Effect of the distance between the micro/nanostructures on pool boiling heat transfer with water on a copper heater

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Abstract. Copper heaters were made. On the surface of these heaters the arrays of micrococoons were synthesized from silicon oxide (SiOx) nanowires with different concentrations of micro/nanostructures and hence different average distances between them. Boiling curves were obtained for these samples and it was found that heat transfer enhancement during boiling occurs on them in comparison with a smooth copper surface. It was shown that the effect increases with decreasing concentration of micro/nanostructures and reaches a maximum for microrelief with an approximate concentration of microstructures equal to unity per square micron. It was found that surfaces with micrococoons are sufficiently stable and suitable for enhancing heat transfer during boiling.

1. Introduction

One of the methods to improve significantly the performance of heat exchangers during boiling is the use of micro- and nanomodified surfaces [1, 2]. Micro- and nanomodification includes both micro- and nanostructuring of the surface and deposition of thin films. In particular, arrays of oriented nanowires made of silicon, copper and other materials are used to intensify heat transfer during boiling [3]. Such nanostructures undoubtedly lead to a positive effect, increasing both the critical heat flux and the heat transfer coefficient in comparison with a smooth surface [1-4]. The use of two-scale structuring (for example, arrays of nanowires on a surface with microstructures) further intensifies heat transfer during boiling [2, 3]. But the problem of aging becomes relevant when using one-dimensional high-aspect structures like nanowires [2, 4]. The aging can occur due to insufficient mechanical and chemical stability, insufficient adhesion to the surface. Destruction of nanostructures, change in the chemical composition (oxidation), and surface contamination may occur during boiling under intense hydrothermal and hydromechanical loads. In turn, this will lead to deterioration (degradation) of the heat transfer parameters during boiling and a decrease in the positive effect up to the parameters corresponding to a smooth surface. Oxide materials are of great interest for the use in heat exchange equipment due to their high stability. In particular, SiO2 is an oxide material that is stable under significant hydrothermal loads and is suitable for use on boiling surfaces. In this study nanowires created from SiOx (a non-stoichiometric silicon oxide in composition close to SiO2) were used.

In this work, for the purpose of heat transfer enhancement during boiling, it is proposed to use silicon oxide SiOx nanowires, synthesized by the gas-jet electron beam plasma chemical vapor deposition method [5]. This method is very flexible, allowing the use of substrates of different materials and the synthesis of nanostructures with various morphologies at relatively low...
temperatures. Arrays of microstructures from SiO$_x$ nanowires, the so-called "microropes" and "micrococoons" were synthesized by this method [5, 6]. The microrope is a bundle of silicon oxide nanowires that grows from a submicron catalyst particle in the direction of the substrate. Usually, an array of oriented microropes is formed during the synthesis and it is some analogue of the array of oriented nanowires. The micrococoon is a catalyst particle completely overgrown with SiO$_x$ nanowires. In this case, the catalyst particle may have direct contact with the substrate, as a result of which the adhesion to the surface increases. It was previously shown that the arrays of microstructures made of SiO$_x$ nanowires, consisting of microropes and micrococoons, lead to an increase in heat transfer during boiling [7]. However, the latter are more stable and less susceptible to destruction.

In this work, it is proposed to use the arrays of micrococoons made of SiO$_x$ nanowires on the surface of a copper heater to intensify heat transfer during pool boiling and to study the effect of the distance between the microstructures on the heat transfer parameters.

2. Experimental setup and methods

The arrays of micrococoons from SiO$_x$ nanowires were synthesized by the gas-jet electron beam plasma chemical vapor deposition method on a tin catalyst [5-7]. Hydrogen, a 5% mixture of monosilane in argon, and oxygen were used as processing gases. The synthesis temperature was 280-285°C, the synthesis time was 3 minutes. Copper heaters with a tungsten barrier layer were used as substrates. Several samples were fabricated, the surface of which was covered with arrays of micrococoons with different concentrations, and, accordingly, different average distances between the microstructures. Sample characterization, measurement of the size and concentration of micrococoons were carried out using a JEOL JSM-6700F scanning electron microscope (SEM).

The scheme of the sample is shown in Figure 1. A nichrome wire was reeled up on a core of the copper heater to supply power. Two thermocouples were installed in the core to determine the heat flux. The thermocouple which was placed closer to the boiling surface (0.5 mm) was also used to determine the wall temperature.

Experiments to determine the heat transfer enhancement on modified surfaces were carried out on the specially made installation. The setup scheme is shown in Figure 2. A Teflon cylinder was used as the main body. A Teflon washer of about 50 mm with experimental sample was installed in the body. The liquid level was kept constant (30 mm above the washer). Distilled and degassed water was used as a working liquid. A small hole was used to remove the steam. It was enough to keep the pressure below atmospheric. Pressure was controlled by measuring the saturation temperature of water in the volume. The temperature was approximately 99.8°C.

The calibration accuracy of all used thermocouples was 0.1°C. Data collection from thermocouples was carried out by using an NI-9214 controller. Two Gwinstek GPO-743035 units were used as power sources for the experimental sample and the stabilizing heater.

