An experimental study of the evaporation rate of nanofluid droplets with SiO$_2$ nanoparticles

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Abstract. In this work, experimental data are presented on the evaporation rate of suspended droplets of distilled water and distilled water with the addition of nanoparticles of silicon dioxide during evaporation in an air stream with a low blowing rate. The measurements were carried out at Reynolds numbers calculated from the relative flow velocity Re $<$10. The evaporation rate of suspended droplets of distilled water and nanofluid was compared.

1. Introduction

Studying the processes of evaporation of liquid droplets, consisting of both multicomponent mixtures and containing suspended solid particles, is of great importance in the design of various energy devices [1,2]. The processes of evaporation and combustion of liquid droplets are decisive in cooling the liquid phase in cooling towers and highly heated surfaces of power plants. Evaporation and combustion of droplets is decisive in the combustion chambers of liquid-propellant engines and internal combustion engines when burning fuel oil [3, 4], as well as in chemical technologies, in the application of paints and coatings, in the production of new materials [5]. In recent years, the interest in this topic has significantly increased in the agricultural industry, in the fight against fires, medicine, and biology.

Studies on the evaporation of droplets of nanodispersed liquids occupy a large place in research on the evaporation of liquid droplets. Thus, nanofluids demonstrate new thermal transport phenomena in comparison with pure liquids and suspensions with macro particles. Such phenomena include: an increase in thermal conductivity when nanoparticles are added to a liquid; nonlinearity of the thermal conductivity of nanofluids from temperature, concentration and size of nanoparticles; increase in critical heat flux during boiling, etc. This suggests that the study of the thermophysical properties of nanofluids is of great fundamental and practical interest. In evaporative processes and the combustion processes of nano-liquid droplets, the search for new effects is also underway.

An analysis of recent publications shows that there are much fewer works on the evaporation of droplets of nanofluid compared with evaporation of droplets of pure liquids and binary mixtures consisting of pure liquids. Among the studies on droplets with nanofluid, there are more publications on the droplet evaporation from a surface than those on a suspended droplet.

From the studied literature it follows that the evaporation of nanofluid droplets, as a rule, deviates from the linear law $d^2$, which is valid for the evaporation of droplets of pure liquids. The authors attribute this effect to an increase in the concentration of nanoparticles on the droplet surface or at the nanofluid-surface interface (for sessile droplets), which reduces the effective area of the liquid for evaporation. The initial concentration of nanoparticles increases the evaporation rate under some
conditions, and at other conditions it neither causes the effect, nor slows down the evaporation process. This indicates the optimal initial concentration of nanoparticles in the base fluid for certain conditions of the droplet evaporation. The initial concentration and external conditions of evaporation affect the evolution of the nanofluid droplet size, the evaporation rate before the formation of the shell, and its structure.

2. Experimental setup
The experiments on droplet evaporation were carried out on a setup developed at the Institute of Thermophysics SB RAS (Figure 1). The setup design allows one to simulate the evaporation process of a droplet moving in the flow, to vary the initial conditions of the incoming flow (velocity and temperature) and to ensure their uniformity during the experiment. The droplet is fixed on a thread with a thickness of not more than 100 microns. The suspension material has a sufficiently low thermal conductivity $\lambda \approx 0.15$ W/mK and high heat resistance, enabling experiments in a wide temperature range $T_0 < 150 ^\circ C$. It is possible to carry out experiments on this setup, both in a stationary medium and when gas flows around a droplet at the velocity range $u_0 = (0.1 \div 3) \pm 0.05$ m/s. To create a laminar flow in the drop suspension region, a profiled confuser is used in the design and a flow stabilization system is installed. The experimental setup allows changing the flow temperature $T_0$ in the range from room temperature $\sim 20 ^\circ C$ to $150 ^\circ C$ with uncertainty of $\pm 0.2 ^\circ C$. The flow temperature is regulated through a predetermined level of the reference voltage on the triac power controller. The temperature is recorded by two platinum resistance thermometers installed in the upper and lower parts of the working area.

