Features of heat transfer during the evaporation of a drop of nanofluid

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Abstract. In the present work, experimental studies of factors affecting heat and mass transfer during the evaporation of droplets of nanofluids with SiO₂ nanoparticles (base liquid - water) were carried out in a wide range of mass concentrations and initial environmental parameters (temperature and flow rate). According to the results of the study, it was found that the effect of nanoparticles under forced convection depends on the initial environmental conditions.

1. Introduction
Currently, in many applications related to energy, the possibility of switching from traditional coolants (for example, water) to nanofluids is being considered due to their higher coefficient of thermal conductivity. For example, this concerns the tasks of heat removal from the surface of printing devices, in micro and nanoelectronics. It was found that the use of highly diluted nanodispersions as a coolant can significantly increase the critical heat flux density in boiling-type installations. Despite the increased interest in research of this kind, the process of evaporation of droplets of nanofluids has not been studied in detail. So, in works on visualization of an evaporating lying drop, they report on the existence of internal flows in the drop [1], the presence of hydrothermal waves [2]. It should be noted that the presence of a nano- or microdispersed phase in a liquid affects its thermophysical properties, such as thermal conductivity, heat capacity, viscosity, etc. [3].

In a review paper [4], the author shows that nanofluids demonstrate new thermal transport phenomena in comparison with pure liquids and suspensions with macro particles. The author [5] offers references to papers describing new thermal phenomena of various nanofluids. Such phenomena include: an increase in thermal conductivity when nanoparticles are added to the liquid; the nonlinearity of the thermal conductivity of a nanofluid by the temperature, concentration, and size of nanoparticles; increase in the critical heat flux during boiling, etc. This suggests that the study of the thermophysical properties of a nanofluid is of great fundamental and practical interest. In the evaporation processes and processes of burning the droplets of the nanofluid, new effects are also being sought.

In the present work, experimental studies of factors affecting heat and mass transfer during the evaporation of droplets of nanofluids with SiO₂ nanoparticles (base liquid - water) were carried out in a wide range of mass concentrations and initial environmental parameters (temperature and flow rate).

2. Experimental conditions
The nanofluid was a suspension with a mass concentration of 2% - 7% silicon dioxide (SiO₂) with an average particle diameter of 10 nm in distilled water. Evaporation occurred in a weakly mobile...
medium at a rate of 0.1 m/s - 0.2 m/s, with a temperature of 23.5°C and 105°C. In the experiment, the Reynolds number of the air flow is $Re_0 = 12.6$.

The drop was suspended on a holder, which is a crosshair of horsehair threads with a diameter of 0.105 mm. Figure 1 is a photograph of the droplet on the holder. The use of crossed fiber holder increases the number of successful droplet generation during suspension; the drop has a spherical shape and does not lose it during evaporation; it does not move along the holder unlike the horizontal fiber; it is less subject to vibration by the incoming flow. A comparison of the effect of a single holder and crossed fibers on the droplet evaporation was made in [5]. The authors show that the holder of crossed fine fibers almost does not supply excess heat to the droplet. At present, this type of holder is used in experiments [6, 7] along with the traditional suspension of a drop on a single holder.

![Figure 1. A droplet of liquid on a horsehair holder.](image)

The incoming air flow was fed from below and had a uniform velocity distribution in the droplet location section. The flow was formed by a special equalizing channel. A change in droplet diameter was registered by a digital microscope; the drop surface temperature was registered by a thermal imager. The experimental setup, instrumentation, measurement and data processing techniques are described in detail in [8].

To prepare colloidal solutions with silicon dioxide nanoparticles, a rather well-known method was used: by sequentially mixing them in a mixer followed by ultrasonic exposure to destroy large agglomerates (200–500 nm). To eliminate the formation of agglomerates, the samples were subjected to ultrasound with parameters $f = 44$ kHz (frequency) and $N = 50$ W (power).

3. Results

The data on the dynamics of thermal conductivities of the studied liquids are presented below. Initial conditions are indicated on the graphs, where $u_0$ is flow velocity, $T_{0}$ is the flow temperature, $T_0$ is a droplet temperature and $\varphi$ is relative humidity. The thermal conductivity of the nanofluid was calculated according to Maxwell theory [10]. According to the results of the study, it is found that the effect of nanoparticles under forced convection depends on the initial environmental conditions.
So at high flow temperatures and in a weakly mobile medium, nanofluids with mass concentration of nanoparticles less than 4% do not significantly affect heat transfer. Without heating the flow, the effect of concentration of nanoparticles in the liquid is linear.

The curves presented for the dynamics of the thermal conductivity of water droplets and nanofluids monotonically decrease with an asymptotic approach to the static region, the value of which is greater, the higher the concentration of nanoparticles in the base fluid. According to the authors of [11], two mechanisms are involved in the process that controls the instantaneous evaporation rate: an increase in temperature on the droplet surface due to absorption of radiation by nanoparticles, which enhances evaporation; the accumulation of particles on the surface of the droplet, which reduces the effective area ratio and, thus, inhibits evaporation. In the early stage of evaporation, the first mechanism prevails, so that the rate of evaporation is higher than without radiation. However, at a later stage of the evaporation process, the effective surface area available for evaporation decreases and therefore the overall evaporation rate decreases. The effect of the behavior of thermal conductivity of nanofluid droplets under conditions of free and forced convection, discovered in our experiments, is explained
by a similar mechanism. At the early stage of evaporation, while the effective area of the liquid phase of the drop is sufficient, the surface temperature of the drop is close to the saturation temperature of water. As this area decreases due to an increase in the concentration of nanoparticles on the surface, which can occur due to the flow inside the droplet, causing centrifugal movement of the nanoparticles, the surface temperature of the droplet increases gradually with a gradual decrease in the growth rate.

**Conclusion**

Evaporation of suspended droplets of a nanofluid with the addition of SiO$_2$ nanoparticles into distilled water was studied experimentally. The studies were carried out under conditions of free and forced convection. The data obtained on a change in the thermal conductivity of nanofluid droplets were compared with similar values obtained for the base fluid.

Generalization of the results showed that at high flow temperatures and in a weakly mobile medium, nanofluids with a mass concentration of nanoparticles less than 4% do not significantly affect heat transfer. Without heating the flow, the effect of concentration of nanoparticles in the liquid is linear.

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