Evaporation of a suspended nanofluid droplet

To cite this article: A D Nazarov et al 2018 J. Phys.: Conf. Ser. 1105 012095

View the article online for updates and enhancements.

You may also like

- Experience in registration of evaporation of liquid drops on a substrate by the capacitive method
  A V Kokorin, A D Nazarov and A F Serov

- Influence of Naturally Occurring Organic Surfactants on the Surface Tension of Sessile Droplets and Atmospheric Aerosols Measured with a Quasi-Elastic Laser Scattering System
  Derrick Michael Mott, Mao Fukuyama and Akihide Hibara

- Surfactant’s Impact on the Evaporation Intensity and a Vapor Embryos Generation Kinetics within the Water Droplets
  M P Anisimov, V I Terekhov and N E Shishkin
Evaporation of a suspended nanofluid droplet

A D Nazarov*, N B Miskiv and E M Bochkareva
Kutateladze Institute of Thermophysics, 630090 Novosibirsk, 1 Lavrentiev ave., Russia

*E-mail: nazarov@itp.nsc.ru

Abstract. The experimental results on evaporation of the suspended droplets of distilled water with the addition of 0.1% silicon dioxide with an average particle diameter of 10 nm in a stationary ambient and in an air flow of 0.1 m/s at a temperature of 25°C to 260°C and 500°C are presented. A comparison is made with the evaporation droplet parameters of the base liquid. Experimental data show that during evaporation the change in the surface temperature of the nanofluid droplets is qualitatively similar to the dynamics of the surface temperature of the mixture droplets, consisting of two pure components with different degrees of volatility.

1. Introduction
Evaporation of liquid droplets is widespread in various technologies. Therefore, the study of this process to identify ways of intensification and improving the efficiency of power facilities is very important. For example, the development of high-capacity heat exchangers, increasing the efficiency of cooling with sprays, burning liquid fuels and many other practical applications need new fundamental knowledge about gas-droplet flows with phase transformations. To date, there has not been a unified theory of the evaporation of droplets of multicomponent mixtures, which would explain all effects obtained by researchers in experiments. It should be noted that the single droplet evaporation was the subject of study by many authors, but the literature review showed insufficient experimental data, in addition, the available data are often contradictory.

In a review paper [1], the author shows that nanofluids demonstrate new thermal transport phenomena in comparison with pure liquids and suspensions with macro particles. The author of [1] 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 on 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 data on the rate of evaporation and surface temperature of suspended drops of distilled water and distilled water with the addition of silica nanoparticles upon evaporation in a stationary ambient and in an air flow of different temperatures are given. The evaporation of suspended distilled water and nanofluid droplets is compared.

2. Experimental conditions
The nanofluid was a suspension with a mass concentration of 0.1% silicon dioxide (SiO₂) with an average particle diameter of 10 nm in distilled water. Evaporation took place in a stationary ambient
and air flow at a speed of 0.1 m/s, with a temperature of 24 °C – 25 °C and 50 °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 fibers 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 [2]. 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 [3, 4] along with the traditional suspension of a drop on a single holder.

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. The registration of the change in droplet diameter was carried out by a digital microscope, the drop surface temperature by a thermal imager and associated image processing software. The error in determining the average surface temperature of the droplet was 5%. Detailed experimental setup, instrumentation, measurement and data processing techniques are described in [5].

3. Results

The comparison of droplet evaporation of distilled water and a nanofluid in a stationary ambient is presented in Figure 2. To generalize the experimental data the expression for changing the droplet size obtained from the diffusion theory of evaporation of Spalding [6] was used:

$$\left(\frac{d}{d_0}\right)^2 = 1 - A \cdot \frac{t}{d_0^2}$$

Here $d$ and $d_0$ [m] are the current and initial values of the droplet diameter, $t$ [s] is time. The value of the parameter $A$ characterizes the droplet evaporation rate depending on the initial conditions of the experiments. The experimental results showed that the presence of nanoparticles in water at a concentration of 0.1% slows down the rate of evaporation as compared to the water droplet evaporation. The evaporation of water droplets occurs according to the linear law $d^2$. The evaporation dynamics of nanofluid droplets is nonlinear and consists of two sections; each of them can be approximated by straight lines with different angles of inclination.

Figure 3 compares the experimental data on the dynamics of the water and nanofluid droplet surface temperature during evaporation. The graph shows the adiabatic temperature of the evaporation of water under the conditions of the experiment $T_{ad}$. The water droplet temperature at the beginning of the evaporation process, reaching the saturation temperature, remains almost unchanged throughout the observation period. This behavior of the drop surface temperature is characteristic of drops of pure liquids.
The surface temperature curve of the nanofluid droplets is more typical of drops of a solution consisting of a mixture of two pure liquids with different degrees of component volatility [7]. The surface temperature of the droplets of such liquids has a transition from a temperature region close in value to a lower saturation temperature to the saturation point of the other component. The change in surface temperature characterizes the dynamics of the change in the droplet diameter during evaporation. The surface temperature of the beginning of evaporation (section 1, figure 3) of nanofluid drop corresponds to law 1 (figure 2), the temperature region after the transition period (section 2, figure 3) – to law 2 (figure 2).

