An experimental investigation of the effect of coating on heat transfer during quenching

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Abstract. The work is aimed at studying the effect of galvanic nickel coating of a stainless steel cylinder on the quenching. In order to compare the results, the polished stainless steel cylinder was used as a sample. In addition, the influence of the formation of an oxide layer on the cooling process was studied. The experiments were carried out in water and ethanol with different subcoolings. The oxidized porous nickel coating led to increasing of the transition temperature from stable film boiling to intensive boiling regime. It was especially noticeable for cooling in water at high subcooling due to the higher cooling intensity caused by vapour layer thinning.

1. Introduction
Cooling of high-temperature bodies is of interest for many industries, in particular, for nuclear power. Accident at the Fukushima Daiichi NPP in 2011 led to a hydrogen explosion and release of radioactive fission products into the environment during the accident. After these events, many world scientific centers began studies to exclude the possibility of a steam-zirconium reaction and to find new, accident-resistant materials [1]. In the scientific literature, such nuclear fuel for NPP is usually called Accident Tolerant Fuel (ATF).

Tolerant fuel concepts aim to delay the onset of destructive processes in the event of accidents (by reducing the rate of oxidation at high temperatures and also by potentially delaying the explosion). Therefore, it is important to reliably understand how the new fuel will behave under accident conditions, especially reflooding of the core. When the core of a nuclear reactor is re-flooded, a film boiling regime takes place. It is characterized by low heat transfer coefficients and cooling rates. In this case, it is necessary to achieve a transition from film boiling to a more intensive cooling regime for cooling the fuel rods heated to high temperatures as quickly as possible.

British scientists discovered a special regime of heat transfer with a very high intensity during cooling of the hot spheres in 1986 year (so-called “microbubble boiling”) [2]. It was observed in water with subcooling more than 22°C. It was later confirmed by experiments on cooling spheres [3] and cylinders [4] made of different metals. However, such regime was not observed in nonaqueous liquids (ethanol, isopropanol, perfluorohexane) in a wide range of subcooling [5]. It was possible to achieve the transition to the microbubble boiling regime only in ethanol at high pressures (0.7–0.9 MPa), when it was managed to avoid the high viscosity of ethanol at high subcooling [6].
In addition, it is known that heat transfer during cooling of high-temperature bodies is influenced by the properties of the cooled surface. Changing of the material and structure of the cooled surface or the deposition of coatings can significantly increase the transition temperature to an intensive cooling regime. For example, the effect of the coating with low thermal conductivity applied to a copper plate was studied in [7]. Experiments have shown that the low thermal conductivity coating reduces the cooling time of this plate. In the work [8], cylindrical samples made of stainless steel and copper were cooled. The surface of some of the samples was oxidized. As a result, a developed oxide structure with low thermal effusivity was formed on the copper sample and intensified the cooling process. Oxidation of the stainless steel sample did not lead to significant changes in the quenching process. It is due to the resistance of this material to oxidation. Another authors showed that the transition temperature to intensive boiling regime for oxidized and rough cylindrical samples made of zirconium is higher than for a polished surface [9].

An approximate physical model of incipience of highly intensive cooling regime during film boiling was developed and reviewed in [10]. This model explains the mechanisms of occurrence of the special intensive cooling regime. According to it, the protrusions of the roughness of the cooled surface and waves on the vapor/liquid interface can cause local and short-term liquid/solid contacts. Local contacts between cooling liquid and cooled surface is possible when the temperature of these roughness protrusions lower than the attainable limiting liquid temperature, while the average surface temperature can be much higher. The experimental data available to date are in qualitative agreement with this model. However, further experiments are required to verify and correct this model.

So, the cooling of high-temperature bodies is multifactorial process, which is influenced by both the properties of the cooling liquid and the properties of the cooled surface. This paper discusses the experimental results of cooling of high-temperature cylindrical samples made of stainless steel without and with the galvanic nickel coating in different cooling liquids.

2. Experimental facility and test samples
The experiments were conducted under atmospheric pressure at the experimental facility shown in [11]. Test sample is heated by high-frequency inductor. When temperature of the test sample achieves a required value (400–700°C), the sample is transferred to the vessel with a liquid. Liquid temperature is regulated with copper coil, connected to a thermostat. During the cooling process, the signal from the thermocouples passes through the connector NI SCXI-1303 to the measuring module NI SCXI-1102. The measurement results acquired enter a personal computer through USB-interface, a time dependence of temperature is plotted in the Lab View program.

The working samples are stainless steel cylinders with the same size: 10 mm in diameter and 50 mm in length. The bottom part had a spherical shape to reduce the end effects. Two thermocouples were mounted in each cylinder – central and lateral (not reaching 0.5 mm to the surface). One of the stainless-steel cylinders was coated with a nickel electroplated coating with a thickness of 30 μm. Stainless steel cylinders were pre-polished, the profilometry results showed that arithmetic average value of roughness profile (Ra) is 0.75 μm. Polishing was carried out using vibratory finishing equipment by Walther Trowal in Finishing Technology Center (Moscow). Ra of stainless steel cylinder with nickel electroplated coating is 5 μm. The results of optical microscopy of the surface of stainless-steel cylinders are shown in Figure 1.
3. Results and discussion

