 1 nm to 1 μm) for natural convection regime over a horizontal and vertical plate was proposed by Guha and Samanta [30,31]. Different parameters such as: free convection, Brownian

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