The experimental investigation of the evaporation rate of nanofluids based on different fluids

A S Lobasov¹,², A V Minakov¹,²
¹Siberian Federal University, 660074, Krasnoyarsk, Russia
²Institute of Thermophysics SB RAS, 630090, Novosibirsk, Russia
perpetuityrs@mail.ru

Abstract. The evaporation of the nanofluids based on Al₂O₃ nanoparticles and different fluids was experimentally investigated. The distilled water and isopropyl alcohol were used as based fluids. The average diameter of Al₂O₃ particles were 100 nm. The investigations of fluids evaporation rates were carried out using the Simultaneous Thermal Analyzer STA 449 Jupiter (NETZSCH). The investigation of the evaporation rate dependence on the carrier media was carried out. It was found that the average relative evaporation rate of fluids increased, and the time of complete evaporation, respectively, decreased with an increase in the volume concentration of nanoparticles. Also, it was found, that the absolute value of the evaporation rate significantly depends on the type of base fluid. However, the relative value of the evaporation rate for different base fluids remains approximately the same.

1. Introduction

Over the past decades, researchers have attempted to apply nanotechnology to various energy systems, such as electric generators, fuel cells, batteries, and solar cells. Nanotechnologies have also been used to increase the heat transfer potential of conventional fluids, such as water and oil, to improve the efficiency of thermal systems. This can be done by adding solid nanoparticles (1-100 nm in size) to the fluids. The presence of additional nanoscale particles has a significant effect on the evaporation of fluids. At the same time, the rate of evaporation is a key parameter influencing the efficiency of various technological processes. The addition of nanoparticles to the base fluid makes it possible to regulate that parameter, and, accordingly, to control these processes. This allows an increase in heat transfer intensity during cooling various devices. The term "nanofluid" [1] means a two-phase system consisting of a carrier fluid and nanoparticles of a high-conductivity material. Typical carrier fluids are water, organic liquids (ethylene glycol, oil), and polymer solutions. Materials for nanoparticles are metals, metal oxides, and carbon nanotubes. Numerous studies have shown that nanofluids have some special properties [2]. For example, the thermal conductivity of nanofluids significantly higher than the thermal conductivity of the carrier fluid. The nanoparticles almost do not sediment and erode the flow channels in contrast to large dispersed particles.

Most of the heat is dissipated through the evaporating region of the thin film, thereby the nanofluids can be used as potential next-gen cooling fluids that improve heat transfer through the evaporating thin film. In this regard, nanofluids are successfully used for cooling various devices,
creating new systems for transporting and producing heat, in microelectromechanical systems (MEMS), in the creation of lubricants, in air and water purification systems, etc [2-8].

Unlike most of the works, where investigate the evaporation of nanofluids from droplets, in [9] was carried out the study of nanofluids evaporation from a large surface (18.8 × 12.8 cm) and volume (600 ml). It that research were used the nanofluids based on Al₂O₃ particles of 13 nm, 20 nm and 80 nm average sizes and TiO₂ particles of 21 nm average sizes at various volume concentrations (up to 2 vol.%). It was shown as the result that most nanofluids have a lower evaporation rate compared to the base fluid, especially at high volume concentrations of nanoparticles, but several nanofluids at low volumetric concentrations show larger values of the evaporation rate compare to the water. The paper concluded that the nanofluids evaporation rate, as well as their saturated vapor pressure, may increase or decrease depend on volume concentration and type of nanoparticles.

According to the data of different researches, adding of nanofluids to the pool of a solar desalter in the solar energy absorption devices can improve the efficiency of its work at an average of 50% [10-12]. A very high heat flux and a significant temperature gradient can be achieved in micron heat pipes, compact heat exchangers and fuel cells with intense evaporation of the nanofluids near the triple line, which makes it possible to increase their efficiency up to two times [13,14]. It is well known, that at firefighting the decrease of the source temperature is achieved due to the evaporation process of extinguishing liquid. So, in [15] it was found that a significant intensification of the evaporation of water droplets can be reached by adding 50-500 μm carbon particles. In this case, the heating time and complete evaporation time of the droplets decreased by 2-3 times.

