

Contents lists available at [ScienceDirect](http://www.sciencedirect.com)

Chemical Engineering Research and Design

journal homepage: www.elsevier.com/locate/cherd

Effect of various key factors on the law of droplet evaporation on the heated horizontal wall

S.Y. Misyura ^{a,b,*}^a Institute of Thermophysics Siberian Branch, Russian Academy of Sciences, Lavrentiev Ave. 1, Novosibirsk 630090, Russia^b National Research Tomsk Polytechnic University, pr. Lenina 30, Tomsk 634050, Russia

ARTICLE INFO

Article history:

Received 24 July 2017

Received in revised form 23 October 2017

Accepted 20 November 2017

Keywords:

Water droplets evaporation

Droplet heat transfer

Structured surface

Natural convection

ABSTRACT

Water evaporation in a wide range of initial droplet diameters and at different wall temperatures on structured surface was studied experimentally. With an increase in the wall temperature from 31 to 72 °C and an increase in the initial droplet diameter, exponent n in the evaporation law increases from 1 to 1.37. Under the transitional regime, exponent $n = 1.6$ reaches its maximum. Usually, while simulating droplet evaporation, a linear relationship of the evaporation rate of water vapor and droplet radius R is considered ($dm/dt \sim R^n$, $n = 1$). In this paper, it is shown that exponent n increases with a growth of the wall temperature. In generalization of droplet evaporation rate, the exponent for the Rayleigh number (Ra) is 0.457 due to the predominant role of gas convection. For large water drops (for air–vapor mixture over the droplet surface) high Reynolds numbers are achieved ($Ra = 2 \times 10^5$). A diffusion vapor layer on the droplet surface and boundary layer of air on the surface of the heated cylinder, whose diameter exceeds the droplet diameter, are formed. A neglect of free convection understates simulation results in comparison with experimental data more than by the factor of 10. The sequence of key factors, taking into account their influence on the rate of droplet evaporation, is as follows: 1) convection in a vapor–gas medium; 2) effect of wall roughness, wettability, and convection in a liquid; 3) thermal inertia of the metal wall. The calculation methodology for a sessile drop enables a qualitative analysis for a high-temperature gas-droplet flow.

© 2017 Institution of Chemical Engineers. Published by Elsevier B.V. All rights reserved.

1. Introduction

Heat transfer and droplet evaporation are important in such fields as inkjet printing and liquid lithography techniques (Sirringhaus et al., 2000), microelectronics (Arcamone et al., 2007), control of droplet evaporation rate for DNA macromolecules (Fang et al., 2006), spray cooling, ice production (Wu, 2014), and microlense fabrication from solvent droplets (Bonaccorso et al., 2005). The studies of droplets evaporation on the structured surfaces for different droplet diameters are interesting for a wide range of technical applications.

An increase in the diameter leads to a significant change in wall cooling, and this leads to a shift in the droplet boiling regime (Misyura,

2016a,b). Low heat transfer between carbon nanotube porous film and water droplets has been observed (Bogya et al., 2016). The large droplets are the intermediate state for the description of both liquid droplets and thin liquid layer. For this case, with increasing diameter, the dependence of droplet evaporation rate on its diameter leads to dependence on the square of the base radius. It is assumed that a change in the evaporation law is caused by a change in natural convection, which is characterized by Grashof and Prandtl numbers (Carrier et al., 2016). Sessile droplet drying at free convection is accelerated. If the heater length is many times greater than the droplet radius, natural convection above a droplet increases the vapor flux and evaporation rate by more than 20–30%, even for moderate wall temperature of about 60–70 °C (Saada et al., 2010). The small droplets, falling on the heated wall, move along

* Correspondence to: Institute of Thermophysics Siberian Branch, Russian Academy of Sciences, Lavrentiev Ave. 1, Novosibirsk 630090, Russia.

E-mail address: misura@itp.nsc.ru

<https://doi.org/10.1016/j.cherd.2017.11.033>

0263-8762/© 2017 Institution of Chemical Engineers. Published by Elsevier B.V. All rights reserved.

the wall, interact and merge with each other, while the large droplets interact and form a thin liquid film. The characteristic example of such evaporation, when fine droplets, large droplets, and thin liquid film are simultaneously available, is the flow in minichannels at high heat fluxes (Nakoryakov et al., 2014). Droplet boiling for solutions differs from single-component liquids and it depends on components concentration (Nakoryakov et al., 2014, 2011, 2012; Misyura, 2015).

Currently, an increased attention is paid to creation of the structured surfaces with high hydrophobic and hydrophilic properties and studying wettability on this wall (Gau et al., 1999; Misyura, 2017a). The superhydrophobic surfaces can be effectively used for various tasks: self-cleaning; increasing condensation intensity and heat transfer; preventing icing and reducing wall friction. It is shown that the onset of the pinning regime (contact droplet line is attached, $d = \text{const}$) is delayed by changing the wall surface topography. Usually, while simulating droplet evaporation, a linear relationship of the mass flux of vapor and droplet radius is considered. Evaporation of small water droplets (1 mm diameter) located on a solid wall at the temperature of wall and air of 22 °C, when we can neglect the Marangoni flow and convection in the liquid and gaseous phases, is studied in detail. The growth of the droplet diameter of easily volatile liquids leads to significant intensification of evaporation due to vapor convection (Carle, 2016). Experimental investigation of mixtures and foreign inclusions in water droplets under high-temperature gas is presented in Volkov et al. (2015). The influence of forced air convection on sessile drop evaporation is considered in Bin et al. (2011) and Semenov et al. (2015). Evaporation, boiling and explosive breakup of heterogeneous droplets in a high-temperature gas is presented in Kuznetsov et al. (2016) and Volkov et al. (2014). The effect of droplets concentration on the evaporation in a high-temperature gas flow is presented in Kuznetsov and Strizhak (2015) and Volkov et al. (2016).

