

# Study of pool boiling of distilled water on SiO<sub>2</sub> nanoparticle-coated wire

M I Pryazhnikov<sup>1,2</sup>, A V Minakov<sup>1,2</sup>

1 Siberian Federal University, 79 Svobodny pr., Krasnoyarsk, 660041, Russia

2 Institute of Thermophysics SB RAS, 1 Acad. Lavrentiev pr., Novosibirsk, 630090, Russia

E-mail: arrivent@yandex.ru

**Abstract.** Experimental results of pool boiling of distilled water on bare nichrome wire and SiO<sub>2</sub> nanoparticle-coated wire are presented. Nano-coated wires were obtained by first boiling them in SiO<sub>2</sub>-water nanofluid. The nanofluid was prepared based on distilled water and SiO<sub>2</sub> nanoparticles. The average size of the nanoparticles was 100 nm. The volume concentration of particles was equal 2%. Boiling curves of distilled water were obtained on bare nichrome wire and SiO<sub>2</sub> nanoparticles coated wire. The coating increased the critical heat flux during boiling of water.

## 1. Introduction

The use of different methods for modifying the heat exchange surface to increase critical heat flux (CHF) is an actual task of mitigating the limitations of the critical heat flux density. In recent years, profound interest has been shown in the study of heat and mass transfer during boiling on surfaces coated with nanoparticles [1-4]. In particular, this is due to the appearance of new types of coolants, which have a significant effect on the properties of the heating surface during boiling (change of wettability and roughness). Nanofluids can be attributed to such coolants. Nanofluids are two-phase systems consisting of a based fluid and nanoparticles. The size of nanoparticles is less than 100 nm.

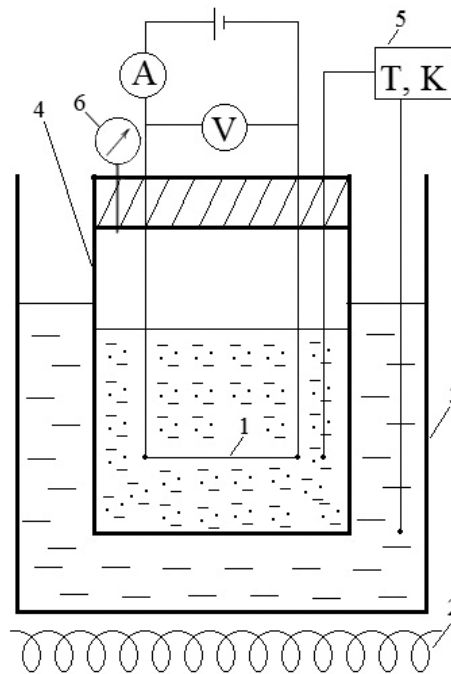
A significant (up to two or more times) increase of the critical heat flux density at low (0.001 – 0.1% vol.) concentrations of nanoparticles is one of the remarkable properties of nanofluids [1-4]. The results of experimental studies and observations [1-9] of the heating surface show that the main reason for this phenomenon is the appearance of a layer (coating) of nanoparticles on heater surface, which is formed directly during boiling. The coating of nanoparticles affects the boiling crisis in several ways. First, the coating has a specific surface morphology, which leads to a significant increase in roughness and wettability of the surface. Secondly, an additional suction of liquid to the surface of the heater is organized due to the formation of a porous structure, which is due to capillary forces.

The problem of describing the formation of surface coating during boiling and its influence on the boiling process and the boiling crisis is connected with the study of the physicochemical properties of the surface and the effect of surface phenomena on the layer formation and morphology.

In the present work, experimental results of pool boiling of distilled water on SiO<sub>2</sub> nanoparticle-coated wire are presented.