2. Experimental apparatus and procedures

The investigations of the evaporation rate of nanofluids based on Al₂O₃ nanoparticles and different fluids was experimentally investigated. The distilled water and isopropyl alcohol were used as carrier fluids. The average diameter of Al₂O₃ particles were 100 nm. Aluminium oxide nanoparticles were purchased from the “Plasmotherm” company, Moscow. The volume concentrations of the nanoparticles were varied from 0.5 to 4%. Such choice of nanoparticles concentration ranges is dictated by the requirements for colloidal stability of suspensions.

A standard two-step method was used to prepare the nanofluids. To destroy the conglomerates of nanoparticles a container with nanofluid was placed for half an hour in the “Sapphire” ultrasonic bath after adding the necessary amount of nanopowder to the fluids. Further sonication didn’t change the properties of the suspensions. Sedimentation stability of highly concentrated suspensions after the sonication persisted for several days.

The investigations of fluids evaporation rates were carried out using the Simultaneous Thermal Analyzer STA 449 C Jupiter (NETZSCH, Fig. 1a), which combines simultaneous measurements of mass changes (thermogravimetry) and heat fluxes (differential scanning calorimetry). Built-in top-loading electromagnetic microbalances have a high-precision resolution in the sub-microgram range, as well as measurement stability. The behaviour of the sample under the given temperature program conditions is studied in the process of simultaneous thermal analysis. The measured values are the mass changes, the absolute temperature of the sample and the temperature dependence of the difference between the heat fluxes of the sample and the etalon. Measurements are performed synchronously on the same sample in the same conditions. The device scheme is shown in Fig. 1b.

A sample of nanofluid is placed in a corundum crucible. Several crucibles of different volume were used in the work (20.0 and 85 μl). The crucible with the liquid is installed in the thermostat of the device on a special holder, which is connected to highly sensitive balance. A platinum/platinum-rhodium holder (TG-DSC sensor type S) was used. Further, using the highly sensitive heater, the necessary law of temperature variation in the thermostat is set. During the experiment, the weight loss of the sample is recorded. That device allows to vary the initial and final temperature of the sample during the heating process, as well as its heating rate and isothermal holding time.

In this study, the samples of the nanofluids were heated from 25°C to 50°C by the temperature program at a rate of 1.0 K/min in a dynamic atmosphere of air with a flow rate of 30 ml/min with
followed isothermal holding for 30 minutes. The temperature during the experiment coincided with a sufficiently high degree of accuracy for all samples. Three independent measurements were carried out for each sample of nanofluid. The discrepancy between the evaporation rates between these measurements did not exceed 4%.

3. Results and discussion

The typical behaviour of the sample mass in the process of evaporation from a crucible with a volume of 20 μl for water-based nanofluid depending on the time of the experiment is shown in Fig. 2a. The volume of the crucible with the fluid in such case is comparable to the size of the droplets. Fig. 2a represents the dependence of the mass loss rate of nanofluid on the concentration of nanoparticles: the higher the concentration of nanoparticles, the faster the mass loss of the fluid. In addition, it is necessary to note one important point, about which didn’t mention anything in previous studies. The volume of nanofluid consists of the volume of the fluid itself and the volume of the nanoparticles. Thus, nanofluid contains less fluid, that can evaporate, compared to pure fluid. This effect is very clearly seen in Fig. 2a. After full evaporation of the fluid, on the scales remains a mass equal to the mass of the nanoparticles, corresponding to their initial concentration in the solution. At high concentrations of nanoparticles this effect can very significantly affect on the interpretation of the results. For example, for a volume concentration of nanoparticles of 4%, the remaining mass of nanoparticles is about 16%. It is comparable with the magnitude of the nanoparticles addition effect on the evaporation rate. Therefore, to eliminate this point, the loss rate of the pure fluid mass in the process of evaporation without taking into account the mass of the nanoparticles was analyzed in this work. Such analysis, apparently, was made for the first time. An example of such data is shown in Fig. 2b, which represents the time dependence of the remaining mass of fluid as a percentage of the initial mass. As can be seen, in this view, the rate of evaporation monotonously increases with an increase in the concentration of nanoparticles.

