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The effect of Weber number, droplet sizes and wall roughness on crisis of droplet boiling

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ABSTRACT

Various boiling modes in a wide range of droplet sizes and wall temperature under droplet T_w were studied experimentally. Dynamics of droplets boiling is determined not only by T_w, Weber number We, wall roughness but also by the droplet shape. Application of two different methods of forming a suspended spheroid (ellipsoid) for $We = 0$ and $We > 1$ allowed separate investigation of the influence of the key factors on evaporation. To form the spheroids with $We = 0$ (no droplet fall, $V_0 = 0$ m/s), the limiting rings were used. For $We = 0$, an increase in pressure inside a droplet and its disintegration were excluded because there was no fall. An increase in roughness at $We = 0$ promotes an increase in Leidenfrost temperature T_L, and conversely, at $We > 1$, high roughness leads to a decrease in T_L due to the pressure drop in liquid and decay of a spheroid. With the growth in the initial diameter of a suspended drop at $We = 0$, temperature T_L increases significantly and approaches the value of T_L at pool boiling in water. The lower value of this temperature is also consistent with theoretical predictions. Experimental data demonstrate the importance of taking into account the size maldistribution of droplets for the correct prediction of the uneven temperature field on the heated wall surface.

1. Introduction

Film and spray cooling are widely used in heat exchangers. The size of constructions, energy costs and cost price of technology depend on cooling efficiency. Often, the heat flux is unevenly distributed over the surface, and under the non-stationary regimes, the separate regions of critical wall overheating can occur. The local boiling crisis leads not only to wall destruction, but also to the destruction of the whole construction. Film boiling is accompanied by periodic contact between superheated liquid and wall, periodic, jump-like release of steam and hydraulic impact in the long heat exchangers with a narrow cross-section of the channel. Much attention is paid to prediction of two key temperatures: temperature of boiling crisis beginning T_{CR} and Leidenfrost temperature T_L. At T_{CR}, liquid starts separating from the walls, and this leads to a decrease in the heat transfer coefficient. Transient regime of boiling crisis is between T_{CR} and T_L. This regime is accompanied by periodic contact between liquid and wall. At Leidenfrost temperature, a stable steam film is formed between the wall and liquid (film boiling). At that, heat transfer decreases repeatedly due to low thermal conductivity of steam. To date, the transition regime is investigated less thoroughly because of experimental and theoretical difficulties. Since under this regime, there is a short-term adhesion of a droplet with the heated wall, it is important to consider the key factors influencing evaporation of not only a suspended spheroid, but of a sessile droplet as well. The process of evaporation of the sessile droplets and film of single-component liquids on the hydrophilic surface is investigated in Refs. [1–7]. The behavior of droplets on a hydrophobic surface is studied in Refs. [8,9]. The evaporation dynamics depends on contact angle, thermo-capillary flow and Marangoni stresses [10–13]. When a droplet falls on the wall, its stretching depends on the dynamic contact angle. Sliding dynamics and the rate of droplet fall and contact angle decrease are determined by the difference between the potential energy barrier of the contact line and capillary free energy [14,15]. In the case of extremely fast droplet heating during a contact with the wall there is a significant change in evaporation rate and it has considerably non-linear character. The droplet spreading time over the wall depends on the average value of dimensionless wall roughness $R^* = R_a/d_0$, contact angle and Weber number We, Reynolds number Re and Ohnesorge number Oh [10]. It is shown that the dynamic contact angle decreases from 110° to 50° during 5–6 ms at the fall of a small droplet on the cold wall. Analysis of fluid flow and particle transport in evaporating droplets exposed to infrared heating were studied by Thokchom et al. [16]. A change in the evaporation regime depends on the thermal-

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Nomenclature

a	thermal diffusivity
a_1	$a_1 = (\sigma/(g(\rho_l - \rho_v)))^{1/2}$
d	droplet diameter
$d_1 = d_0/a_1$	nondimensional droplet diameter
g	free fall acceleration
Fo	Fourier number, $Fo = \alpha t_1/r_0^2$
r	droplet radius
t	time
t_1	the total evaporation time
T_L	Leidenfrost temperature
T_s	droplet interface temperature
T_{CR}	temperature of the boiling crisis beginning
T_w	wall temperature
V_0, u_0	droplet fall velocity
V	droplet volume
We	Weber number, $\rho_l d_0 u_0^2/\sigma$

