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Research Paper

Contact angle and droplet evaporation on the smooth and structured wall surface in a wide range of droplet diameters

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HIGHLIGHTS

- Structured wall relief influences droplet wettability.
- Marangoni force and contact angle depend on the droplet diameter.
- Droplet evaporation on the structured surface differs from one on a smooth wall.
- Dependencies for the form of small and large droplets are different.

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ABSTRACT

Droplet evaporation in a wide range of initial volumes of 1–1000 μl on the structured and smooth surfaces was studied experimentally. It is found that the static contact angle on the structured surface for the steady equilibrium depends on the droplet shape and initial diameter; it has an extreme. With the increasing wetting diameter of water samples from 2 to 30 mm, the contact angle increases first, reaches a maximum, then decreases and tends to a constant value. To determine the contact angle, the authors have performed the comparisons by different methods in a wide range of droplet sizes. A wide range of droplet sizes is usual for spray cooling. Approximation dependences for determining droplet volume were obtained in a wide range of droplet sizes. For the droplets with the initial diameter less than 1 mm, middle and large droplets, as well as for the small initial contact angles and angles of about 85–90°, different kinetics of evaporation will be observed. Kinetics of droplet evaporation on the structured surface differs from evaporation on a smooth wall. Dimensionless Fourier number (*Fo*), derived by the initial droplet diameter and total time of evaporation, decreases with an increase in the wall temperature and initial droplet diameter. For large droplet diameter and a high wall superheating the derivatives $d(Fo)/d(T_w)$ and $d(Fo)/d(d_0)$ tend to zero.

1. Introduction

The evaporation and boiling processes are widely used in technical apparatuses. Effectiveness of technological processes depends on their correct description and designing. Droplet evaporation depends on a number of key factors: droplet shape and contact angle, free convection in liquid and external gas, geometric and thermophysical properties of wall surface, wall superheating and interfacial surface subcooling, external gas pressure, and Marangoni surface forces. It is necessary to consider the impact of all these factors during evaporation of large droplets and high wall superheating. Kinetics of droplet evaporation depends on its diameter. Evaporation of a droplet with the size of 0.1 μm or less depends strongly on the surface tension, which leads to very high evaporation rates and significant difference from the equilibrium model. According to the Hertz - Knudsen equation, the non-equilibrium character and underestimated values of evaporation rates are typical of the range from 0.1 to 100 μm [1]. Evaporating droplets with the size from 100 μm to 3 mm have the well-described geometrical shape. The droplets with the sizes from 3 mm to 30 mm change their shape from a lens to quasi-flat surface, which significantly complicates the theoretical analysis. Numerical simulation taking into account the Marangoni strength and convection inside the small droplet was carried out in [2]. Extremely weak influence of the thermocapillary forces is explained by the low wall temperature of 40–50 °C and small droplet volume of 1–1.4 μL. The difference in temperature on the interfacial surface of liquid was about 1 °C. Low gradients of surface temperature and surface tension lead to very weak convection

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Nomenclature

a	thermal diffusivity
d	droplet diameter
Fo	Fourier number, $at_1/r_0 2$
h	droplet height
L	characteristic length
Ma	Marangoni number, $\frac{h^2 \Delta T}{\mu a L}\left(\frac{d\sigma_{lg}}{dT}\right)$
R	radius of curvature
r	droplet radius
S	droplet area
T	temperature
V	droplet volume
We	Weber number, $\rho_l d u^2/\sigma$

Greek symbols

σ	surface tension
θ	static contact angle
μ	viscosity
ρ	density
t	time
t_1	total time of evaporation