Figure 4 shows the comparative curves of the change in the water and nanofluid droplet diameter during evaporation in an air stream with a velocity \( u_0 = 0.1 \) m/s. It should be noted that the parameters of the droplet evaporation ambient (temperature and humidity) are the same as for a stationary ambient. The experimental results showed that the water and nanofluid droplet evaporation in a sluggish ambient is qualitatively identical to evaporation in a stationary ambient. The linear law \( d^2 \) is preserved for water. The decrease in the nanofluid droplet diameter is slower in comparison with the water droplets, the evaporation dynamics of the nanofluid droplet is nonlinear and consists of two intersecting lines.

The surface temperature dynamics of water and nanofluid droplets when evaporating in the air flow is \( u_0 = 0.1 \) m/s and in a stationary ambient are similar (figure 5). In the graph, the temperature \( T_{ad} \) corresponds to the adiabatic temperature of evaporation of water under the experimental conditions.
Table 1 shows the parameter A values of formula (1) of the D.B. Spalding evaporation diffusion theory [6], obtained from the experimental data of evaporation of a drop of water and a nanofluid in a stationary and air stream with a velocity \( u_0 = 0.1 \text{ m/s} \) at the same temperature and humidity of ambient. In the table, the parameter A for a nanofluid droplet belongs to the expression characterizing the initial evaporation period, corresponding to section 1, figures 2 and 4.

According to the table 1, it is clear that although the evaporation rate of water and nanofluid droplets varies in absolute value, however, the influence degree of ambient on the evaporation rate is the same. The evaporation rate of the droplets of both liquids in the flow with a velocity \( u_0 = 0.1 \text{ m/s} \) as compared to evaporation in a stationary medium is increased by 100%.

Figure 6 shows the dependence of the diameter change of the liquids under investigation in the air flow with a velocity \( u_0 = 0.1 \text{ m/s} \) and a temperature \( T_0g = 50^\circ\text{C} \). The influence of the flow temperature significantly reduces the droplet evaporation time of both liquids. The evaporation rate of nanofluid drop coincides with the evaporation rate of water droplet. However, even under these conditions, the nanofluid droplet evaporation dynamics is nonlinear and consists of two intersecting straight lines. The inflection is observed at a value \( (d/d_0)^2 = 0.3 \). For comparison, \( (d/d_0)^2 = 0.85 \) corresponds to evaporation of a nanofluid droplet in a stationary ambient (figure 2); \( (d/d_0)^2 = 0.75 \) - in the flow with the velocity \( u_0 = 0.1 \text{ m/s} \) (figure 4).

Table 2 shows the parameter A values of formula (1) obtained from the experimental evaporation data of water and nanofluid droplets in the air stream with a velocity \( u_0 = 0.1 \text{ m/s} \), temperatures of 25 \( ^\circ\text{C} \) and 50 \( ^\circ\text{C} \). In the table, the parameter A for the nanofluid droplet belongs to the initial section 1 in figures 4 and 6.

The data given in table 2 allow one to compare the influence degree of ambient on the evaporation rate of water and nanofluid droplets. It can be seen from the table that the change in the evaporation rate of both liquids at incoming flow temperature of 50 \( ^\circ\text{C} \), compared with the evaporation rate in a 25 \( ^\circ\text{C} \) temperature flow, is approximately the same, and is an average increase of 5 times.

Table 1. The evaporation rates of water droplets and nanofluids at temperatures of 24 \( ^\circ\text{C} \) – 25 \( ^\circ\text{C} \) for two cases: without airflow and in sluggish ambient.

|                | 0 m/s | 0 m/s | 0.1 m/s | 0.1 m/s |
|----------------|-------|-------|---------|---------|
|                | I I I I | I I I I |         |         |
| Water droplet  | 0.86e-9 | 0.9e-9 | 1.64e-9 | 1.8e-9  |
| Nanofluid droplet | 0.77e-9 | 1.1e-9 | 1.5e-9  | 2.16e-9 |

Figure 6. The change in the relative size of the water and nanofluid droplets during evaporation in the air flow with a velocity \( u_0 = 0.1 \text{ m/s} \) and a temperature \( T_0g = 50^\circ\text{C} \).

Figure 7. The change in the temperature of the surface of water and nanofluid droplets during evaporation in the air flow with a velocity \( u_0 = 0.1 \text{ m/s} \) and a temperature \( T_0g = 50^\circ\text{C} \).
Table 2. The evaporation rates of water and nanofluid droplets in a sluggish ambient for two different temperatures of the incoming flow.

|                | 25°C I | 25°C II | 50°C I | 50°C II |
|----------------|--------|---------|--------|---------|
| Water droplet  | 1.64e-9| 1.8e-9  | 9e-9   | 10.5e-9 |
| Nanofluid droplet | 1.5e-9 | 2.16e-9 | 9e-9   | 10.8e-9 |

The experimental temperature dependences of the droplet surface of the liquids studied presented in figure 7 show that the water droplet temperature does not change throughout the evaporation process and corresponds to the saturation temperature for these conditions. The graph shows the adiabatic temperature of the evaporation of water under the conditions of the experiment $T_{ad}$. The surface temperature of the nanofluid droplets has a character similar to behavior of the droplet surface temperature of a pure liquid mixture with different volatile grades.

