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The role of convection in gas and liquid phases at droplet evaporation

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ABSTRACT

The article presents the measuring results of droplet velocity and temperature fields using non-contact optical methods: Particle Image Velocity (PIV), Planar Laser Induced Fluorescence (PLIF) and Thermal imager. The novelty of the work is that the influence of free convection in gas and liquid is investigated experimentally and theoretically and that the key criteria affecting heat and mass transfer are determined. The analysis of experimental data has shown that in the initial period of water drop evaporation, the predominant role in the heat exchange is played by the thermal Marangoni convection. However, for an aqueous salt solution, in spite of the strong influence of the surfactant, the dominant role passes to the solutal Marangoni convection (Ma_C). In the first seconds after the drop falling, convection and heat transfer in liquid are maximal. Under such conditions it is important to realize an accurate numerical simulation to assess the degree of wall cooling and calculate the non-stationary evaporation. When simulating heat transfer, it is incorrect to neglect free convection in gas or liquid due to their strong nonlinear influence on each other. The heat exchange in the drop is extremely conservative to convection in the liquid (the Peclet number Pe = 100 and the Nusselt number Nu = 4).

1. Introduction

1.1. Applications of droplet evaporation

Research into the droplet evaporation processes helps to better understand the laws of heat and mass transfer both inside the liquid and in the gas vicinity of the drops, which is important for the correct modeling of a wide range of technologies: spray cooling [1], microelectronics [2], combustion in gas-drop flows [3], fire fighting [4], power engineering [3,5,6], absorption heat pumps [6], sol-gel-technology [7], etc. Environmental issues and reduction of harmful emissions of fuel combustion have become the most important in recent decades and are associated with the evaporation of drops [3].

Evaporation of water droplets at fuel combustion decreases the combustion temperature and the efficiency of the combustion technology of natural raw materials. The flow of vapor and fine water droplets is formed when burning methane hydrate, which leads to a decrease in the combustion temperature of the fuel [8,9].

Since the methodology for assessing the key parameters proposed in this article can be applied to a wide range of problems related to non-stationary and non-isothermal processes, the review will touch upon some issues that are usually unrelated to each other. In particular, spray cooling leads to uneven cooling of the wall when drops of different sizes fall on the wall. In addition, the drops affect each other, and their joint effect has to be taken into account. It is especially important to consider the droplet size and thermophysical properties of the liquid as well as the heated solid wall in the first seconds of the drop falling when the heat exchange in the liquid changes rapidly [9]. The size of the drops is especially important to consider at high heat flows. Drops with different diameters falling on the wall can evaporate both in the bubble boiling mode and in the boiling crisis mode at a tenfold decrease of the heat transfer coefficient.

In the study of the behavior of the gas-drop flow and the emulsions, it is important to calculate not only the heat exchange between small drops and liquid (gas), but also to assess the resistance of drops to their destruction and that of the drop diameter to external disturbances [10,11]. To describe the behavior of multiphase flows and emulsions, it is crucial to consider the degree of flow turbulence and the energy of turbulent pulsations [11,12].

Unsteady heat transfer in droplets and thin layers is extremely difficult to model if the whole process of cooling and crystallization lasts for a fraction of a second. Therefore, it is important to know factors that are responsible for these processes. A typical example of such technologies is the creation of thin nano- and micro-coatings. The quality of the coating and its structural properties depend on the wall material, evaporation rate and convection in the thin layer of the solution

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Nomenclature

a	thermal diffusivity
C	mass concentration
c_p	heat capacity of liquid
D	diffusion coefficient
D	heater diameter
d	droplet diameter
d_e	equivalent diameter
F	area of droplet surface
g	gravitational acceleration
j	evaporation rate
Ma_C	solutal Marangoni number
Ma_T	thermal Marangoni number
m	droplet mass
Nu	Nusselt number
P	hydrostatic pressure
Pe	Peclet number
q	heat flux density
r	radius
r	latent evaporation heat
Ra	Rayleigh number
R	droplet radius
t	time
T	temperature
u	velocity of liquid
V	velocity of liquid
z	coordinate