## 2. Experimental apparatus and procedure

The scheme of the used experimental setup is presented in figure 1. The investigated fluid in amount of 300 ml was placed in a high sealed glass flask (4) 8 cm in diameter. A nickel-chromium wire heater with the length  $L$  of 40 mm and the diameter of 0.1 mm was emerged into the flask filled with fluid. The wire was fixed by copper bus leads with the cross section of  $10 \times 2$  mm to supply voltage. The heater was energized by means of AKIP-1122 power source. The applied voltage and load amperage in the circuit was recorded using a GDM-78261 voltmeter ("V" and "A" in figure 1, respectively). The flask with the test fluid was sealed, so that the condensate formed in the upper part of the flask dripped back into the flask, maintaining saturation conditions in the working chamber. The fluid temperature in the flask was controlled by means of a chromel-copel thermocouple, which was connected to the TRM-200 temperature meter (5). The tail end of the thermocouple was located at the same level with the nickel-chromium heater at a distance of 2 cm from it. The absolute pressure in the flask was measured using digital precision manometer DM5002M (6). In the experiments the pressure was atmospheric and constant.



**Figure 1.** The scheme of the experimental setup.

The flask with the test fluid was placed in a water bath (3) with the constant temperature, which was about  $0.5^\circ\text{C}$  below the boiling point, maintained by means of electric heater (2). Thus, in this paper we investigated the boiling close to saturation conditions. The temperature control in a water bath was conducted using another chromel-copel thermocouple connected to the TRM-200 meter. Some times after placing the flask into a water bath, the temperature in the flask and water bath equalized. After the nickel-chromium heater was energized, the heat flux density was measured. The programmable current power supply allowed increasing the heater voltage with a fixed predetermined step. Thus, it was possible to control the heat flux growth rate and, thereby, to fix the onset of the boiling crisis.

The boiling heat flux density on the heater was determined by the ratio:  $q = Q/S = IU/S$ , where  $S = \pi dL$ ,  $S$  – is the lateral surface area of the heater between the current-carrying wires,  $Q$  – is the heat flux released by the heater,  $I$  – is the electric current in the heater circuit,  $U$  – is the voltage drop

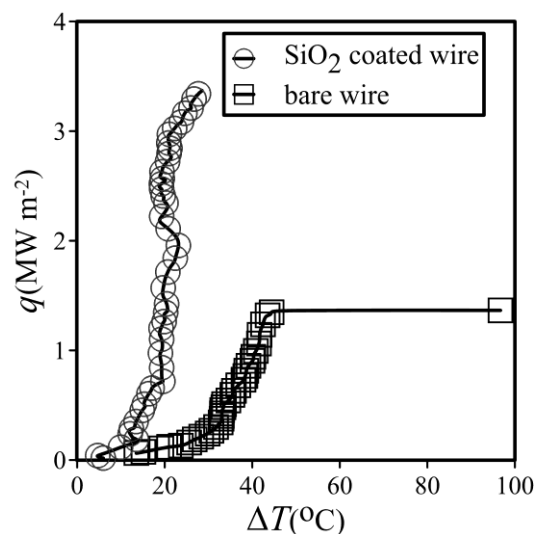
in the heater. Heat generated at the lead wires was negligible. The total error in determining the heat flux density was about 2%.

Studying the boiling processes requires also the knowledge of the heater surface temperature. Since for the nickel-chromium the dependence of resistance  $R$  on temperature within the investigated temperature range is close to linear  $R = R_0[1 + A(T - T_0)]$ , then by measuring the resistance of the heater and knowing the temperature coefficient of resistance  $A$ , we can find the average temperature of heater:  $T = T_0 + (R/R_0 - 1)/A$ . Here  $R_0$  – is the heater resistance at the temperature  $T_0$ . To determine the temperature coefficient of nickel-chromium electrical resistance, we have performed special series of resistance measurements of the used nickel-chromium wire. It was found that  $A=0.00012$  1/K. The total error in determining the temperature of the heater was about 3 %.