The observed effect in the surface temperature behavior, traced during the nanofluid droplet evaporation in different ambient of this study, is unexpected. When studying the literature, a source was found [8], where graphs of the droplet surface temperature change with a similar character are given. This publication investigated the evaporation of suspended drops of ethanol mixture with the addition of graphite nanoparticles when heated by infrared radiation. The presented curves of the droplet surface increased monotonically with an asymptotic approach to the static section, the greater the value, the higher the concentration of nanoparticles in the base liquid (nanoparticle concentration 1%, 3%, and 5%). According to the authors of [8], two mechanisms controlling the instantaneous evaporation rate participate in the process: 1) an increase in the temperature at the surface of the drop due to the absorption of radiation by nanoparticles, which enhances evaporation and 2) the accumulation of particles on the surface of the drop, which reduces the effective area ratio and, thus, reduces evaporation. At the early stage of evaporation, the first mechanism prevails, so that the evaporation rate is higher than without the radiation. However, at a later stage of the evaporation process, the effective surface area available for evaporation decreases and, consequently, the overall evaporation rate decreases. The effect of the surface temperature behavior of nanofluid droplets found in experiments is probably explained by a similar mechanism. In the early stage of evaporation, while the effective area of the liquid phase of the droplet is sufficient, the temperature of the droplet surface is close to the saturation temperature of the water. As this area decreases due to an increase in the concentration of nanoparticles on the surface, which can occur due to the flow within the droplet causing centrifugal movement of the nanoparticles, the temperature of the droplet surface gradually increases with a gradual decrease in the rate of rise. But, perhaps, the mechanism has a different nature. Caution in explaining the behavior of the surface temperature of a nanofluid droplet in case is based on the fact that the concentration of nanoparticles was insignificant (0.1%). In further studies it is necessary to carry out experiments with higher values of nanoparticle concentration.

4. Conclusion

An experimental study of evaporation of nanofluid suspended droplet prepared by mass concentration by adding 0.1% of SiO$_2$ nanoparticles to distilled water was carried out. The investigations were carried out in a stationary ambient and in an air flow with a velocity of 0.1 m/s with the same values of humidity and temperature (24°C–25°C) for both conditions and in an air flow of 0.1 m/s at 50°C. A comparison is made between the obtained data of the change in the diameter and the temperature of the droplet surface with similar values of the base liquid.

A generalization of the results showed that, in comparison with the evaporation of distilled water droplets, the nanofluid droplets evaporate slower in a stationary and sluggish ambient at the same temperature and humidity values. The droplet evaporation rate in a flow of 50°C is the same for droplets of both liquids.

The nanofluid droplet evaporation dynamics is nonlinear and consists of two sections, which can be approximated by straight lines with different angles of inclination. The surface temperature of the
nanofluid droplets has a character similar to behavior of droplet surface temperature of a pure liquids mixture with different specific heat of vaporization. The evaporation rate change of drops of water and water with the addition of 0.1% of SiO₂ nanoparticles is the same when the parameters of the evaporation ambient change.

Acknowledgments
This work was supported by the Federal Agency for Scientific Organizations (FASO Russia) No. AAAA-A17-117022810196-0).

References
[1] Stephen U S Choi 2008 Heat Transfer Engineering 29(5) 429–31
[2] Masato M, Hiroshi O, Naoya K, Masao K, Yuichiro W and Shinichi Y 2005 Combustion and Flame 141 241–52
[3] Yang J R and Wong S C 2002 An experimental and theoretical study of the effects of heat conduction through the support fiber on the evaporation of a droplet in a weakly convective flow Int. J. Heat Mass Transfer (Taiwan) 45 ed W Minkowycz (Amsterdam: Elsevier) No 23 pp 4589–4598
[4] Chauveau C, Halter F, Lalonde A and Gökalp I 2008 Conf. ILASS (Como Lake)
[5] Bochkareva E M, Terekhov V V, Nazarov A D and Miskiv N B 2017 Integrated experimental and theoretical study of evaporation process of nonideal solutions J. Physics: Conf. Series 891 012010
[6] Spalding D B 1963 Convective mass transfer (New York: McGraw–Hill) p 448
[7] Tuyen T B Nguyen Subhasish M Mayur J Sathe Vishnu Pareek J B and Joshi G M 2018 Experimental Thermal and Fluid 91 329–44
[8] Saad T, Sayan B and Li Q 2017 Int. J. Heat Mass Transfer 114(541)