The experimental investigation of the effect of nanoparticle material on the evaporation rate of nanofluids

A S Lobasov\textsuperscript{1,2}, A V Minakov\textsuperscript{1,2} and M I Pryazhnikov\textsuperscript{1,2}

\textsuperscript{1}Siberian Federal University, 660074, Krasnoyarsk, Russia
\textsuperscript{2}Institute of Thermophysics SB RAS, 630090, Novosibirsk, Russia

Abstract. It was experimentally investigated the nanofluids evaporation rate in this study. The nanofluids were prepared using the distilled water and different nanoparticles. The nanoparticles of aluminium oxide, silicium and zirconium dioxides, as well as the nanodiamonds were used. The average diameters of the particles were as follows: SiO\textsubscript{2} – 25 nm, ZrO\textsubscript{2} – 105 nm, Al\textsubscript{2}O\textsubscript{3} particles – 43 nm and nanodiamonds – 5 nm. The Simultaneous Thermal Analyzer STA 449 C Jupiter (NETZSCH) was used to carried out the study of the evaporation rates of fluids. The dependence of the evaporation rate on the material of the nanoparticles was investigated. It was found in that study that the evaporation rate significantly depends on the nanoparticles material. Moreover, based on the obtained results it was shown, that the evaporation rate of nanofluids monotonically increases with an increase of nanoparticles volume concentration.

1. Introduction
The advanced miniature electronic components require high heat flux dissipation rate to maintain uniform temperature. The evaporating thin film, which is characterized by high heat transfer rates due to its small thickness, is widely used in micro heat pipes and in modern applications such as MEMS and nanotechnology systems. Evaporate thin liquid film dissipate a lot of heat, thereby determining the maximum heat transfer capability in devices based on phase transformations. Thus, new ways to improve thin-film heat transfer and increase the area of the evaporating thin film are of great importance both in scientific and technological terms. To control the fluids evaporation rate it was proposed to add nanoparticles into the base fluid. That potential next-gen cooling fluids known as nanofluids can improve heat transfer coefficient of the evaporating thin film. It should be noted that the properties of nanofluids have been studied by researchers for almost 20 years. The term "nanofluid" was firstly proposed in [1] to define a two-phase system, in which the carrier fluid contained the nanoparticles with high thermal conductivity coefficient. Water, some organic liquids (oils, glycols) and polymer solutions are usually carrier fluids. The nanoparticles are most often obtained from metals and their oxides, as well as used the carbon nanotubes. As it was shown in numerous studies the nanofluids are very interesting non-conventional media with some special properties [2]. For example, the value of nanofluids thermal conductivity coefficient significantly higher, than of the carrier fluid (from percents to hundreds of per cent for nanotubes). In addition, The nanoparticles, in contrast to large dispersed particles, weakly sediment and do not cause the flow...
channels erosion. In this regard, nanofluids are successfully used as coolants for various devices, as lubricants, in microelectromechanical (MEMS) and water and air purification systems, etc. [2-8].

in most works studied the evaporation of nanofluids from droplets, but in [9], in contrast, was investigated evaporation from a large surface (18.8 × 12.8 cm) and volume (600 ml). Al₂O₃ nanoparticles of 13 nm, 20 nm and 80 nm average sizes and with TiO₂ nanoparticles of 21 nm average size at various volume concentrations were used. The evaporation rates of most nanofluids, as it was shown in the result, had lower values, than of the base fluid, especially as the nanoparticles concentration increase. However several nanofluids showed larger values of the evaporation rate, than of water, at low volumetric concentrations. It was concluded in the paper that, depending on nanoparticles volume concentration and type, the evaporation rates of nanofluids, as well as their saturated vapour pressures, may increase or decrease.

According to the different researches data, using the nanofluids in the solar energy absorption devices, e.g. the pool solar desalter, can increase their efficiency by an average of 50% [10-12]. The efficiency of fuel cells, compact heat exchangers and micron heat pipes can be twofold increased by the evaporation of the nanofluids near the triple line due to a significant temperature gradient and a very high heat flux [13, 14]. It was found as a result of firefighting investigations [15] that the intensification of the evaporation process of extinguishing liquid leads to a significant reduction of the source temperature. It was also found in that study, that the using of nanofluids with 50-500 µm carbon particles caused a substantial intensification of the water droplets evaporation, namely, two-three bold decreasing of the heating time and complete evaporation time of the droplets.

2. Experimental apparatus and procedures

The investigations of the evaporation rate of nanofluids based on the distilled water and different nanoparticles were carried out. The nanoparticles of aluminium oxide, silicium and zirconium dioxides, as well as the nanodiamonds, were used. The average diameters of particles were as follows: SiO₂ – 25 nm, ZrO₂ – 105 nm, Al₂O₃ – 43 nm and nanodiamonds – 5 nm. Metal oxides nanoparticles were purchased from the “Plasmotherm” company, Moscow. The powder of nanodiamonds was produced by Joint Stock Company Federal Research & Production Center ALTAI, Biysk-city. The volume concentrations of the metal oxides nanoparticles were varied from 0.5 to 6%. The volume concentration of the diamond nanoparticles were varied from 0.0625 to 1%. Such concentration ranges of nanoparticles were selected to maintain the colloidal stability of suspensions.

To prepare the nanofluids used a standard two-step method. First, the necessary amount of nanopowder was added to the water, after that a container with nanofluid was placed for half an hour in the ultrasonic bath to destroy the nanoparticles conglomerates. The properties of the suspensions didn’t change during further sonication. The sedimentation stability of metal oxides suspensions persisted for several days after the sonication even for high concentrations of nanoparticles. The nanodiamond suspensions were stable during the day.

