The drop evaporation on a heated substrate with single wall nanotubes coating

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Abstract. Evaporation of a sessile nanoliter water droplet was investigated experimentally at the substrate temperature of 30 °C. The studies were performed on the two substrates made of copper. One of them had no coating and was polished to the root mean square roughness of 20 nm. Another one was coated with single wall nanotubes (the root mean square roughness is 62 nm). The research has shown that specific rate of evaporation (mass loss per unit of the drop surface area) on the substrate with nanotubes coating is up to 20 percent higher in comparison with the substrate without coating.

1. Introduction

The phenomenon of liquid drop evaporation, which takes place in a variety of technological systems in power engineering, agriculture, medicine, cooling systems, chemical and other industries [1], has been actively investigated during the last few years [2-6]. In most experimental and theoretical studies found in the literature, isothermal evaporation of water droplets has been studied. Publications on nonisothermal evaporation of liquid droplets are very limited.

The main objective of the present work is to study the effect of nanotubes coating on the dynamics and evaporation of the sessile liquid drop in quasistationary conditions when it is heated from the substrate. It is assumed that due to the multifarious influence (variative wettability, thermal conductivity of wall layer, surface structure at the micro- and nanoscale) the use of the nanotubes coating allows to intensify the evaporation process.

In this paper, we study evaporation of a liquid drop into the open atmosphere. The initial drop volume was less than 1 μl. A drop of liquid is placed on a surface with controlled wettability. The drop is heated until quasi-stationary heat transfer between the solid substrate and liquid drop. Distilled deionized nano-filtered water of Milli-Q Company is used as the working fluid. The use of water with relatively high boiling point as a working fluid allows to study in detail the influence of temperature difference between the solid surface and surrounding atmosphere on the rate of evaporation and heat transfer. In this work the temperature difference between the solid and external atmosphere was about 10 °C.
2. Experimental setup

The experiments on water drops evaporation in the open atmosphere were made on the experimental stand the scheme of which is presented in Fig. 1. The base of the test section is an aluminum plate of 15 mm thickness with the heater attached to its bottom side. A Peltier element with dimensions 40x40 mm$^2$ was used as a heater. On the upper side of the aluminum plate, the investigated substrate was fixed. Measurement of the surface temperature of the studied substrate was carried out using a thermocouple, fixed at a distance of 1-2 mm from the contact line of the liquid drop. The temperature under the substrate was measured by three thermocouples of K-type. Thermocouples were placed radially at different distances from the center of the substrate and served to measure the temperature distribution along the substrate radius. The experimental setup was covered with transparent box made of PMMA, which has dimensions of 1000x800x900 mm$^3$. The relative humidity of air in the box during the experiments was 20-30%.

![Figure 1. The scheme of the experimental setup.](image)

Two optical methods were used in the work. The first one is the shadow method, consisting of a halogen light source Edmunds Optics MI-150 connected by a fiber optic lightguide with a lens system that produces a beam of parallel light of 50 mm in diameter on one side of the working area, and a PointGray fast speed camera with a 10X Mitutoyo microscope lens, which was connected through Novoflex focusing bellows from the opposite side. The spatial resolution of such a system was 0.5 μm / pixel, and the shooting frequency was up to 500 frames per second. Obtained shadow photos of the liquid drop profile were processed by the KRUSS Drop Shape Analysis software.

The second optical technique used is 5 megapixels Imaging Source camera with 20X Mitutoyo microscope lens, which was placed above the liquid drop and allowed visualization of evaporation process from the top and control the drop symmetry. If the drop lost its symmetry, the experiment was repeated.

Two substrates made of copper were investigated. One of them had no coating and was polished to the root mean square roughness of 20 nm. Another one was coated with single wall nanotubes orientated along the surface. The coated substrate had the root mean square roughness of 62 nm. The morphology of the working surfaces was analyzed using a scanning electron microscope (HITACHI S3400N) and atomic force microscope (Solver Pro NT MDT), Fig. 2.
Figure 2. The SEM image (left) and height histogram (right) of the substrate with the single wall nanotubes coating.

3. Experimental results

The experiment began with a preliminary preparation of the investigated substrate, which consisted in a thorough cleaning of the working surface. Then the substrate was placed in a reservoir with distilled water for a day. Thereafter, to remove residual water from the surface the substrate was flushed with clean compressed air designed for cleaning optical components. A liquid drop of pre-set size was placed on the surface, heated to the desired temperature, using a high-precision dispenser Lenpipet. The lens used in the shadow method was focused (depth of field was a few hundreds of µm); and after that the periodic shooting was performed until complete evaporation of the liquid droplet. The upper camera was switched on simultaneously with the shadow method.
(c) \( T_{sec} \) vs Base Diameter, mm

(d) \( T_{sec} \) vs Height, mm

**Figure 3.** Dependences of different parameters of droplet vs evaporation time. (a) – the volume of droplet, (b) – the surface area of droplet, (c) – the diameter of droplet base and (d) – the height of droplet. Blue lines and dots are data for polished copper substrate, red – copper substrate with nanotubes coating. Initial temperature of all substrates was \( T=30^\circ\text{C} \). All data was synchronized for the moment of full droplet evaporation.

Dependences of various parameters of a sessile liquid drop during evaporation vs time are shown in Fig.3 for the substrate temperature of \( T=30^\circ\text{C} \). The obtained data are synchronized in time for the moment of complete evaporation of the droplet. It is seen that in spite of the fact that the liquid drop on the coated substrate had slightly higher initial volume, the time of evaporation for this drop is slightly lower, compared with the drop on the substrate without coating.

(a) \( T_{sec} \) vs Contact Angle, deg
Figure 4. The dependences of contact angle (a) and specific evaporation rate (b) on time. Blue lines and dots – data obtained with the polished copper substrate; red – copper substrate with nanotubes coating. The dotted lines in figure (b) are the trend lines of the corresponding data. Initial temperature of all substrates was $T=30\,^\circ\text{C}$. All data was synchronized for the moment of full droplet evaporation.

The dependences of the contact angle and specific rate of liquid evaporation on time at different substrates are shown in Fig. 4. The evaporation rate was calculated as a loss in the droplet mass per unit of droplet surface area per unit of time. All the data were synchronized to the time of complete evaporation of liquid droplets. It is seen that the specific rate of evaporation on both substrates increases with time, which is in agreement with the results of [2, 3] where the evaporation of liquid drops with initial volume of about 100 µl was studied. Also, it is seen that at the final stage of the drops evaporation, the specific evaporation rate for the drop on the substrate with nanotubes coating is about 20 percent higher in comparison with the polished substrate. It is worth noting, that at the final stage all the main parameters of both drops (volume, base diameter, contact angle,...) are very close (Figs. 3, 4a). This means that the use of the nanotubes coating allows to intensify the sessile liquid drop evaporation. We expect that with increase of the substrate temperature, the difference between the specific evaporation rate between the coated and uncoated surfaces will increase.

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