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Modeling of heat and mass transfer for dropwise condensation of moist air and the experimental validation

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ABSTRACT

A single droplet model is developed to describe the droplet growth during dropwise condensation of moist air on a cold substrate. The condensation process is divided by the droplet surface into two parts. The first step, i.e. the processes of mass transfer from the surroundings to the droplet surface, is modeled by the Kinetic theory and the laws of continuum fluid dynamics formulated using the two-region concept (Knudsen layer and continuum region) at any droplet size and at any concentration of non-condensable gas (NCG). The second step, i.e. the heat transfer across the droplet, is governed by Fourier's law of heat conduction. These three regions (the continuum region, the Knudsen layer and the region inside the droplet) are incorporated by the matching both the mass flow rates and the energy flow rates. From these, the droplet growth rate, the nucleation size of droplet, the temperature at the droplet surface and Knudsen layer interface can be evaluated depending on different conditions. For this, a numerical algorithm is developed to reflect the droplet dynamics sufficiently detailed, including nucleation, growth/coalescence, slide-off/fall-off, re-nucleation. This is applied to the simulation of the entire condensation process by putting the growth rate and minimum radius from single droplet model into the growth algorithm. Additionally, dropwise condensation experiments of moist air in different relative humidity (RH) are carried out for validation of the simulation results. Good agreement is obtained which demonstrates that the present droplet growth model for dropwise condensation of moist air is credible. The current model and experiments also indicate that the diffusion resistance of water vapor in air from the free stream toward the droplet surface has a significant influence for the heat transfer performance of dropwise condensation of moist air.

1. Introduction

Dropwise condensation, which is a phase change process accompanied by the complex simultaneous heat and mass transfer, has attracted a growing interest since the first discovery by Schmidt et al. [1]. More interest for this phenomenon is concentrated on the condensation mechanism and the potential heat transfer improvement compared with those found from filmwise condensation [2]. Due to much higher heat transfer coefficients, filmwise condensation and dropwise condensation became key heat transfer processes in many industrial applications, for instance, compact condensers, refrigeration, cooling systems of nuclear power plants and in the petrochemical industry [3–5]. In those industrial fields, it is impossible to remove all NCG and therefore the condensation of water vapor with the presence of NCG plays an important role in research of condensation.

Othmer [6] was the first to pay attention to the condensation of steam in the presence of NCG. In contrast to the pure vapor, its partial pressure is reduced and subsequently, the saturation temperature of bulk drops down. Furthermore, the vapor/liquid interface is actually impermeable to the NCG and close to it the NCG accumulate during the condensation process forming a non-condensable diffusion layer. The latter one is responsible for the creation of a temperature difference between the bulk and the liquid/vapor interface, acting as a diffusion barrier for the vapor moving to the interface. Huang et al. [7] presented a review article for the research history of condensation in the presence of NCG. They reviewed the experiments, the mechanism and the model progresses of condensation in the presence of NCG. In their article, particular attention was given to summarize the experiments and the physical model of heat transfer for filmwise condensation with NCG including a brief review about dropwise condensation

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Nomenclature

D	diffusion coefficient, m^2/s
h	specific enthalpy, J/kg
k	thermal conductivity, W/m K
Kn	Knudsen number, –
L	latent heat, J/kg
M	mass flow rate, kg/s
N	available droplet number, –
N_s	nucleation site density, m^{-2}
$N(r)$	droplet size distribution density, $m^{-2}\ \mu m^{-1}$
P	pressure, bar
Q	heat flow rate, W
q	heat flux, W/m^2
r	droplet radius, μm
T	temperature, K
u	bulk velocity, m/s
v	diffusive velocity, m/s

Greek symbols

ΔT_{dd}	temperature difference between the dew point and droplet surface, K
ΔT_{dw}	temperature difference between the dew point and wall, K
ΔT_{mw}	temperature difference between the moist air and wall, K
ΔM	solving deviation for mass flux, –
σ	surface tension, N/m
ρ	density, kg/m^3
β	experimental coefficient, –
λ	mean free path of molecular, nm
μ	dynamic viscosity, Pa s
φ	area coverage ratio, %

Subscripts

d	droplet
ds	droplet surface
dew	dew point of moist air
i	interface between the Knudsen layer and continuum region
m	moist air
NCG	non-condensable gas
RH	relative humidity
sat	saturation
v	vapor
w	wall

experiments with NCG. For now, the research about the filmwise condensation has been finished perfectly. As seen in [7], a depth understanding for the mechanism of filmwise condensation and the influence of NCG on heat transfer performance is presented.

