



Influence of the noncondensable component on the characteristics of temperature change and the intensity of water droplet evaporation

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ABSTRACT

The removal of vapor molecules from a droplet surface is an important stage of evaporation in a vapor–gas mixture. In this work, with the evaporation of a water droplet in a vapor–gas medium as the example, the influence of the noncondensable component on the intensity of the evaporation process and the characteristics of the temperature change is examined. The heat supplied to an interface is often assumed to be entirely utilized for evaporation, with the formed vapor removed from the evaporation surface through diffusion. However, the diffusion flux develops at a distance of some mean free paths of vapor molecules away from the evaporation surface, that is, in the Knudsen layer. In this layer, because of intermolecular collisions, the molecule–velocity distribution undergoes substantial changes, which are calculated using the methods of physical kinetics. Herein, the system of two Boltzmann kinetic equations for a vapor–gas mixture is used for calculating mass flux density of the evaporating substance near the evaporation surface. The calculation results are then compared with published experimental data.

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1. Introduction

The heat and mass transfer processes of liquid droplets find wide practical applications [1]. These processes have been studied for decades, nevertheless, problems associated with these processes remain an active research area. As noted in [2], one of the basic factors in these processes is the time for complete evaporation of a liquid droplet formed in a vapor–gas medium. In [3], the change in droplet temperature during the evaporation process is discussed. Despite the simplicity of the problem formulation in this field, obtaining solutions in the general case remains difficult, as mentioned in [4]. In relevant literature, monograph [5] warrants attention, in which works by Maxwell and Stefan are discussed in a simple and clear manner; in addition, practically useful equations are presented, which enable one to determine the rate of droplet evaporation as a first approximation. The removal of vapor molecules from a droplet surface is an important stage of evaporation in a vapor–gas mixture. It is often assumed that the heat supplied to an interface is entirely utilized for evaporation, while the formed vapor is removed from the evaporation surface through diffusion. However, the diffusion flux develops at a distance of some mean free paths l of vapor molecules from the evaporation surface, that

is, in the Knudsen layer. In this layer, because of intermolecular collisions, the molecule–velocity distribution undergoes substantial changes, which are calculated through the methods of physical kinetics. This concept was proposed in [6], in which fuel droplet evaporation in hot air is discussed. In [2], this approach was applied to the study of water droplet evaporation in a vapor–gas medium.

The intensity of the evaporation–condensation processes and the characteristics of the heat transfer between a droplet and the environment may be substantially affected by a noncondensable component present in the gaseous medium. This effect was theoretically demonstrated by [7,8] and experimentally confirmed by [9,10]. Kryukov et al. [11] demonstrated that the change in vapor density near an evaporation surface is dependent on the proportion of the noncondensable component in the gaseous mixture; they discussed two possible scenarios through which this phenomenon occurs. In the first scenario, the noncondensable component is completely displaced by vapor from a rather wide region near the evaporation surface. In this case, the vapor density remains nearly unchanged; thus, the diffusion flux is close to zero. In the second scenario, the vapor density gradually varies from a value close to that at the interface to a value corresponding to that very distant from the interface. A simplified approach that accounts for the influence of the noncondensed component in the Knudsen layer is presented in [2].

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Nomenclature

Notation

l	mean free paths of vapor molecules, m
ρ	density of component, kg/m ³
\vec{r}	distance from the evaporation surface, m
T_s	interface temperature, K
T	temperature, K
t	temperature, °C
φ	air humidity
P	pressure, Pa
D	diffusion coefficient, m ² /s
μ	molar mass, kg/mole
f	velocity distribution function of molecules
J	collision integral
n	number density, m ⁻³
ξ	molecular velocity, m/s
R	droplet radius, m

j	evaporated mass flux density, kg/(m ² s)
τ	time, s
Q	heat flux, J/s
q	heat flux density, J/(m ² s)
Nu	Nuselt number
Pr	Prandtl number
Gr	Grashof number
λ	thermal conductivity coefficient, W/(m K)
$\delta\tau$	time interval, s
L_h	specific heat of evaporation, J/kg
c_p	heat capacity, J/(kg K)

Indices

v	vapor
g	gas

In this paper, the evaporation mass flux density is calculated by solving system kinetic equations for a wide range of ρ_v/ρ_g . Thus, the kinetic equations are solved for a very large concentration of the noncondensed component.