This article presents experimental data on the effect of free gas convection on sessile drop evaporation on the horizontal heated wall. Since the processes of heat and mass transfer described in the article are closely related to adjacent problems, it is of great interest to somewhat expand the subject of the review. Further it will be shown that a simple qualitative analysis is suitable both for a single sessile drop and the high-temperature gas-droplet flow and for problems, associated with the joint effect of free and forced convection. Studies of the most simple case of a sessile drop vaporization (without forced gas flow) allow identifying the effect of key factors on evaporation and heat transfer as well as quantitative criterial dependences. The resulting data, in turn, help to conduct a quantitative analysis of more complex non-isothermal multiphase flows.

2. Experimental techniques

Experimental measurements were carried out on horizontal heated structured wall at the air temperature of 23 °C and air pressure of 1 bar. The initial temperature of the liquid droplet was 23 °C. Wall roughness was measured with the help of the optical profilometer “Zygo” (measurement uncertainty of ± 15 nm). The droplets were located on the heated wall of the titanium cylinder with the diameter of 100 mm (Fig. 1(a, c)) and on a horizontal surface of a square form (Fig. 1(b, c)). The wall surface was cleaned by ethanol, then by acetone and left overnight before the experiments. The measuring thermocouples were located near the wall surface (0.1 mm and 3 mm from the surface). The wall surface temperature was determined according to temperature distribution over the wall. The relative measurement error of the thermocouples is 0.1–0.2% in accordance with the calibration. However, larger errors are associated with methodical errors of measurements due to the nonstationary character of the heat transfer near the wall surface. An error associated with the non-linear character of temperature T_w due to nonstationarity was within 1–1.5 °C. This error refers to the “average times” i.e., to quasi-stationary

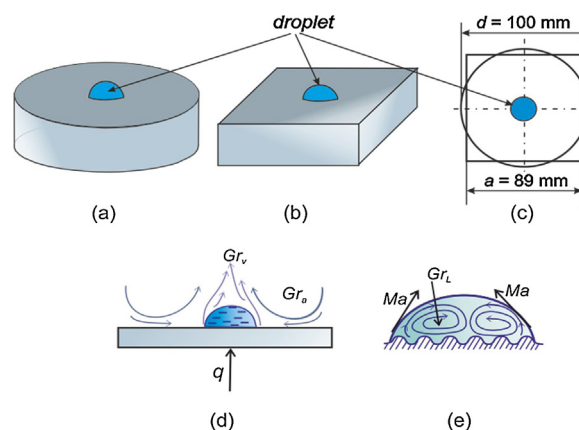


Fig. 1 – Droplet evaporation on the heated horizontal cylindrical (a) and square (b) sections; (c) working section sizes (top view); (d) free gas convection; (e) free liquid convection.

thermal regime (excluding the initial heating of the droplets and the time when the contact line of the droplet loses its stability, and the drop base diameter starts decreasing).

The wall temperature was kept constant automatically in the range of $T_w \pm 0.5$ °C (where T_w is the preset value of the wall temperature). Inside the metal cylinder there was a heater, where using an automatic system of the voltage adjustment was applied to minimize the deviation of the wall temperature from the preset value. The free surface temperatures of water droplet (T_s) were determined by the thermal imager (NEC-San Instruments, 640×512 pixels, resolution of $10 \mu\text{m}$). The droplet temperature of interface T_s was the average surface temperature. The measurement error of infrared camera was within 1 °C. The droplets were formed by a micro-dispenser with the maximal relative volume error below 0.5%. Since the minimal height of the drop exceeded 0.7 mm (at thermal imager measurements), the wall influence on the drop surface temperature measurement T_s was neglected.

The curve inclination for evaporation rate $j = dm_i/dt$ (m_i is the current drop mass) was determined by statistical processing and three recurrent experiments. The spread of values j in recurrent experiments did not exceed 5–7%. The drop mass was measured by weighing. The working section with the drop was placed on the electronic balance. To increase the accuracy of drop mass measurement, the curve inclination for j was determined not until the time of full droplet evaporation t , but only for t when the drop mass decreased two times. For small droplets, the maximal error of evaporation rate measurement did not exceed 25–30%. For the drops with initial radius over 5 mm the measurement error for j was within 10–13%.

The whole experimental setup was under a shell, which provided the constant ambient conditions. External air humidity was 25–30%. Degassed bidistillate was used in all experiments. The droplet contact angle on the structured wall was determined by the optical system and changed within 71–74 °C. The measurement error of the static contact angle of the drop was 5–6%. In all cases, water wets the structured wall under the droplet completely. Since the drop was located on the heated wall, the free convective flow appeared over the heater surface and over the free surface of the drop (Fig. 1(d)). At an increase of the initial drop radius R_0 from 1 to 35 mm the Raleigh number (Ra) increased from 1 (for $T_w = 31$ °C) to 2×10^5 (for $T_w = 72$ °C) (for air–vapor mixture over the drop surface). For drops with large diameters, the free convective flow

Download English Version:

<https://daneshyari.com/en/article/7006340>

Download Persian Version:

<https://daneshyari.com/article/7006340>

[Daneshyari.com](https://daneshyari.com)