Greek symbols

α	heat transfer coefficient
β	thermal expansion coefficient
λ	thermal conductivity
ρ	density
ν	kinematic viscosity
μ	dynamic viscosity
σ	surface tension
σ	Stefan-Boltzmann constant
δ	boundary layer thickness
ω	angular velocity of rotation

Subscripts

0	initial value (t = 0)
1	for salt concentration
2	for water concentration
c	convection
cg	gas convection
cl	liquid convection
i	current value
g	gas
$heat$	heating (droplet heating)
l	liquid
r	radiation
s	droplet free surface
w	wall
v	vapor
e	evaporation
λ	the influence of thermal conductivity
Ma_T	the influence of Ma_T
Ra	the influence of Ra

[13–17]. Rapid cooling of the films and non-uniform crystallization give rise to thermocapillary and concentration Marangoni surface flows, which regulate the rates of heat transfer and evaporation. However, the experimental study of these fast-flowing processes is difficult. It is hard to obtain correct data on the change of the heat transfer coefficient and convection rate in the film and the droplet over time.

An important role is played by the solutal Marangoni flow in thin films of solutions and drops, when a new crystalline phase is formed on the surface of the solution. Crystallization leads to a change in the concentration field around the crystals that leads to appearance of concentration gradients of solution components. This is the resulting surface solutal Marangoni flow that leads to the motion of crystals [18].

Modern technologies allow creating structured wall surfaces in different ways: by mechanical processing, chemical etching, treatment with a high-power laser, hot plasma spraying, cold gas-dynamic jets, etc. These methods change the wettability [19–22] of the wall and lead to a change in the heat transfer coefficient. The structured wall significantly affects the wettability, heating and evaporation of the droplet and increases the convection in the liquid and the evaporation rate of the droplet (compared to a smooth surface [23]).

1.2. The influence of convection and methods of flow visualization

In the question about the effect of convection on the evaporation and heat transfer of a droplet or thin film, it is necessary to consider convection both in the gas and liquid phases. If the length of the heater is many times greater than the diameter of the droplet, then free air convection is formed over the hot wall and accelerates the droplet evaporation. The simulation has shown that gas convection increases the rate of evaporation by 20–30% [24]. Experimental studies of recent years clearly show that in reality, convection in the gas can greatly increase the rate of evaporation. At that for this effect to be substantial, heating the wall to high temperatures is not necessary. Convection should be also taken into account when a large-radius drop (R_0 > 20 mm) evaporates at room temperature [25] or when a highly volatile liquid evaporates [26,27].

In the experimental study of small volumes of the medium in fast processes, there are difficulties associated with the resolution of devices and their accuracy, as well as with methods of statistical processing of huge arrays of data for various random fields. Modern computing capabilities and high-velocity non-contact methods for visualizing the instantaneous fields of temperature and velocity allow obtaining statistical information with high spatial and temporal resolution: Shadow Photography (SP) [28], Planar Laser Induced Fluorescence (PLIF) [4], Particle Tracking Velocimetry (PTV) [29,30], Interferometric Particle Imaging (IPI) [31,32], Stereo PIV [33,34], Particle Image Velocimetry (PIV) [35]. These optical methods enable detecting the effect of free convection on the evaporation rate and heat transfer and today are widely used in the study of droplets, films, sprays, micro-channel, heterogenic flows, two-phase (vapor-liquid) flows and emulsions, boundary layers and crystallization processes in multicomponent solutions. These measuring technologies diagnose flows for internal volumes. Measurements of temperature characteristics on the surface of a drop, film, crystal are also of interest. Modern thermal imaging devices also have high spatial resolution and performance. Experimental thermal imaging techniques allow measurements in various liquids and solutions [36,37].