2. Problem statement and mathematical description

2.1. Problem statement

Consider a spherical liquid droplet with initial radius R placed in a gaseous mixture composed of the vapor of this liquid and a noncondensable component. Initially, the temperatures of the droplet and the mixture are equal. The partial density of the vapor at a position far from the droplet surface is assumed to be a constant and lower than the equilibrium value corresponding to the droplet surface temperature; in the case of water, this means that the humidity of the ambient medium is lower than 100%. Under these conditions, the droplet begins to evaporate, its temperature decreases, and heat transfers from the ambient medium—which retains its higher temperature—to the droplet surface. The problem scheme is illustrated in Fig. 1.

The kinetic region (i.e., the Knudsen layer) is near the interface surface (Fig. 2). The length of this region is several mean free paths of vapor molecules. The vapor molecules are assumed to be removed from the external boundary of the Knudsen layer due to diffusion. In this case, the mass flux from unit surface area per unit time can be estimated using the following expression [12]:

$$j = -\frac{2DP_\infty}{dR_{mix}T_\infty} \ln \left[\frac{1 - \varphi_k \frac{P_s(T_s)}{P_\infty} \frac{\mu_{H_2O}}{\mu_{mix}}}{1 - \varphi_\infty \frac{P_s(T_\infty)}{P_\infty} \frac{\mu_{H_2O}}{\mu_{mix}}} \right] \quad (1)$$

Here, D is the diffusion coefficient; P_∞ and T_∞ are the pressure and temperature of the mixture far from the droplet surface, respectively; T_s is the droplet temperature; φ_∞ is the air humidity far from the evaporation surface; R_{mix} is the individual gas constant of the vapor–gas mixture; μ_{H_2O} and μ_{mix} are the molar masses of water and the vapor–gas mixture, respectively; and $P_s(T_s)$ is the saturation pressure of water vapor at temperature T_s .

As evident from (1), the value of air humidity at the outer boundary of the Knudsen layer (φ_k) is necessary to determine the mass flux density of the evaporating substance. In [2], this value is determined from the condition of equality between the diffusion and kinetic fluxes. The parameters of the vapor–gas mixture far from the droplet are assumed to remain constant throughout the calculation period. Thus, to determine the evaporation intensity, the value of the mass flux density of the substance evaporating from the interfacial surface is essential. In this paper, this value (mass flux density) is calculated by applying molecular-kinetic theory. This approach makes it possible to account for the influence of the noncondensable component on the evaporation intensity; moreover, this approach makes it possible to account for the peculiarities of intermolecular collisions in the Knudsen layer when calculating the mass flux density of the evaporating substance. As evident from the problem statement (see Fig. 2),

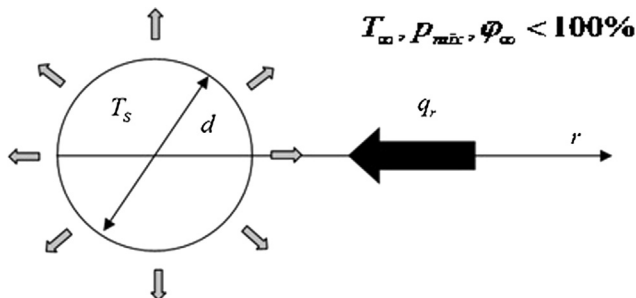


Fig. 1. Schematic of the droplet evaporation problem. T_s and d are the droplet temperature and diameter, respectively, and T_∞ , P_{mix} , and φ_∞ are the mixture parameters at a position distant from the evaporation surface.

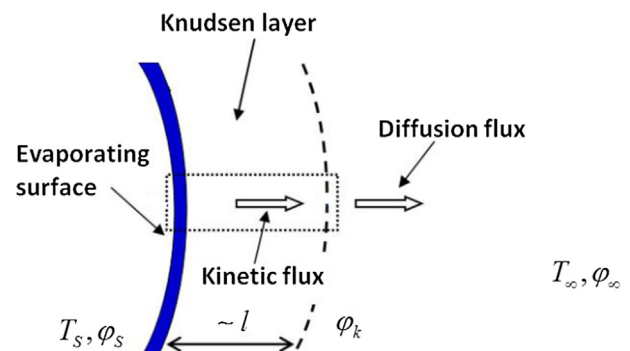


Fig. 2. Conjugate approach to the problem of droplet evaporation. T_s is the evaporating surface temperature, φ_s is the air humidity at T_s , φ_k is the air humidity at the external boundary of Knudsen layer. Dotted parallelepiped is domain used for kinetic analysis further.

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