A new model for the processes of droplet condensation and evaporation on solid surface

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ABSTRACT

A new model is developed to describe quantitatively the processes of droplet condensation and evaporation on solid surface in the presence of non-condensable gas. By comparing the distance between vapor molecules and droplet surface with the mean free path of vapor–gas mixture, the environment outside droplet is divided into two regions with their own regimes of mass and energy transfers which are governed by kinetic theory and continuum flow theory, respectively. These two regimes are incorporated by matching the mass and energy fluxes from these two regions. The new model presents the non-equilibrium dynamic process of condensation and evaporation. In addition, the effects of solid surface on the droplet condensation and evaporation including the transfers of mass and heat are successfully considered which is suitable for any droplet size and any surface size (particle or flat). More parameters related to the condensation on solid surface can be obtained by the new model and, subsequently, empirical or fitting intermediate quantities are avoided. The critical degree of supercooling, the temperature of vapor–gas mixture at Knudsen layer interface, the variation rates of droplet radius are simulated by our model to prove that our model is credible. The results indicate that an approximate replacement of a homogeneous model in the simulation of droplet condensation and evaporation on solid surface is unsuitable.

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1. Introduction

The phase transition is a very common phenomenon in atmospheric physics [1], gas cleaning technology [2], and multiphase flow [3]. It is, however, a complicated research subject in physical perspective. The phase transition can be classified into two types, homogeneous transition [4,5] and heterogeneous transition [6,7]. Heterogeneous transition, a much common in daily life phenomenon, includes crystallization [8], coating film [9], surface cooling [10] and so on.

The processes of droplet condensation and evaporation (vapor ⇆ liquid) are typical phenomena in the phase transition. Phenomenological theories on the processes of droplet condensation and evaporation have been developed by many authors. In the initial stage of the study history, the theoretical studies went forward by two different ways: the models were developed in continuum limit [11] and molecular kinetic limit [12], respectively. Maxwell [13] used the continuum theory of diffusion and thermal

conduction to treat the growth of a single droplet. Hertz [14] and Knudsen [15] analysed the growth rate of small droplet in the molecular kinetic regime. Wagner and Pohl [16] developed a first-order theory of droplet growth in monodisperse droplet ensembles. Then, much effort has been put into modeling a transitional growth regime between continuum limit and molecular kinetic limit: Gyarmathy [17] used an interpolating fit between the continuum regime and molecular kinetic regime, and Young [18,19] divided the environment outside the droplet into two regions and incorporated the transition within the model. When the solid surface is introduced in the vapor–liquid phase transition, the theoretical study becomes much more complicated. Vemuri and Kim [20] derived a theoretical formula to predict the drop-size distribution of small drops which grow mainly by direction condensation by considering the resistances to heat transfer. Hanchak et al. [21] presented a novel one-dimensional model of the evaporation of liquid water droplets from a hot surface. Liu and Cheng [22,23] developed an improved thermodynamic model to calculate some critical parameters, such as critical radius, droplet nucleation and condensation heat flux.

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Nomenclature

A_{dv}	surface area between droplet and vapor
C_p	specific heat at constant pressure
D	binary diffusion coefficient
d	distance between vapor molecules and droplet surface
e	total energy per unit mass
$\dot{E}$	energy flux
h	enthalpy
J	nucleation rate
k	thermal conductivity
k_B	Boltzmann constant
Ke	Kelvin number
L	latent heat
L_{dvs}	perimeter of the three-phase contact line
m	mass
$\dot{M}$	mass flux
p	pressure
$\dot{Q}$	total conduction heat transfer rate
$\dot{q}$	heat flux per unit area
R	specific gas constant
S	saturation ratio
r	radius of curvature
T	temperature
t	time
u	bulk velocity

Greek

β	an experimental coefficient with a best fit value
ΔG_{des}	desorption energy per water molecule
ΔG_{sd}	surface diffusion energy per water molecule
ΔT	degree of supercooling
δ	mean jump distance of one water molecule

λ	mean free path of vapor molecules
μ	dynamic viscosity
ϕ	half of the central angle of the part of surface contacting with droplet
ψ	half of the central angles of droplet
ρ	density
σ	surface tension
θ	contact angle between droplet and surface

Subscripts

α	molecules addition from vapor
β	molecules diffusion from surface
$+$	flux in positive direction
$-$	flux in negative direction
d	droplet
ds	droplet surface
eq	equilibrium region
g	non-condensable gas
i	interface of Knudsen layer
l	liquid
m	vapor–gas mixture
ss	solid surface
v	vapor

Superscripts

sat	saturated vapor
′	relative velocity
∗	critical parameters

In spite of the continuous advance and the wide application for the study, the theoretical research on the processes of droplet condensation and evaporation on solid surface (e.g. particle, flat) still has some gaps: 1. Almost all existing models are only suitable for the specific size ranges of droplet and solid surface; 2. Many previous models only considered the effect of solid surface on the energy transfer, however, the effect of solid surface on the mass transfer is also significant, which has been proved in the study of heterogeneous nucleation. These gaps may be ascribed to two main reasons. One is that how to classify and incorporate different regimes of mass and energy transfers in the processes of droplet condensation and evaporation on solid surface is still problematic. The other is that it is difficult to consider the effects of solid surface on the droplet condensation and evaporation, especially in the non-equilibrium region near the droplet surface where the effects of solid surface have a significant contribution to the droplet condensation and evaporation.

In this paper, we shall develop a new model for the processes of droplet condensation and evaporation on solid surface in the presence of non-condensable gas. Different from choosing the droplet diameter as the characteristic length, we compare the distance between vapor molecules and droplet surface with the mean free path of vapor–gas mixture to divide the environment outside droplet into two regions which have their own regimes of the mass and energy transfers, and incorporate two different regimes by matching the mass and energy fluxes from these two regions. The effects of solid surface on the droplet condensation and evaporation are also considered in the new model by means of our kinetic model [6]. In Section 2, the model and the method are described in detail. In Section 3, four specific cases are simulated to validate our model. A brief summary of our model and results is provided in Section 4.

2. Model and method

In this section, we shall present our physical model and calculating method for the processes of droplet condensation and evaporation on solid surface. For convenience, we only discuss the situation of condensation, because the evaporation is the inverse process of the condensation.

As shown in Fig. 1, there are three parts in the schematic view of the condensation of droplet on solid surface in the presence of non-condensable gas: solid surface, droplet and vapor–gas mixture. It should be noted that the subscripts 'v', 'g', 'm', 'd', 'ds', 'ss', 'i' and 'eq' denote the parameters of vapor, non-condensable gas, vapor–gas mixture, droplet, droplet surface, solid surface, vapor–gas mixture at interface of Knudsen layer and vapor–gas mixture in equilibrium region, respectively.

2.1. Solid surface

The solid surface is regarded as an ideal heat reservoir whose temperature keeps unchanged, i.e. T_{ss} = const. This assumption is reasonable because the size of solid surface is always larger than that of droplet in the scope of our investigation. It is also assumed that the heat conductivity coefficient of solid surface is large enough to make the temperatures of contacted liquid and vapor to be same as that of solid surface, because the thermal contact between liquid (or gas) and solid is much more efficient than the