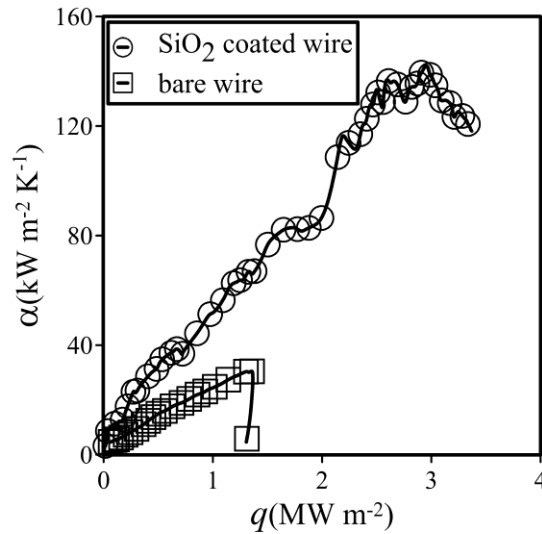
### 3. Experimental results

Nano-coated wires were obtained by first boiling them in SiO<sub>2</sub>-water nanofluid. The nanofluid was prepared based on distilled water and nanoparticles of silicon. The volume concentration of particles was equal 2 %. For preparation of nanofluid we used the standard two-step process. After adding the necessary quantity of nanopowder to water, obtained nanofluid was first thoroughly mixed mechanically and then it was placed in an ultrasonic disperser for half an hour to destruct the particles conglomerates. No surfactants were added to the nanofluid. The average size of the nanoparticles was 100 nm. The first three kinds of nanopowder were acquired from the “Plazmoterm” company. The SiO<sub>2</sub>-water nanofluid was preheated to the boiling point. After the nickel-chromium heater was energized. The heat flux density was 1 MW/m<sup>2</sup>. The SiO<sub>2</sub>-water nanofluid was boiling on wire for 25 minutes under these conditions. The deposits of SiO<sub>2</sub> nanoparticles were formed on the wire surface.

The series of water boiling experiments was conducted on SiO<sub>2</sub> nanoparticles coated wire. Boiling curves of distilled water were obtained on bare wire and SiO<sub>2</sub> nanoparticles coated wire (see figure 2). The dependence of the heat transfer coefficient on heat flux density was also obtained (see figure 3). According to our information, distilled water has critical heat load  $q_{CHF}$  in the range 1.0–1.3 MW/m<sup>2</sup>, which agree with many works in which the boiling of water on thin wires of similar size was studied, for example, in work [10]  $q_{CHF}=1.15$  MW/m<sup>2</sup>, in work [11]  $q_{CHF}=1.15$  MW/m<sup>2</sup>, in work [12]  $q_{CHF}=1.2$  MW/m<sup>2</sup>. Figures 2-3 show that the coating of SiO<sub>2</sub> nanoparticles increased the critical heat flux during boiling of water. The relative critical heat flux density is 2.7 (the ratio of critical heat flux density on coated wire to the critical heat flux on bare wire).



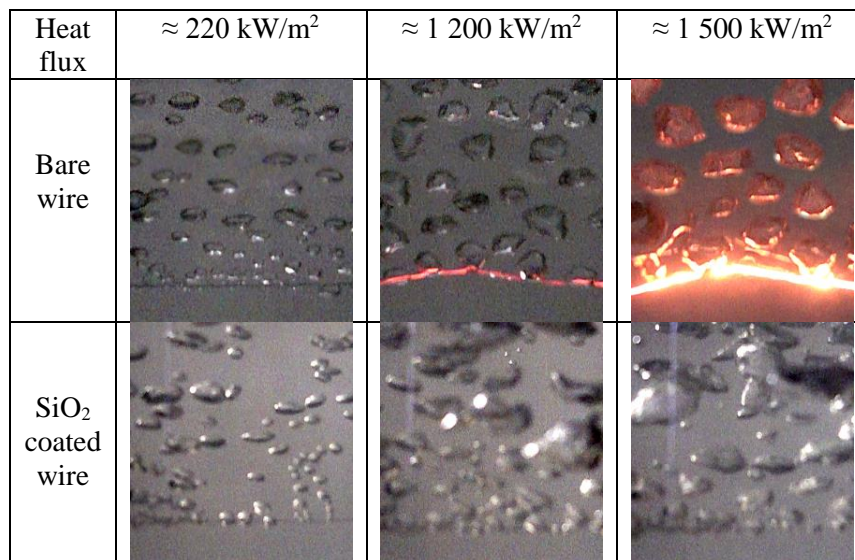
**Figure 2.** Pool boiling curve for distilled water.