Greek symbols

σ	surface tension of liquid
θ	contact angle
ρ	density

Subscripts

0	initial value ($t = 0$)
cr	critical
l	liquid
s	droplet surface
w	wall
v	vapor

physical properties of liquid and wall as well as on the ratio of droplet diameter to the wall thickness [17]. A degree of wall cooling and further boiling regime will depend on the droplet diameter and *Bi* and *Fo* numbers for both liquid and wall. Dynamics of nucleate boiling in a droplet is different from the pool boiling [18,19]. Dynamics of transient processes at liquid boiling using structured packing and structured wall is investigated in Refs. [20,21]. Droplets evaporation of pure liquids differs significantly from desorption of salt solutions [22–24]. For solutions, it is important to take into account not only the equations of energy and momentum, but also the diffusion equation. Neglecting diffusion can lead to multiple overestimation of theoretical estimate relative to the experimental data. The behavior of droplets in the gas flow and their combustion are examined in Refs. [25–27]. The behavior of methane-water droplets flow during combustion was considered in Refs. [28–30]. The behavior of a droplet impacting a solid surface and liquid and boiling crisis were studied in Refs. [31–39]. The pressure of liquid inside a droplet increases significantly due to the droplet fall on the wall. As a result, the process of nucleate boiling is impeded and temperature T_L increases [40–42]. Effect of surface microroughness, surface and physical properties was studied by Benjamin et al. [43].

The most of studies on the droplets evaporation were carried out for the small droplet sizes. Now in literature, there are few data on the complex investigation of the behavior of the middle and large droplets at the Leidenfrost temperature as well as the behavior of droplets under the transition region of boiling crisis. The studies of droplets evaporation in a wide range of their diameters are interesting from the points of theory and practice. At high wall overheating, an increase in the droplet diameter leads to a significant wall cooling, and this influences the boiling regime. There is a wide range of tasks on the stray wall cooling. In the flow of droplet-gas medium, the droplets coalesce fast and there is always a wide range of droplet sizes. Droplets, falling on the wall, move along the surface, interact and merge with each other.

The purpose of this work is to study the transition regime of boiling crisis in a wide range of diameters of a suspended droplet, wall overheating ΔT_w, *We* numbers, as well as studying the influence of wall roughness and *We* number on the Leidenfrost temperature. Since at the fall of a droplet with $We \gg 1$ many key factors affect simultaneously on T_L, the method of studying the behavior of a spheroid with $We = 0$ is suggested; this method excludes the fall of a droplet on the wall, pressure increase in the droplet and droplet decay. This method allows us to investigate film boiling of the suspended droplets with the diameter from 1 to 25 mm. It is impossible to form the spherical droplets of such large sizes in the case of the free fall.

2. Experimental data and analysis

2.1. Evaporation of suspended droplet in a wide range of initial volumes

The experiments were carried out in the air temperature 21 °C and pressure 1 atm. The initial liquid temperature was equal to the ambient air temperature 21 °C. Relative air humidity was 35%. Droplets were located on the horizontal heated wall of the aluminum cylindrical working section. The cylinder diameter was 65 mm and its height was 45 mm. Measuring thermocouple was located near the wall surface (0.1 mm from the surface). The wall temperature was kept constant automatically with the accuracy within 1 °C. The liquid surface temperature was determined by the thermal imager. For these purposes, NEC R500 infrared camera (640 × 512 pixels) was used. Emissivity was changed with accuracy of 0.01 °C. The difference between the temperature values measured by the thermocouple and thermal imager did not exceed 2 °C. When measuring the temperature of droplet or spheroid surface (T_s) by the thermal imager, the average height of the liquid layer was more than 1 mm and the error of T_s measurement did not exceed 2 °C. Due to relatively thick water layer ($h > 1$ mm), the wall hardly affects the measurements of thermal imager. The droplets were formed by the micro dispenser with the maximal relative volume error below 1.5%. Before starting the experiment, the wall surface was cleaned by alcohol solution from dust and contamination. The state of the surface was registered by a microscope to control the persistence of surface properties. RMS roughness was measured before and after each experiment. The optical profilometer Zygo NewView 8000 with 3D surface visualization (uncertainty of measurement is $\mp$15 nm) was used. Due to surface oxidation, physical-chemical properties of surface and RMS roughness can be varied, and it can lead to a substantial change in the contact angle and the area of the droplet base. Therefore, surface treatment and microscopic control allowed us to carry out the experiments under the identical conditions. The whole experimental system was under a shell, which provided constant ambient conditions. Before the experiment, the ambient air was dehydrated using silica gel and water bidistillate was degassed thoroughly by means of boiling, to reduce the amount of dissolved gas. Degassed bidistillate was used in all experiments. In every experiment the dosed batches of bidistillate were placed on the heating surface with the help of high-precision batcher (Fig. 1a), located normal to the wall at a distance of several millimeters from the wall surface; this excluded droplet impact and its splitting. Photographic measurements of the shape and area of the sessile droplet bottom and the shape of spheroid have shown good reproducibility of