

Effect of Temperature and Wettability of the Substrate with Nanotubes Coating on the Evaporation of Water Droplets

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Abstract. The paper presents an experimental study of evaporation of a millimeter-sized sessile water droplet into open atmosphere in a wide range of the temperature difference (from 0 to 76 K) between the solid substrate and the atmosphere. Two copper substrates were used in the experiments. One of them was polished to the root mean square roughness of about 20 nm. Another one was coated with a micrometer-thick film of single-walled carbon nanotubes. With the help of precise drop shape analysis system, the mode of droplet evaporation with pinned contact line was studied. No appreciable difference was detected in evaporation droplet dynamics between the two substrates for the substrate temperatures from 24 to 100 °C.

1 Introduction

The evaporation of drop deposited on a heated substrate is successfully applied in industrial processes such as spray cooling, printing and coating technologies, the manufacture of new electronic and optical devices and medical tests. Also the study of evaporating liquid droplets is important to understand the mechanisms that occur in complex systems (clouds, fog, etc.) [1]. The greatest interest is caused by the fact that evaporation of liquid drops substantially intensifies heat transfer and affects the flow within the droplet.

As established by Deegan et al. [2], the evaporation mass flux along the liquid-gas interface is non-uniform and is the largest near the contact line, which creates radially outward fluid flow inside the droplet. Picknett and Bexon [3] were among the first to study evaporation of a sessile liquid drop on a solid substrate. They found that droplet evaporation occurs in two main modes: constant contact radius (pinned contact line) and constant contact angle (moving contact line). Sobac and Brutin [4] showed that substrate wetting properties play an important role in the process of the drop evaporation. Hu and Larson [5] studied vapor diffusion during sessile droplet evaporation both numerically and analytically, and proposed correlations for evaporation rates. Popov [6] derived an improved vapour diffusion model that can be used to calculate the evaporation rate for a

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droplet in a wide range of contact angles. In most experiments, evaporation of sufficiently large droplets was studied with relatively small temperature difference between the heated substrate and the ambient gas (see, for example, recent papers [7-9]).

In our paper, the process of evaporation of liquid droplets having an initial volume less than $1 \mu\text{l}$ is studied under the temperature difference between the solid substrate and the atmosphere of up to 76 K. One of the working substrates is smooth, whereas the other one is coated with a thin film of single-walled carbon nanotubes. The main objective of our work is to study the effect of nanotube coating on the dynamics and evaporation of the sessile liquid drop. It is assumed that due to various factors (increased thermal conductivity of the substrate surface layer, surface structure at micro- and nanoscale, ...) the use of the nanotube coating may intensify the evaporation process. This intensification is expected to be more pronounced for smaller droplets under higher temperatures of the substrate.

2 Apparatus and Experimental Techniques

Studies of the sessile liquid drop evaporation were performed with the use of DSA100 drop shape analysis system produced by KRUSS (scheme and photos are shown on Fig.1 and Fig.2). This device consists of three main parts: a high-precision dosing system with the dosing step of $0.1 \mu\text{l}$, a motorized object table with program-driven movement in 2 horizontal axes, and the optical shadow system, which includes 50 W light source and a CCD camera with a resolution of 780×580 pixels (viewing field could vary from 3.7×2.7 mm to 23.2×17.2 mm) (Fig.2 left). An opened into atmosphere Peltier chamber was used for heating substrates (Fig. 2 right). It can maintain the specified temperature of the bottom wall with an accuracy of about 0.1 K.

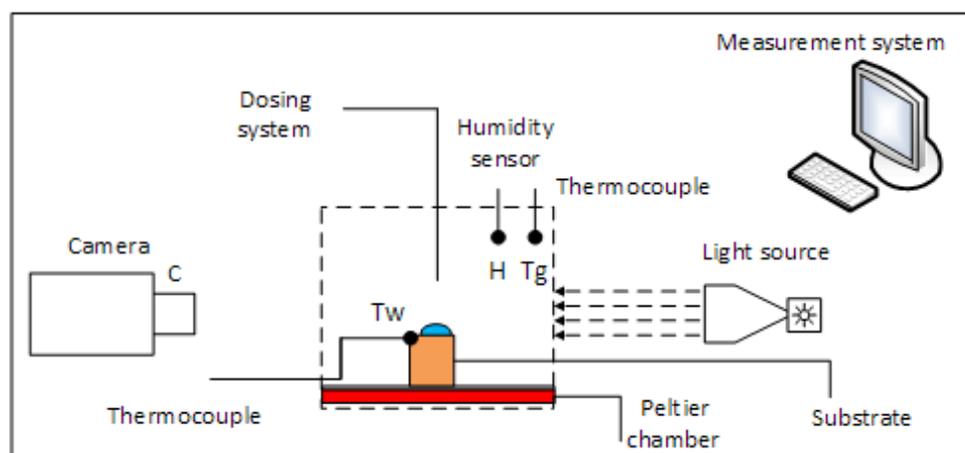


Fig.1. The scheme of experimental setup.