**Figure 3.** Dependence of heat transfer coefficient on heat flux density.

Figure 2 shows that the boiling curve of the coated wire is shifted to the left (in the region of smaller surface superheating). This suggests that the heat transfer coefficient at boiling of distilled water is higher than for bare wire (see figure 3). This agrees with the results of other experimental studies, for example [4].

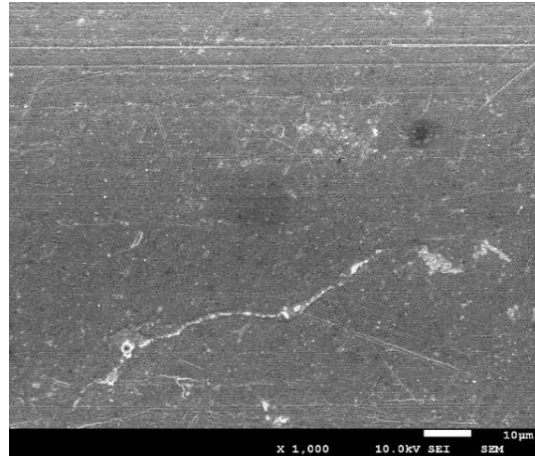
The video of the boiling process was recorded using the Sony Cyber-shot DSC-RX100. The Sony RX100 IV allows to provide for high frame-rate video at up to a staggering 1000 frames per second. Figure 4 shows photographs of pool boiling at different heat flux densities on bare wire and on SiO<sub>2</sub> nanoparticles coated wire. It can be seen that the flow visualization of the boiling process is different for the same heat flux density.



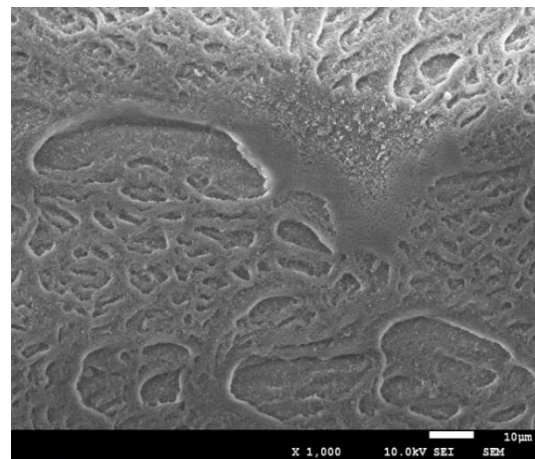
**Figure 4.** Flow visualization of the boiling at various heat fluxes.

Besides measuring the critical heat flux we have investigated also the heaters surface structure after boiling. This was done using transmission electron microscope JEM-2100 (JEOL, Japan) equipped

with an energy dispersive spectrometer Oxford Inca x-sight. Figures 5 and 6 show SEM images of bare wire and SiO<sub>2</sub> nanoparticles coated wire after boiling of distilled water.



**Figure 5.** SEM images of nickel-chromium wire after boiling of distilled water.



**Figure 6.** SEM images of SiO<sub>2</sub> nanoparticles coated wire after boiling of distilled water.

### **Conclusion**

In this work experimental study of pool boiling of pure distilled water (without nanoparticles) on nanoparticle-coated wire are conducted. Nano-coated wires were obtained by first boiling them in SiO<sub>2</sub>-water nanofluid. Boiling curves of distilled water were obtained on bare wire and SiO<sub>2</sub> nanoparticles coated wire (see figure 2). The dependence of the heat transfer coefficient on heat flux density was also obtained (see figure 3). Figures 2-3 show that the coating of SiO<sub>2</sub> nanoparticles increased the critical heat flux during boiling of water. The relative critical heat flux density is 2.7 (the ratio of critical heat flux density on coated wire to the critical heat flux on bare wire).

It can be seen that the heater surface is covered by fairly dense deposits (see figure 6). A microscopically rough surface is formed by depositing particles on the surface of the heater. Particle deposition on the heater surface plays the key role in the enhancement of CHF. Thus, the critical heat flux is directly related to deposits of nanoparticles on the heater surface. The electron microscopy has shown that the thickness of deposits reaches about 5-10  $\mu\text{m}$ . Additional work is needed to study characterization of layer growth to understand the whole mechanism.

### Acknowledgments

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