Subscripts

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

inside the droplet. It is shown in this work as well as in [3] that while approaching the final stage of droplet evaporation, the evaporation rate decreases and deviation from linearity of the evaporation law increases. This fact is rightly associated with a decrease in the interface liquid-gas area in time. Simultaneously with a decrease in the area and evaporation rate, the opposite trend is observed. With time, the height of a droplet decreases and interface temperature increases [2], and this should increase the rate of evaporation. However, the applied wall superheating of 40–50 °C is insufficient to influence significantly the growth of the interface temperature. As a result, the cumulative effect leads to a drop in the evaporation rate. Results of numerical simulation for a small droplet with the room temperature are presented in [4]. It is shown that near the contact line the evaporation flow increases repeatedly. The total impact of this effect on the total flow on the entire interface is negligibly small and evaporation flow on the droplet surface can be assumed quasi-constant. An influence of wall properties on different boiling regimes is presented in [5]. A change in the boiling regime depends on the thermal-physical properties of liquid, wall and vapor as well as on the ratio of droplet diameter to the wall thickness [5]. There is a wide range of tasks on spray wall cooling. The cooling behavior of the water droplets spray strongly depends on initial droplet sizes. The smaller the initial droplets radius, the faster droplets freezes [6]. 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. As a result, the wall is cooled both by the small droplets of the millimeter size and by the large ones with the diameter of a wetted spot of several millimeters. This method of cooling usually leads to very uneven distribution of temperature and evaporation rate over the wall surface [7], and this affects the quality of technology. In addition, the large droplets interact and form a thin film. At that, kinetics of evaporation will strongly depend on the characteristic dimensions. One of the effective ways of highly heated wall cooling is the use of droplet-gas curtain [8]. It is noted that the efficiency of this curtain relates to initial concentration of liquid (droplets) in gas. Small droplets merging on the wall and formation of a thin film demonstrate the meaninglessness to increase liquid concentration because this leads to film thickening and heat flux reduction. Theoretical analysis of the joint influence of all forces on droplet geometry and formation of a static equilibrium contact angle is rather complicated. Thus, the influence of gravity and capillary forces on the shape of small droplets at a change in the Bond number (Bo) from 2 to 200 and Capillary number (Ca) from 0 to 8 was examined in [9]. Small droplet spreading is investigated in [10] by taking into account the capillary and adhesion forces. The droplet height has an extremum at increasing the initial droplet volume, and this extremum is defined in [11] by means of the variation method. Sliding dynamics and the rate of droplet and contact angle decrease are determined by the difference between the potential energy barrier of the contact line and capillary free energy [12,13]. It can note some papers, considering evaporation on the hydrophilic and hydrophobic surfaces. The process of evaporation of the sessile droplets on the hydrophilic surface is investigated in [14–21]. Deposit uniformity is enhanced by multy-sized nanoparticles and droplet evaporation controls deposit profiles [21]. The behavior of droplets on a hydrophobic surface is studied in [22–25]. The metallic coatings with rough surfaces and with the droplet water contact angle of 155 °C were prepared via the three thermal spray processes [24]. More groove area or smaller droplet will make the anisotropy more significant and this fact is of great importance for the technical application of microstructured surfaces [25]. Influence of the contact angle is considered in [3,24–27]. The combined influence of the contact angle and Marangoni stresses is investigated in [28,29]. Droplet surface cooling depends on wall material [30]. A wide range of droplets sizes is not only important to consider a wall cooling effect, but also for spray technologies. The cooling performance of the system is enhanced for wider drop-size distributions [31]. The droplet size also influences on transfer characteristics of high temperature gas flow [32]. The droplets evaporation of solutions is dependent on components concentration [33–37]. The behavior of a droplet impacting a solid surface and boiling crisis were studied in [5,38–40]. Droplets spreading and wettability on the structured wall surface are considered in [41–43]. In contrast to a smooth surface, where the contact line can advance continuously, on a repellant surface, the contact line has to overcome an air region between ledges [44]. In the pinned regime, the depinning contact angles increase with decreasing contact fraction and the substrate heating promotes the contact line depinning. In the moving regime, the motion of droplet is characterized by periodic stick–slip events and oscillations of contact-angle [45].

Thus, at present, most experimental and theoretical studies deal with the small droplets and spheroids with the diameter less than 3 mm, and they related to the low wall temperatures (up to 50–60 °C). Evaporation kinetics for medium and large droplets will differ from small ones. The experimental data of the current study relate to droplet diameters from 1 to 30 mm; and evaporation of