The Simultaneous Thermal Analyzer STA 449 C Jupiter (NETZSCH, figure 1a), that can measure mass changes (thermogravimetry) and heat fluxes (differential scanning calorimetry) simultaneously, was used to investigate the fluids evaporation rates. Built-in top-loading electromagnetic microbalances had a high-precision resolution in the sub-microgram range, as well as measurement stability. In the process of simultaneous thermal analysis was studied the sample behaviour under the given conditions of temperature program. The changes in the mass of the sample, the absolute temperature of the sample and the temperature dependence of the heat fluxes discrepancy between the sample and the etalon were measured. These measurements were synchronously performed in the same conditions and on the same sample. The scheme of the device is shown in figure 1b.

A sample of nanofluid was placed in a corundum crucible. In the work were used several crucibles of different volume (20.0 and 85 µl). The crucible with the liquid was installed in the thermostat of the device on a special platinum/platinum-rhodium holder (TG-DSC sensor type S) connected to highly sensitive balance. After that, the necessary law of temperature variation was set in the thermostat, by means of the highly sensitive heater. The sample weight loss was recorded during the experiment. The
initial and final temperature of the sample, as well as isothermal holding time and sample heating rate, can be managed during the heating process in that device.

The samples of the nanofluids were heated from 25°C to 50°C at a temperature rate of 1.0 K/min with followed isothermal holding for 30 minutes in this study. The experiment was conducted in a dynamic atmosphere of air. The flow rate of air was 30 ml/min. The temperature during the experiment coincided with a sufficiently high degree of accuracy for all samples. The time dependence of temperature and mass of the sample was measured three times for each nanofluid. The discrepancy between the evaporation rates in these measurements did not exceed 4%.

Figure 1. Simultaneous Thermal Analyzer STA 449 Jupiter (a) and its scheme (b): 1 – protective tube; 2 – heater; 3 – sample holder; 4 – protective heat shield; 5 – vacuum valve; 6 – thermostatic control; 7 – vacuum-tight housing; 8 – gas outlet; 9 – control thermocouple; 10 – vacuum system.

3. Results and discussion

The typical behavior of the sample mass during the experiment for the nanofluid with silicon dioxide particles is shown in figure 2 as time dependence of the relative increase in the mass of evaporated nanofluid:

$$\eta = \frac{m_{nf} - m_w}{m_{nf}} \cdot 100\%,$$

(1)

where $m_{nf}$ is the mass of evaporated nanofluid, and $m_w$ is the mass of evaporated water at the same conditions.

As one can see, as the concentration of nanoparticles increases the evaporation process proceeds faster. However, the evaporation rate increased by about 12% only, even at very high particles volume concentration (6%). Similar measurements for other nanofluids were carried out as well. The obtained results were qualitatively similar to those described above and are shown in figure 3 as the dependence of the relative evaporation rate $w(\phi)$ on the particles concentration. Here, the relative evaporation rate is that of the nanofluid related to the evaporation rate of pure water under the same conditions. It was found qualitatively similar, but quantitatively different behaviour of the evaporation rate dependences on the concentration of the particles for different materials. The evaporation rate of nanofluids
increases with an increase of the nanoparticles concentration, moreover that value reaches a plateau at high concentrations of nanoparticles. It may be seen that nanofluids with oxide particles have close evaporation rates. For these nanofluids the evaporation rate dependence on the material of the nanoparticles is quite weak.

![Graph](image1.png)

**Figure 2.** The time dependence of the relative increase in the mass of evaporated nanofluid compared to the mass of evaporated water for different volume concentrations of SiO$_2$ nanoparticles.

![Graph](image2.png)

**Figure 3.** The dependence of the relative evaporation rate on the particles concentration.

Analyzing the experimental results it can be concluded that the dependence of nanofluid evaporation rate is described by correlation $w(\phi) = 1 + a\phi^b$ with good accuracy. The $a$ and $b$ coefficients were determined for all studied nanofluids: $a = 0.115, b = 0.428$ for diamond particles; $a = 0.033, b = 0.551$ for silicium dioxide particles; $a = 0.034, b = 0.419$ for aluminium oxide particles; and $a = 0.053, b = 0.294$ for zirconium dioxide particles. As can be seen, the nanofluid with nanodiamond particles evaporated much faster than that with other particles, but even at a sufficiently high concentration of nanoparticles (1 vol.%) the increase of the evaporation rate was about 12%.
4. Conclusions
The evaporation of nanofluids based on the distilled water and different nanoparticles at different volume concentrations has been experimentally investigated. The nanoparticles of aluminium oxide, silicium and zirconium dioxides, as well as the nanodiamonds were used. The investigations of fluids evaporation rates were carried out using the Simultaneous Thermal Analyzer STA 449 C Jupiter (NETZSCH). The effect of nanoparticles on the evaporation rate of nanofluids without taking into account the mass of nanoparticles was investigated for the first time, in contrast to previous works.

The dependences of the evaporation rate of nanofluids on the nanoparticles volume concentrations have been obtained. It was demonstrated in the experiments that the evaporation rates increase monotonously with an increase of the nanoparticles concentration. However, the increment that value is not very significant. The maximum increase of the evaporation rate due to the nanoparticles adding was following: about 10% at a fairly high concentration of 6 vol.% for oxide nanoparticles and about 12% at 1 vol.% concentration for diamond nanoparticles. The evaporation rate of nanofluids was compared to the evaporation rate of the base fluid. It has been established that nanodiamond particles have a significantly greater effect on the evaporation rate compared to metal oxide particles. However, it should be noted that diamond nanoparticles were the smallest in this study, their size was about 5 nm. It is reasonable to expect the evaporation rate of nanofluids will depend on the average size of nanoparticles, just like the other properties of nanofluids, such as thermal conductivity and viscosity. Such investigations are planned to conduct in future.

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