Experience in registration of evaporation of liquid drops on a substrate by the capacitive method

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Abstract. This paper presents the results of an experimental study of the dynamics of evaporation of nanoparticle droplets based on distilled water with a mass concentration of SiO2 nanoparticles of 0.1%, 0.5%, and 7% lying on a metal surface. The drop height was changed over time using original equipment, which is based on an integrated approach to the combined use of capacitive and optical recording methods. The experimental results show that the change in the height of nanoparticle droplets with concentrations of 0.1%, 0.5%, and 7% is linear over the main part of the evaporation time interval. A deviation from the linear law is observed at the final stage, at the time interval of complete evaporation. The time for complete evaporation of droplets of nanoparticle fluids with a concentration of 0.1% increases by 20%, for droplets with a concentration of 0.5%, it increased by 28% in comparison with the evaporation of droplets of the base liquid. The particle concentration of 7% does not lead to an increase in the evaporation rate of droplets in comparison with the evaporation of low concentration droplets. Before the formation of a jelly-like residue of nanoparticles, the evaporation rate of droplets with a particle concentration of 7% is comparable to the evaporation rate of droplets with a concentration of 0.1%.

1. Introduction
The relevance of studying the dynamics of evaporation of sessile droplets has increased significantly in recent years. This is due to the fact that the processes of droplet evaporation on a substrate are used in many practical applications, from industrial to biological systems [1 - 3]. Analysis of recent publications has shown a significant increase in the number of studies on droplet evaporation. Thus, a review by Brutin, D., & Starov, V. (2018) [3] highlighted the importance of the topic, especially in energy applications, in such advanced technologies as spray cooling, DNA analysis and complex liquid printing.

The experiment continues to be one of the main methods for studying the process of droplet evaporation. This is especially true for the study of the evaporation of droplets of complex composition, which include mixtures of liquids and nanoparticle fluids. At present, experiments implement mainly the optical measurement methods using photo-, video-, thermographic equipment [4, 5], and methods with the use of lasers [6]. Researchers use the weighting method [7], or register the parameters of an evaporating droplet by changing the resonance properties of a piezoelectric element [8]. The above listed main research methods have a significant drawback associated with the laboriousness of processing primary data.

To some extent, electrical measurement methods are free from this drawback, which is understood as the registration of an electrical signal that depends on the physical parameter of the object under
There are practically no experimental studies using electrical methods in the literature. The unpopularity of the use of electrical methods is due to the fact that these methods often require contact of the probe of the primary sensor with the object. This is unacceptable in the case of studying the evaporation of a liquid droplet, since this can change the shape, the line of contact of the lying droplet and, most importantly, change the heat and mass transfer of the droplet.

This paper describes the developed equipment for the study of an evaporating droplet on the surface, which is based on an integrated approach to the combined use of capacitive and optical methods for recording the main parameters of an evaporating droplet. The capacitive method allows the use of a primary sensor with a probe that is not in contact with a liquid drop. The capacitive method is free from the drawbacks of most electrical methods, but has their advantage, which is the ability to register a digital signal by a computer, which allows quick data processing and obtaining the result.

Using the developed equipment, data on the change in the height of nanofluid droplets over time are obtained; the dynamics of evaporation with a droplet of a base liquid on a metal substrate is considered.

2. Equipment and measurement technique
The principle of the research method lies in the fact that two methods of recording the parameters of an evaporating liquid drop are simultaneously used: capacitive (digital) and visual methods. The capacitive method provides information about the height and shape of the droplet in the form of a digital signal. The visual method allows simultaneous obtaining of a digital image of an evaporating liquid droplet. Both methods complement each other, and this provides more complete and most reliable information about the process of evaporation of a liquid droplet.