Based on these data was determined the evaporation rate \[ \Theta = \frac{\theta_2 - \theta_1}{\tau_2 - \tau_1} \] , which shown in Fig. 3a. Here \( \theta \) is the speed of mass loss, and \( \tau \) is the consequent time moment. It was found that the average relative evaporation rate of fluids increased, and the time of complete evaporation, respectively, decreased.
with an increase in the volume concentration of nanoparticles. As can be seen, the absolute value of the evaporation rate significantly depends on the type of base fluid. However, if considered the relative value of the evaporation rate, which is determined as the ratio of the nanofluid evaporation rate to the base fluid evaporation rate, then that value for different base fluids remains approximately the same. It can be clearly seen in Fig. 3b. As can be also seen from that figure, the evaporation process proceeds faster as the concentration of nanoparticles increases. However, even at very high volume concentration of particles (4%) that increase was only about 7%. As the nanoparticles concentration increases the evaporation rate of nanofluids increases too, and at high concentrations of nanoparticles the evaporation rate reaches a plateau. An analysis of the experimental results shows that the dependence of the evaporation rate of a nanofluid is described with good accuracy by the next correlation: $\Theta_{nf}/\Theta_f = 1 + a\varphi^b$. The coefficients $a$ and $b$ were determined for all studied nanofluids: $a = 0.054$, $b = 0.242$ for water-based nanofluid; $a = 0.05$, $b = 0.313$ for IPA-based nanofluid.

![Figure 2](image1.png)  
**Figure 2.** The time dependence of the remaining mass of nanofluid ($a$) and remaining mass of base fluid ($b$) for different volume concentrations of Al$_2$O$_3$ nanoparticles.

![Figure 3](image2.png)  
**Figure 3.** The dependences of evaporation rates ($a$) and relative evaporation rates ($b$) of nanofluids based on pure water and isopropyl alcohol on the volume concentration of Al$_2$O$_3$ nanoparticles.
4. Conclusions
The evaporation of the nanofluids based on Al₂O₃ nanoparticles at different volume concentrations and different fluids was experimentally investigated. The distilled water and isopropyl alcohol were used as based fluids. The average diameter of Al₂O₃ particles were 100 nm. The investigations of fluids evaporation rates were carried out using the Simultaneous Thermal Analyzer STA 449 C Jupiter (NETZSCH). Unlike most of the previously performed work on this topic, there was the first investigation of the nanoparticles effect on the evaporation rate of the nanofluids without taking into account the mass of nanoparticles in this paper.

The dependences of the evaporation rate of nanofluids on the volume concentration of nanoparticles are obtained. It was shown as a result of the experiments that the average relative evaporation rate of fluids increased, and the time of complete evaporation, respectively, decreased with an increase in the volume concentration of nanoparticles. It was found, that the absolute value of the evaporation rate significantly depends on the type of base fluid. However, if considered the relative value of the evaporation rate, which is determined as the ratio of the nanofluid evaporation rate to the base fluid evaporation rate, then that value for different base fluids remains approximately the same. In such case, the increment of fluids evaporation rate is not very significant. The maximum increase of the evaporation rate due to the nanoparticles adding compared to the base fluid is about 7% at a fairly high concentration of 4 vol.%. Like the other properties of nanofluids, such as viscosity and thermal conductivity, it is also obvious to expect the dependence of the evaporation rate on the nanoparticles average sizes. Such investigations are planned to conduct in future.

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