Measurement of the surface temperature of the copper substrate was carried out using a thermocouple, fixed at the distance of 1-2 mm from the liquid drop. The substrate surface temperature in each experiment was constant. The temperature and relative humidity of the ambient air during the experiments was 24-25 °C and 20-30 %, respectively. Distilled deionized nano-filtered Milli-Q water was used as the working liquid. The initial liquid drop volume was about $1 \mu\text{l}$. Kruss DSA Advance software allowed us to process shadow photos of evaporating liquid droplets in fully automatic mode (real-time determination of the droplet volume, base diameter and contact angles).

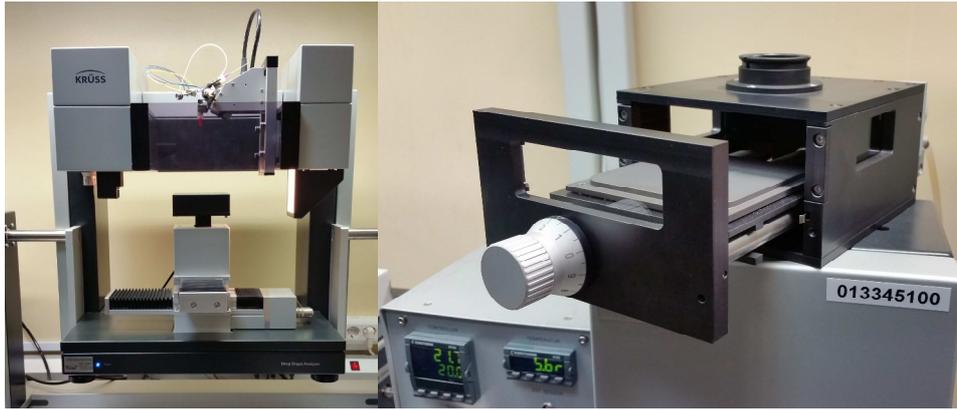


Fig.2. The photos of Krüss DSA100 (on the left) and Peltier chamber (on the right).

Two substrates made of copper having size of 10x10x10 mm were used. The working surface of both substrates was polished so that the root mean square roughness was about 20 nm. The first substrate had no coating. The surface of the second substrate was spray-coated with single-walled carbon nanotubes. The thickness of the coating is estimated to be on the order of 1 μm . The morphology of this surface was analysed using a scanning electron microscope (HITACHI S3400N), as well as using an atomic force microscope (Solver Pro NT MDT). The root mean square roughness of the coated substrate was about 60 nm. Degradation or any significant change of the nanotube coating after the experiment was not observed. The wettability of both substrates is very close. At room temperature, the static advancing contact angle for both substrates is $85 \pm 8^\circ$, whereas the static receding contact angle is $23 \pm 6^\circ$.

3 Results

Dependences of the main parameters of the sessile liquid drop during evaporation vs dimensionless time are shown in Figure 3, where t_d – final moment before complete evaporation of the droplet. Results are presented for the substrate surface temperatures 40, 60 and 90 $^\circ\text{C}$. It can be seen (Fig. 3(a)) that contact angles for copper surface are smaller than contact angles for coated one in all stages of droplet evaporation. The volume of the droplets during evaporation is presented in Figure 3(b). Initial volume of the droplet from the dosing system was 2 μl . The difference in initial volume of the droplets in the figure is due to the time needed for the droplet to spread and when the contact line was pinned the experiment was started. Figure 3(c) demonstrates that the droplet evaporation occurs in the mode with constant contact diameter (the contact line is pinned, D_0 – initial diameter of the droplet). When the contact angle reaches value about 10° the contact line starts moving so that both the contact diameter and the contact angle decrease (this was the case for all substrate temperatures studied). Unfortunately, the DSA100 KRÜSS software is not capable to faithfully measure contact angles less than 10° (Fig. 3(a)). That is why below we present data for the droplet evaporation mode with constant contact diameter only. The slight variation of the contact diameter (see Fig. 3(c)) at the very last stage of the evaporation mode with pinned contact line is due to the measurement uncertainty of the software (as seen from Fig. 3(c), this uncertainty does not exceed 5%). From Fig. 3 (a,b,c,d) one can see that qualitatively the evaporation dynamics on both surfaces does not differ. However, quantitative comparison of data sets presented in Fig. 3 (a,b,c,d) is difficult as we have some variation in the initial diameter, contact angle and volume of the droplets. It is

known (see, for example, [4]) that for a sessile liquid drop in the evaporation mode with constant diameter the mass loss per unit time is proportional to the droplet diameter and does not depend on the droplet volume and contact angle.