The primary transducer of the capacitive meter is a sensor with a capacitive probe connected to the oscillatory circuit of the generator. The primary transducer is installed on the movable head of the coordinate device (KU). The probe of the capacitive meter is directed towards the surface with a lying drop. The height of the capacitive probe relative to the surface with the drop is regulated by a special microscrew. The coordinate device is capable of moving the movable head with the primary transducer installed on it along the orthogonal coordinates X and Y with a step of 2 microns. When a drop is scanned in time, the frequency of the generator is transmitted to the computer in a digital form, the value of which is proportional to the change in the drop height (Fig. 1).

The evaporating droplet is visualized using a digital microscope mounted motionlessly on the working table of the coordinate device. The microscope allows you to transfer to a computer a digital image of the drop profile obtained from the side relative to the substrate surface.

The technique for measuring the droplet height by the capacitive method is as follows. The coordinate device moves the primary transducer with a capacitive probe from a position above the center of the drop to a position outside the drop. The period of movement of the probe is 9 s. As a result, the equipment records a change in frequency over time in the form of rectangular pulses (Fig. 2). The top of the pulse corresponds to the position of the probe outside the drop (frequency Fs), the
time interval between pulses corresponds to the position above the drop ($F_d$). The value $\Delta F = F_s - F_d$ is a value proportional to the drop height. The relative measurement technique allows you to get rid of the temperature and time drifts of the primary converter generator.

![Diagram of the change in the signal frequency of the measuring generator](image)

**Figure. 2.** Diagram of the change in the signal frequency of the measuring generator: $F_s$ is the frequency value when the probe is positioned outside the droplet boundary; $F_d$ - above the drop.

The capacitive method can give reliable values about the drop height only if there is a calibration dependence of the change in the probe capacitance on the drop height of a particular liquid $C = f (h)$. The use of a digital microscope in the measuring complex allows implementing the calibration procedure of a capacitive meter without resorting to the use of additional equipment. The calibration dependence is obtained at the initial stage of measurements by simultaneous recording of the drop height by visual and capacitive methods. Having calibration dependencies, the capacitive method allows a larger number of experiments in a series, in contrast to the visual method, since the time for processing primary data is significantly reduced. At the same time, an increase in the data sample increases the reliability of the result using statistical processing methods.

The total uncertainty of registration of the drop height is estimated according to the method [9] and is 3% for the capacitive method and 2% for the visual method.

3. **Experimental conditions and results**

With the use of the developed equipment and measurement technique, data on time variation of the height of nanofluid droplets based on distilled water with a mass concentration of SiO$_2$ nanoparticles of 0.1%, 0.5%, and 7% on a metal surface are obtained. The dynamics of evaporation is compared with that for the drops of the base liquid (see Fig. 3).

Silica nanoparticles (AEROSIL 200) were hydrophilic circular particles with an average diameter of 12 nm. To prepare a nanofluid of a certain mass concentration, the components were weighed on an HR-250AGZ electronic balance with a measurement error of 0.1 mg. Then the nanoparticles and the base liquid of the required masses were mixed manually. To obtain a stable homogeneous mixture with a minimum degree of particle agglomeration, ultrasonic treatment was used as described in [10].

The base for the evaporating drops was a polished steel surface. Drops were applied to the substrate with a dosed pipette. The initial volume of the investigated droplets differed from each other by 1 - 2% and, on average, was about 2 mm$^3$. The values of temperature and humidity of the environment in the experimental series are indicated in the graphs in Figure 3, and differ from series to series by no more than 1%. The substrate temperature was equal to the ambient temperature. The observation was carried out until the complete evaporation of the droplets. The dynamics of changes in the height of a droplet of water and nanofluids shown in Fig. 3 was obtained by averaging over the results of five measurements. The RMS deviation of the measured data of the drop height did not exceed unity.
The law of a change in the height of distilled water droplets until complete evaporation retains a linear relationship [11-13]. The change in the height of nanofluid droplets with concentrations of 0.1% and 0.5% is linear over the main part of the evaporation time interval. A deviation from the linear law is observed at the final stage, at the time interval of complete evaporation. These results are consistent with those of other authors [14, 15]. This confirms the correct functioning of the equipment and the applied registration method.