The understanding of mechanism and theory of dropwise condensation of pure steam, as presented in [2], was strongly been improved. Many researchers had experimentally found that even a small concentration of NCG brings a significant reduction in the heat transfer performance of dropwise condensation [8–13]. Tanner and his coworkers [8,9] reported an experimental comparison of dropwise condensation with and without NCG at atmospheric pressure and low pressure. The results demonstrated that the heat transfer performance of dropwise condensation with NCG strongly depends upon the concentration, the steam pressure and the NCG composition. The experimental comparison of filmwise and dropwise condensation of steam with the presence of NCG was performed by Chung et al. [10]. They concluded that dropwise and filmwise condensation fell in similar range of the heat transfer rates in the presence of air. For the solutal Marangoni condensation, Wang and Utaka [11] found that the effect of NCG was remarkable for the domain controlled by dropwise condensation. Ma et al. [12] measured the heat transfer characteristics of dropwise condensation for a variety of NCG concentration, saturation pressure and surface sub-cooling degree. The results showed that dropwise-condensation heat transfer coefficients of steam with air concentrations of 0.5–5% can be increased by 30–80% compared with those for filmwise condensation. Danilo et al. [13] studied the coupling between fully developed turbulent convection and dropwise condensation of unsaturated humid air, and the role of the relative humidity level. The research about dropwise condensation in presence of NCG is mainly focused on the experiments. The conclusion is that, like filmwise condensation, NCG goes against the heat transfer of dropwise condensation losing its advantage over the filmwise condensation. For the enhancement of dropwise condensation in the presence of NCG, Ghosh et al. [14] designed patterned surfaces capable of controlling of three key factors, namely achieving optimal spatial nucleation, minimizing the departing droplet size, and facilitating rapid drainage of condensate. To account for the influence of NCG, the difference between the dew point temperature in the bulk and the surface temperature on the droplet ($\Delta T_{dd} = T_{dew} - T_{ds}$) was introduced into single droplet thermal resistance model of pure steam condensation developed by Rose [15]. The term ΔT_{dd} acts to reflect the decrease of vapor mass fraction from the free flow to the droplet surface as the driving force for condensation mass transfer rate. As a plausible simplification, a fractional constant reduction of the effective driving temperature difference was assumed to estimate the condensation rate. However, in practice, an exact definition of ΔT_{dd} and the corresponding condensation rate must be rated on the solution of the coupled mass and energy equations. Because of the contradictory, the heat transfer model of dropwise condensation considering NCG is rarely investigated.

In absence of NCG, the vapor keeps on an equilibrium state and the heat transfer of dropwise condensation depends on the heat resistance from the droplet surface to the cooling side. With NCG, the complex simultaneous heat and mass transfer resistance reduces the condensation rate, and therefore its accurate description becomes necessary. Fig. 1 intuitively gives a schematic view of a droplet on a cold substrate in the process of dropwise condensation with and without NCG.

Basically, the growth process of droplets has a multi-scale feature as the droplet radius spreads from the initial radius of some nanometers to the departure size at millimeter scale. That means the mechanism of the heat and mass transfer processes depends to a large extent on the Knudsen number Kn, which is described as the ratio of the mean free path of vapor molecules to the droplet diameter. For very small Kn corresponding to the big droplets, the heat and mass transfer process is determined by the laws of continuum fluid dynamics. For very large Kn in the initial stage of growth, the continuum hypothesis is not suitable and the kinetic theory is applied to describe the impingement process of vapor molecules. However, the growth processes occur consecutively. Hence, a useful growth model is necessary to consider the intermediate case where $Kn = O(1)$.

For condensation and evaporation of droplets in carrier gases, the Gyarmathy model [16] and the Young model [17,18] are two classic growth models having different descriptions for the transition between the continuum and kinetic regimes. The Gyarmathy