Before the main series of experiments, test experiments were carried out on a smooth copper surface, the results of which were consistent with the main correlations. Heat losses were less than 20% at a nominal heat flux above 80 W/cm$^2$. The error in determining the heat flux was less than 5% at fluxes over 40 W/cm$^2$ and less than 2% at fluxes over 80 W/cm$^2$.

![Figure 1. Scheme of a copper heater.](image-url)
3. Experimental results and discussion

In the studies, the concentration of micro/nanostructures was used as a measure of the average distance between them. Three samples were made with different concentration of cocoons. Figure 3 shows SEM images of an array of micrococoons of silicon oxide nanowires on the surface of a copper heater with a tungsten barrier layer for sample # 1 before (Figure 3a) and after the boiling experiment (Figure 3c). It can be seen from the figure that micrococoons have grown on surface # 1, which is strongly "overgrown" with chaotically oriented microropes from small catalyst particles. The concentration of cocoons was 4.8 μm$^{-2}$. The contact angle of the surface was 11 ± 2° (Figure 3b). After experiments on boiling, the concentration of micrococoons does not change. However, the small micropores were largely destroyed, and the contact angle increased several times. The data obtained confirm the result from [7] that microropes are mechanically unstable and easily break down during boiling.

Figure 3. Morphology of sample # 1 before experiment (a) and after experiment (c), contact angle before experiment (b).

Figure 4 shows SEM images of an array of micrococoons of silicon oxide nanowires on the surface of a copper heater with a tungsten barrier layer for sample # 2 before (Figure 4a) and after the experiment (Figure 4c).
Figure 4. Morphology of sample # 2 before experiment (a) and after experiment (c), contact angle before experiment (b).

It can be seen from Figure 4 that only micrococoons have grown on surface # 2, there are no microropes. The concentration of cocoons on surface # 2 was 6.8 μm², which is about one and a half times more than that on surface # 1. The contact angle of the surface was 36 ± 2° (Figure 4b). After the boiling experiments, the surface morphology (Figure 4c) and the contact angle did not change.

A thick layer of SiOₓ was deposited on the array of micrococoons made of SiOₓ nanowires of surface # 3 to significantly reduce the concentration of microstructures (and hence increase the average distance between them). Therefore, in addition to overgrown cocoons with a diameter of less than 1 µm, microstructures with a diameter of several microns were observed (SEM images in Figure 5a, 5b). The concentration of microstructures (overgrown micrococoons) was 0.8 μm², which is approximately 5 times less than on surface # 1. The contact angle of the surface was 56 ± 2° (Figure 5c). After the experiments on boiling, the surface morphology did not change; the contact angle of wetting also remained at the level of 56 ± 2°.

Figure 5. Morphology (a, b) and contact angle (c) of sample # 3 before the experiment.

Boiling curves were obtained for these samples. Experimental data compared with the Rohsenow correlation [8] for a smooth copper surface are shown in the graph in Figure 6. It is seen that all samples with a micro/nanostructured surface show boiling heat transfer enhancement as compared to a smooth copper surface. However, for samples # 1 and # 2 with a higher concentration of micro/nanostructures, the increase is insignificant and is approximately the same for both samples although the concentration of micrococoons on them differ by about one and half times. It can be assumed that this is due to the too dense arrangement of microstructures and too small sizes of the nucleation sites, insufficient for their activation. For sample # 3, the concentration is much lower and
the characteristic distances between microstructures are noticeably larger. For this sample, the effect of heat transfer enhancement is more significant.

Figure 6. Boiling curves for micro/nanostructured surfaces # 1-3 and Rohsenow correlation for smooth copper surface [8].

A similar tendency to an increase in the effect of boiling heat transfer enhancement with an increase in the distance between nanostructures is observed in [9], where boiling heat transfer on a surface with arrays of oriented metal nanowires was studied. Also, sample # 3 has a larger contact angle due to the fact that nanowires and other structures on the surface are covered by a layer of SiOₓ. However, this difference is insignificant (56° for surface # 3 and 36° for surface # 2) and cannot be the reason for noticeable differences in heat transfer. Thus, the main factor determining the heat transfer enhancement in this case is the presence of microrelief with concentration of microstructures of about one per square micron. A larger concentration of microstructures leads to a decrease in the effect and a decrease in the dependence on concentration.

After several boiling experiments on each surface, neither the concentration of micro/nanostructures nor the surface morphology of the samples changed. The surfaces with micrococoons showed good resistance to aging during boiling.

Conclusions

Arrays of micrococoons from SiOₓ nanowires on the surface of a copper core with a tungsten barrier layer with the concentration of micro / nanostructures in the range 0.8 - 6.8 μm² were synthesized. A study of boiling heat transfer on these surfaces has been carried out.

It is shown that heat transfer improves compared a smooth copper surface A relationship between a decrease in concentration and an increase in heat transfer has also been shown. The maximum intensification was achieved for a microrelief with a concentration of microstructures equal to one feature per square micron. A high concentration of microstructures (micrococoons) leads to a decrease in the effect and a decrease in the dependence on concentration.

It is shown that structures of micrococoons made of SiOₓ nanowires are practically not destroyed during boiling. Accordingly, micrococoons are sufficiently resistant to use for heat transfer enhancement.
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