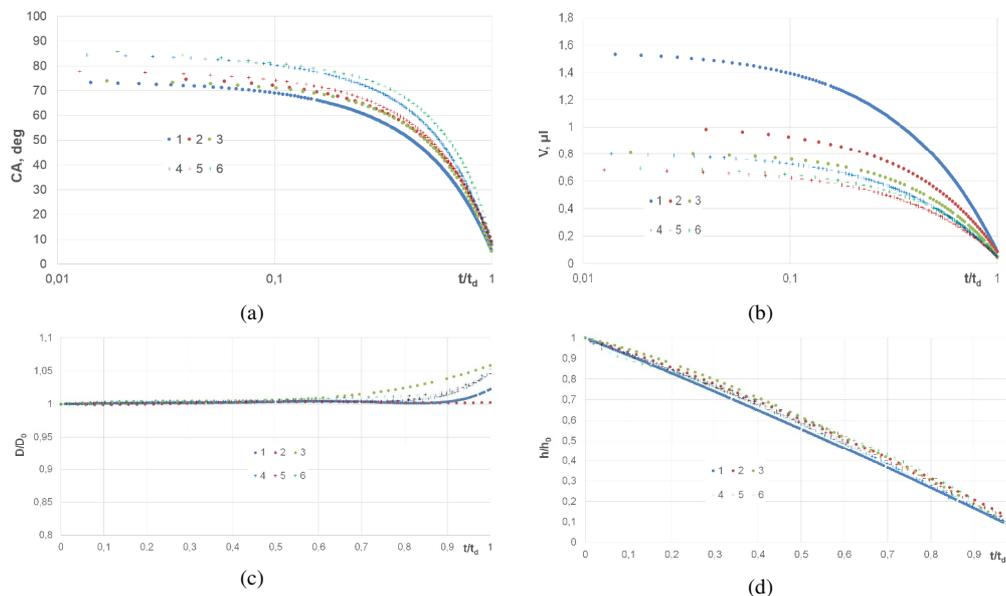


Fig. 3. Dependences of the main parameters of the sessile liquid drop during evaporation vs dimensionless time for different temperatures of substrates. (a) contact angle, (b) droplet volume, (c) dimensionless drop diameter, (d) dimensionless height of droplet. Temperatures: 1, 4 – 40 °C; 2, 5 – 60 °C; 3, 6 – 90 °C. Filled circle signs (1, 2, 3) – surface without coating; crest signs (4, 5, 6) – surface with single-walled nanotube coating.

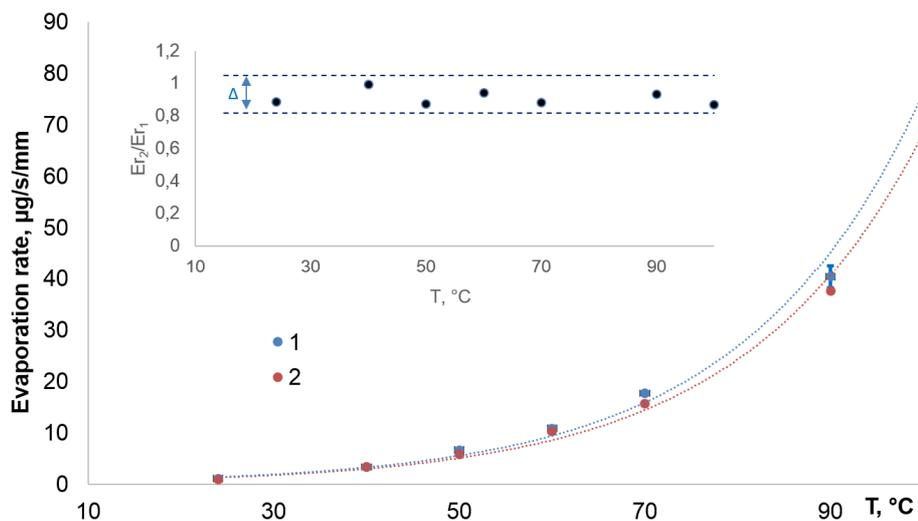


Fig. 4. Droplet mass loss per unit time divided by the droplet diameter vs substrate temperature. Blue (1) – surface without coating (all data for each temperature); Red (2) – surface with single-walled nanotube coating (all data for each temperature). The subfigure is the ratio of evaporation rates vs temperature.

This allows us to quantitatively compare the data for droplets with different initial parameters. Figure 4 shows the droplet mass loss per unit time divided by the droplet diameter vs substrate temperature for both surfaces and for all temperatures studied. Each point in the figure is obtained by averaging all data over the entire evaporation time of each drop (for example, for a temperature of 24 °C, 620 measurements were taken). Within experimental error, no effect of the nanotube coating on the evaporation rate is seen. The difference between data for coated and non-coated surfaces (Δ) does not exceed 12%.

3 Conclusion

The results of the experimental study of evaporation of a microliter (millimeter-sized) sessile water droplet into open atmosphere in a wide range of the substrate temperatures (from 24 to 100 °C) are presented. In the study two substrates made of copper were used. One of them was smooth and had no coating. Another one was coated with a micrometer-thick layer of single-walled carbon nanotubes. The mode of droplet evaporation with constant contact radius (pinned contact line) was studied. It is shown that in the investigated conditions there is no appreciable difference in droplet evaporation dynamics between the two substrates. This indicates that for static macroscopic droplets the nanotube coating has little or no effect on both the wetting properties of the substrate and heat transfer in the substrate. Further work is needed to study the effect of the single walled carbon nanotube coating on the droplet evaporation at the very last stage of the droplet life when the contact line is moving fast and the size of the droplet is comparable to the thickness of the carbon nanotube coating. For this, a measurement optical system with high spatial and time resolution is needed.

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