![Figure 1. Scheme of the experimental setup for studying the process of droplet evaporation.](image-url)
3. Experimental conditions
The object of the study was a mixture of distilled water and nanoparticles of silicon dioxide SiO$_2$ 0.1 wt. %. In this work, we used nano-sized silica powder with the following parameters: purity of 99.95%, S-type, spherical shape, average particle diameter of 12 nm, and specific surface area of 165–195 m$^2$/g (NANOGRAFI Co. Ltd.). The nanofluid was obtained by adding silicon dioxide particles to distilled water using the similar technology [6]. The mixture was first mixed with a mechanical homogenizer for 60 minutes at ~ 1000 rpm. Then it was placed in an ultrasonic device (VGT-200) with power of ~ 50 watts. The duration of ultrasonic mixing was determined by a parametric study of the nanofluid. Thus, for the preparation of colloidal solutions, the known method of sequential mixing followed by ultrasonic influence was used to destroy large agglomerates.

In this work, we studied the rate of evaporation of water and nanofluid, when $d_0 = 1.6–2$ mm at an air flow with a constant temperature $T_{0g} = 24$ °C, and the velocity $u_0 = 0.1$ m/s, the relative humidity of the air flow being $\varphi = 7$ %. The initial temperature of the investigated droplets $T_{0s}$ was equal to the ambient temperature ($T_{0s} = T_{0g} = 24$ °C). The experiments were carried out at an external pressure $P = 1$ atm. A holder with a diameter of 0.1 mm was used to support the droplets (Figure 2).

![Figure 2. A droplet of liquid on a horsehair holder.](image)

To solve the problems posed, we used an experimental method for measuring the rate of evaporation of suspended drops of liquid, based on the classical approach [7]. It includes modern diagnostic methods, such as precision dosing of liquids, digital photography and infrared thermography. These methods, used to measure droplet size and temperature, provide reliable data on the evaporation rate. The authors thoroughly tested this measurement technique, developed procedures for determining the components of the heat flux, as well as the uncertainty of the measured values [8].
4. Results
For droplets suspended in still or weakly moving air (Re < 10), it is customary to generalize the measurement results using the law \( d^2 \). The experimental data processed in this representation are shown in Figure 3.

![Figure 3. Change in relative droplet diameter over time.](image)

1 – water droplet, \( d_0 = 1.7 \) mm; 2 – water droplet, \( d_0 = 1.6 \) mm; 3 – SiO\(_2\) 0.1 wt. %, \( d_0 = 1.9 \) mm; 4 – SiO\(_2\) 0.1 wt. %, \( d_0 = 2 \) mm.

Let us note the linear nature of the dynamics of evaporation of pure water droplets corresponding to the classical law for \( d^2 \). However, when silicon dioxide nanoparticles are added to water, a different character of evaporation (points 3, 4) is observed, similar to the evaporation of a binary liquid with a different degree of volatility of the component [9]. During most of the evaporation time, nanofluid droplets with concentration of 0.1 wt. % (points 3, 4) have a velocity lower than the rate of evaporation of water droplets (points 1, 2). At the initial stage of evaporation, the addition of nanoparticles 0.1 wt. % has a weak effect on the rate of the mass transfer process. This can be explained by the formation of convective flows in the droplet, carrying nanoparticles to the liquid-gas interface. A gradual decrease in the effective evaporation area and, consequently, a slowdown in the dynamics of the droplet occur. In the second stage, the evaporation rate of the nanofluid drops is lower than the evaporation rate of the water droplets. This is due to a decrease in the amount of evaporating liquid.

Conclusion
The evaporation of suspended droplets of a nanofluid with adding SiO\(_2\) nanoparticles into distilled water has been carried out under conditions of free convection. The obtained data on the changing rate of evaporation of nanofluid droplets have been compared with similar values of the base fluid.

At the initial stage all the studied liquids have a similar evaporation rate, regardless of the initial droplet size and concentration of nanoparticles. This suggests that the addition of nanoparticles to the base liquid does not affect the efficiency of evaporation in the initial time interval under conditions close to free convection.
Under free convection, the evaporation rate of nanofluid droplets with concentration of 0.1 wt. % is lower than that of water droplets. The change in diameter corresponds to the $d^2$ law. The curve of droplet diameter of a nanofluid with concentration of 0.1 wt. % has two linear sections. Droplets of nanofluid SiO$_2$ 0.1 wt. % are shown to evaporate similar to binary fluid droplets with different volatility components. It is worth noting that the discovered effect is characteristic of certain external conditions: a motionless or a weakly mobile medium with room temperature.

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