Enhancement of heat transfer for boiling in nanofluid

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Abstract. The paper considers heat transfer during boiling of subcooled water with suspended nanoparticles Al₂O₃ using a suspension from 0.32% to 4%. On a spherical model, the local heat flux per unit area was measured by the method of gradient heatmetry for model temperature of 464 °C and water temperature of 64 °C. The results are compared with the data obtained at the same temperature conditions for pure water. Enhancement of heat transfer was revealed in the entire concentration range - with a maximum at a particle concentration close to 1%.

1. Introduction
Application of Al₂O₃ nanoparticles as a heat exchange intensifiers at boiling controversial, and there is still no consensus on the impact of suspensions on heat transfer [2,3]. Considered temperature conditions (model temperature of \( t_w = 464 \) °C, fluid temperature of \( t_f = 64 \) °C) implemented on pure water demonstrates classic regimes [1]. Figure 1 clearly shows film (I), transient (II), and nucleate (III) boiling regimes. Boiling patterns are confirmed by high-speed imaging. We used these results as a basis for comparison.

Gradient heatmetry is the advanced method for direct measurement of heat flux per unit area (HFPUA). The method is based on the use of heterogeneous gradient heat flux sensors (HGHFS) (figure 2), the action of which is based on the transverse Seebeck effect [4]. When a heat flux of \( q \) passes through the sensor, it appears proportional to transverse thermoEMF

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E_0 = S_0 \cdot A \cdot q
\]

where \( E_0 \) – thermoEMF, mV; \( S_0 \) – volt-watt sensitivity of HGHFS, mV/W; \( A \) – area of HGHFS, m²; \( q \) – heat flux per unit area, W/m².

HGHFS were successfully used for study of boiling and they made it possible to obtain not only the distribution of HFPUA at the surface of the model, but also instantaneous values of its quantity [5].
2. Experimental setup

The installation scheme of our setup is shown in figure 3. Experimental model – sphere 1 – made of VT22 titanium with a dia of $d = 34$ mm with a HGHFS with dimensions of $3 \times 3 \times 0.3$ mm installed at its surface. Using the holder 3, sphere 1 is fixed in the channel furnace 2 and is heated to the required temperature. Uniform heating is controlled by two copper-constantan thermocouples, mounted on the surface and in the core of the sphere, respectively. Upon reaching the desired temperature, the holder 3 releases the model 1, and it is lowered into the water tank 4. All data from the HGHFS and thermocouples are recorded by the measuring computer complex 8 of the NIPXI-1050 type, and the water temperature is monitored by a 5 Fluke 289 multimeter with its own thermocouple. In experiments with pure water was we have used high-speed camera 6 model Evercam 1000-4-M with an illuminant 7.
Figure 3. Experimental setup: 1 – model; 2 – furnace; 3 – holder; 4 – water tank; 5 – Fluke 289 with thermocouple; 6 – high speed Evercam 1000-4-M camera; 7 – illuminant; 8 – MCC NIPXI-1050; 9 – computer; 10 – light emitting diode.

3. Results
The mass concentration of particles of Al₂O₃ were in the range of 0.32% – 4% [6,7], while the particle size did not exceed 1 μm. At mass concentrations of Al₂O₃ equal to 0.32% (figure 4 a) and 1% (figure 4 b), HFPUA significantly increases. Absence of stable film boiling regime reduces the cooling time of the model. Visualization in these modes is impossible due to the optical impermeability of the medium, but the curves show that there is no pronounced nucleate boiling. This qualitatively coincides with the boiling regime in pure subcooled water [1]. \( \tau = 0 \) – the moment of time when the sensor touches the liquid surface.

Figure 4. Dependence of heat flux per unit area on time: a – for pure water vs Al₂O₃ mass fraction of 0.32 %; b – for pure water vs Al₂O₃ mass fraction of 1 %.
According to thermometry data, the section of intensive cooling of the model coincides with the development of nucleate boiling, measured by gradient heatmetry (figure 5). As can be seen from figure 5, with the addition of nanoparticles, an increase in the heat flux is observed, and as a consequence, the cooling rate of the model increases, which can be observed from the slope of the temperature curves.

![Figure 5](image.png)

**Figure 5.** Time dependence of dimensionless temperature and heat flux per unit area in pure water and in Al$_2$O$_3$ with a mass concentration of 2%.

At concentration of Al$_2$O$_3$ particles equal to 4% (figure 6), HFPUA also increases. In this mode, the film boiling regime is qualitatively recorded, which corresponds to low values of heat flux at the beginning of the process. (figure 6). The lifetime of the film and transient regimes is much shorter than in pure water. At such a concentration of particles, developed nucleate boiling is observed, with fluctuations near the maximum value of HFPUA.

![Figure 6](image.png)

**Figure 6.** Dependence of heat flux per unit area on time in pure water and Al$_2$O$_3$ mass fraction of 4%.
Figure 7 shows the dependence of HFPUA on concentration of Al$_2$O$_3$ particles and a comparison with values of heat flux during boiling in pure water. There is a pronounced maximum near 1% concentration.

![Figure 7. Critical heat flux vs Al$_2$O$_3$ mass fraction.](image)

4. Conclusion
It was found that addition of nanoparticles of Al$_2$O$_3$ to subcooled water intensifies heat transfer in entire range of particle concentrations (0.32 - 4%). The optimal result was achieved at a concentration of 1% when the critical value of HFPUA reaches 9 MW/m$^2$, which is 3.6 times more than for pure water. It is planned to continue research for other temperature conditions.

References
[1] Sapozhnikov S Z, Mityakov V Yu, Pavlov A V and Bobylev P G 2020 *Gradient heatmetry for boiling of underheated water on spherical surface* (Journal of Physics: Conference Series) vol 1683
[2] Dedov A V 2019 *A review of modern methods for enhancing nucleate boiling heat transfer* (Teploenergetika) vol 12 pp 18-54
[3] Terekhov V I, Kalinina S V and Lemanov V V 2010 *The mechanism of heat transfer in nanofluids: state of the art (review). Part 2. Convective heat transfer* (Thermophysics and Aeromechanics) vol 17
[4] Sapozhnikov S Z, Mityakov V Yu and Mityakov A V 2020 *Heatmetry* The Science and Practice of Heat Flux Measurement (St.-Petersburg, Springer International Publishing) 209 p
[5] Sapozhnikov S Z, Mityakov V Yu, Pavlov A V, Bobylev P G and Vinogradov M D 2021 *Gradient heatmetry in the study of boiling on spherical surface* (Journal of Physics: Conference Series) vol 1867
[6] Das S K, Putra N and Roetzel W 2003 *Pool boiling characteristics of nano-fluids* (Int. J. of Heat and Mass Transfer) vol. 46 pp 851–862
[7] Wen D and Ding Y 2005 *Experimental investigation into the pool boiling heat transfer of aqueous based-alumina nanofluids* (Springer, Journal of Nanoparticle Research) vol. 7 pp 265–274