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Determination of parameters of heat and mass transfer in evaporating drops

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ABSTRACT

To compute parameters of heat and mass transfer in evaporating drops the emission-diffusion model is proposed. It is based on a dynamic balance between the vapor flow, obtained in the framework of the kinetic approach of Hertz-Knudsen, and diffusive flow of Maxwell. This approach allows taking into account characteristics of small droplet evaporation, where heat and mass transfer processes are not described by the regular diffusion model. The results of computations of the evaporation of free water droplets of different sizes according to regular diffusion and emission-diffusion models are compared. The effect of free convection flow and radiative heat transfer on droplets evaporation is determined. The suggested model is validated by comparison with experimental data obtained at the evaporation of water droplets suspended on polypropylene monofilaments. The form of droplet during evaporation is detected by microphotographing. The temperature of its surface is measured using infrared thermography. The numerical results and the experimental data show good agreement in time of evaporation and temperature of evaporating drops.

1. Introduction

The interest to the study of liquid droplets evaporation is caused by a variety of practical applications, ranging from fuel burning and intensification of heat and mass transfer processes to formation of nanostructures [1–3]. The study of liquid droplets evaporation is a classical fundamental problem, and it is a subject of a large number of works. A comprehensive review of the development of computational models of heating and evaporation of the drops can be found in [4]. However in the processes associated with droplet evaporation, there are still many fundamental issues that need deeper study. At evaporation the droplet size continuously decreases, which leads to the necessity of solving this problem at transient conditions. Accounting for changes in drop sizes requires additional hypotheses. The droplet size is an important parameter which determines the influence of certain factors (surface tension, gravity, the free path of vapor molecules, etc.) on the process of drop evaporation. Its physical model should be chosen depending on which factors are significant. At present, two fundamentally different approaches to solving the problem of evaporation and condensation of drops are used extensively. The first is based on the concept of medium continuity and uses hydrodynamic models [5]. The second approach is based on the molecular-kinetic theory and uses the gas-kinetic models [6].

Hydrodynamic models fairly describe slow evaporation of large droplets. In these models, it is assumed that the vapor at the surface is always in the saturated condition. In the hydrodynamic models, one of possible ways to take into account the influence of heat and mass transfer in evaporation is to use generalized correlations of similarity numbers. Currently, complete models based on the laws of conservation of mass and energy are developed intensively [7–9]. Gas-kinetic models are widely used at higher speed of evaporation and small droplet sizes, when the ratio between the free path length of the molecules and the droplet diameter becomes significant. These models are based on the Langmuir idea of the Knudsen layer. At that, liquid and vapor in the form of continuous media are separated from each other by the Knudsen layer with thickness of the order of free path of the molecules. The problem of evaporation in such statement at a flat interphase was considered in [10–12]. Almost the same approach was used to solve the problem for a free spherical droplet [13–16]. Gas-kinetic models allow obtaining the value of temperature jumps in the Knudsen layer and may be applied at different Knudsen numbers. These and similar works [17–22] pay great attention to a detailed analysis of the molecular kinetics of the considered processes.

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Nomenclature

Bi	Biot number
c_μ	molar concentration of the vapor-gas mixture
c_p	specific heat capacity
D	molecular diffusion coefficient of vapor
d	droplet diameter
g	gravitational acceleration
Gr	Grashof number
h	specific enthalpy
J	mass flux
K	Kutateladze number
L	specific heat of vaporization
m	mass of the drop
Nu	Nusselt number
P	pressure
q	power of heat
r	dimensionless diameter
R	universal gas constant
R_V	gas constant for vapor
S	surface area of the droplet
Sc	Schmidt number, $\frac{\nu}{D}$
Sh	Sherwood number
T	absolute temperature
t	temperature

Greek symbols

$\propto$	heat transfer coefficient
β	coefficient of isothermal expansion
γ	accommodation coefficient
ε	emissivity
θ	dimensionless temperature
Λ	conduction-radiation parameter
λ	coefficient of heat conductivity
μ	molar mass of vapor
ρ	density
σ	Stefan–Boltzmann constant
ν	coefficient of kinematic viscosity
τ	time
φ	relative humidity

Subscripts

a	air
d	droplet
D	diffusion
DM	diffusion model
EDM	emission-diffusion model
HK	Hertz-Knudsen
s	saturated
V,v	vapor
vap	vaporization
w	water
WB	wet bulb

Superscripts

v	vapor
w	water
273	absolute temperature of the reference point

For different practical applications of droplets evaporation, it is necessary to determine several key parameters such as time of evaporation of droplets, their sizes and temperature. In this respect, of great interest are models that combine the two approaches. For instance, [23] shows that accounting of the molecular kinetics in the diffusion model leads to an increase of the evaporation time of small drops in comparison with the conventional diffusion model.

The present work is developing the emission-diffusion model of the droplet evaporation that combines both the kinetic and the diffusive mechanisms.

The validation of various computational models requires comparison with experimental results. For the experimental study of droplets evaporation there is a widely used technique of suspending a drop on a thin filament, which allows obtaining rather good approximation to the conditions of free droplet evaporation [24]. The experiments usually pay main attention to determining the variation of geometrical parameters of the drops using photo and video equipment [1,25,26]. The drop temperature in these studies is measured using contact methods.

The drop suspension on a thermocouple has become widespread due to possible control of the droplet temperature change in the evaporation process. For example, Watanabe et al. [25] investigated the evaporation of drops, suspended on thin thermocouple, to study combustion of isolated droplets of liquid fuel. Gan and Qiao [1] conducted experiments on the evaporation of drops (suspended on thin K-type thermocouple) of different fuel mixtures with the addition of nanoparticles under natural and forced convection. A significant problem in such studies is heat supply to the droplet through the thermocouple due to high thermal conductivity of the thermocouple material, which leads to a significant error of the experiment. Yang and Wong [26] studied the evaporation of drops, suspending them on the end of a thin quartz filament to minimize the heat input to the drop. Similar experiments at elevated pressures and temperatures were carried out by Ghassemi et al. [27]. They found that at low ambient temperatures, the thermal conductivity of the filament mostly influenced the early stage of evaporation, and at high temperatures the influence extended to the whole process. Han et al. [28] considered the effect of heat conduction of the thermocouple and the quartz filament on the evaporation of suspended single droplets under different ambient temperatures. The results showed that the influence of quartz filament on the evaporation of drops was substantially less than the one of the thermocouple, but, nevertheless, there was an increase in evaporation rates, associated with additional supply of heat. Thus, measuring the drop temperature with thermocouples implies significant errors due to the supply of heat through the thermocouple. In addition, such measurements are local and do not provide information about the temperature distribution on the drop surface.

In recent years, measurements of surface temperature of the evaporating drop have been widely done using the infrared thermography technique [29–33]. The advantages of this method are noncontactness, high sensitivity and high-speed performance.

The aim of this work is a comparative analysis of the computational results of free drops evaporation according to the diffusion model [34] and the emission-diffusion model for different diameters of spherical water drops.

The suggested model was validated by comparison with experimental data obtained by the contactless infrared thermography and micro-photographing at the evaporation of water droplets suspended on polypropylene monofilaments.