The experimental results show that the inclusion of nanoparticles prolongs the time of complete evaporation of nanofluid droplets in comparison with the evaporation of droplets of the base liquid (Fig. 3), despite the fact that the humidity and ambient temperature are almost identical. The results show that for nanofluids with concentrations of 0.1% and 0.5%, the decrease in the evaporation rate is proportional to the higher concentration [15]. Under these experimental conditions, the evaporation time to the dry residue of droplets with a concentration of 0.1% of silicon dioxide increases by 20%, this time for the droplets with a concentration of 0.5% increases by 28%, in comparison with the time of complete evaporation of droplets of the base liquid.

The evaporation of nanofluid droplets with a concentration of 7% also has an evaporation rate less than the evaporation rate of water droplets, but, as it can be seen from the figure, they do not obey the regularity that an increase in concentration also increases the evaporation time. The duration of the evaporation process for droplets of nanofluid with a concentration of 7% is much shorter than that for the droplets with a low concentration. The evaporation process for this type of droplets ends with the formation of a jelly-like residue of nanoparticles. But, in the interval of the "life cycle", the form of the dependence of the change in the drop height is qualitatively identical to the dependences of the dynamics of the height of the drops of low concentration.

As a result of the complete evaporation of droplets of nanofluids with a concentration of 0.1% and 0.5%, a residue of nanoparticles remains on the substrate. It is a species that obtained the term "coffee ring" in the special literature [16]. When droplets of low concentration nanofluids evaporate, the trace is a ring with an uneven outer edge. The ring contains a higher concentration of dry nanoparticles than inside this ring formation. The residue from drops of 7% concentration at the end of the evaporation process also looks like a coffee ring with an uneven outer edge. But it is formed differently. Formation begins with the formation of a shell of nanoparticles on the surface. The evaporating object is shaped like a drop. Then, the height of the drop in the center decreases and becomes equal to the height of the outer ring. At the end of the evaporation, a coffee ring forms. Figure 4a shows a photograph of the shell formation, Figure 4b is the residue resulted from complete evaporation.

Figure. 3. Dynamics of changes in the height of droplets of nanofluids and base liquid in time.
Figure 4. Photographs of an evaporating droplet of nanofluid with a concentration of 7% silicon dioxide: a) the beginning of the formation of the shell, 17 min. from the beginning of evaporation. b) dry residue, 19.5 min. from the beginning of evaporation.

4. Conclusion

The measuring complex for studying the evaporation of liquid droplets on a surface based on non-contact methods allows measuring the height of a liquid droplet by a digital method and simultaneously obtaining visual images of the observed object.

The use of the digital capacitive method allows significant reduction in the processing time of the primary experimental data, in contrast to the optical methods, which are mainly used at present to study the evaporation of droplets.

With the use of the developed equipment and measurement technique, data on time variation of the height of nanofluid droplets based on distilled water with a mass concentration of SiO2 nanoparticles of 0.1%, 0.5%, and 7% on a metal surface are obtained. The results agree with the results of other authors, and this confirms the correct functioning of the equipment and the applied registration method.

The experimental results show that the inclusion of nanoparticles prolongs the time of complete evaporation of nanofluid droplets in comparison with the evaporation of droplets of the base liquid. Under the experimental conditions, the time of evaporation to the dry residue of droplets with a concentration of 0.1% of silicon dioxide increases by 20%; this time for the droplets with a concentration of 0.5% increases by 28%, in comparison with the time of complete evaporation of droplets of the base liquid.

Upon evaporation of droplets of nanofluid with a concentration of 7%, the form of the dependence of the change in the droplet height is qualitatively identical to the dependence of the dynamics of the droplet height with a concentration of 0.1%. The evaporation process for this type of droplets ends with the formation of a jelly-like residue of nanoparticles in the form of a coffee ring.

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