Cooling experiments were carried out in liquids with different thermophysical properties – water and ethanol. The temperature-time dependences (cooling thermograms) were obtained. Figure 2 shows the cooling thermograms for stainless steel cylinder with nickel galvanic coating (a) and polished stainless steel sample (b) in ethanol $T_{\text{liq}} = -50^\circ\text{C}$. At high subcooling (in this case, $\Delta T_{\text{sub}} = 128$ K), the transition temperature to the intensive cooling ($T_r$) slightly exceeds the critical temperature of ethanol ($T_{\text{cr}} = 243^\circ\text{C}$). At lower subcooling, the transition temperature is below the critical temperature for ethanol. It can be seen that the $T_r$ during cooling of the cylinder with nickel coating is higher than for the polished sample ($T_r = 300$ and $250^\circ\text{C}$, respectively). Even though the nickel coating is highly heat-conducting to stainless steel and can reduced the $T_r$, the results suggest otherwise. Apparently, this fact was influenced by the porous structure of the electroplated coating. Also, the $Ra$ of this coating is higher than for the polished cylinder. In addition, an oxide layer with low thermal effusivity forms on the nickel coating during heating to high temperatures. So, the combination of the nickel oxide and porous structure led to increasing in the $T_r$. The time of stable film boiling during cooling of the coated cylinder was also reduced - from 15 to 10 seconds.

Table 1 shows the data on the transition temperatures for cooling these cylinders in liquids with different subcoolings, where $T_{\text{liq}}$ is the temperature of cooling liquid and $T_r$ is the transition temperature. Two liquids were chosen as cooling liquids – water and ethanol. These liquids have different thermophysical properties, in particular, viscosity, surface tension and latent heat of evaporation. In Table 1 the stainless-steel cylinder with nickel coating is “Ss + Ni” and the polished stainless-steel cylinder is “Ss”.

![Figure 1. Optical microscopy of the stainless-steel cylinder with the nickel electroplated coating (a) and the stainless-steel polished cylinder (b).](image-url)
Figure 2. Cooling thermograms of the stainless-steel cylinder with electroplated nickel coating (a) and the stainless-steel polished cylinder (b) in ethanol at 50°C.

1 – center temperature, 2 – surface temperature.

In all considered cases, the transition temperature during cooling of the nickel-coated cylinder is higher than for the polished stainless steel. A significant difference is observed in water with subcooling more than 20 K. This is due to the fact that in water under such conditions the vapor film is less thick. Therefore, the possibility of local contacts between cooling liquid and the hot surface increases, and the properties of the cooled surface begin to influence on the heat transfer process during cooling. The nickel galvanic coating appeared to be porous and had a low thermal effusivity oxide layer. This resulted in increasing in the transition temperature compared to the polished stainless steel cylinder. The stable film boiling takes a long time during cooling in ethanol. In this case, the vapor film is thicker, which reduces the possibility of such local liquid-surface contacts during film boiling. As a result, the transition temperature during cooling of the polished sample and the coated cylinder in ethanol have slight differences (less than 30 K).

Table 1. Transition temperatures during cooling of high-temperature cylinders.

|          | \( T_{liq} \), °C | \( T_{tr} \) (Ss+Ni), °C | \( T_{tr} \) (Ss), °C |
|----------|-------------------|--------------------------|-------------------|
| Ethanol  |                   |                          |                   |
| -50      | 300               | 270                      |                   |
| -10      | 270               | 250                      |                   |
| 30       | 240               | 210                      |                   |
| Water    |                   |                          |                   |
| 70       | 480               | 420                      |                   |
| 80       | 410               | 330                      |                   |
| 90       | 320               | 290                      |                   |
| 100      | 290               | 250                      |                   |

After a series of experiments on various liquids, the coated cylinder was additionally oxidized. The sample was heated to a temperature of about 700°C, then cooled in air (cooling to 80°C took about 20 minutes). The repeated experiments were carried out in water and ethanol after the oxidation test for studying the transition temperatures during cooling of the cylinder with formed thicker oxide layer. Figure 3 shows cooling thermograms in 70°C water before and after oxidation. The cylinder was...
heated to a higher temperature after oxidation test for fixing the transition temperature. As expected, in this case the transition temperature increased with the growth of the oxide layer (from 500 to 580°C).

![Cooling thermograms of the stainless-steel cylinder with electroplated nickel coating in water 70°C before (a) and after (b) oxidation.](image1)

**Figure 3.** Cooling thermograms of the stainless-steel cylinder with electroplated nickel coating in water 70°C before (a) and after (b) oxidation. 1 – center temperature, 2 – surface temperature.

Even in ethanol with small subcooling, the transition temperature after oxidation slightly increased with a small decrease in cooling time (Figure 4). In regimes with a lower heat transfer rate during cooling, stable film boiling is maintained for a long time (about 20 seconds for cooling with the initial temperature of 400°C).

![Cooling thermograms of the stainless-steel cylinder with electroplated nickel coating in ethanol 50°C before (a) and after (b) oxidation.](image2)

**Figure 4.** Cooling thermograms of the stainless-steel cylinder with electroplated nickel coating in ethanol 50°C before (a) and after (b) oxidation. 1 – center temperature, 2 – surface temperature.

So, the nickel electroplated coating increased the transition temperature during cooling of high-temperature bodies for all of the considered cooling regimes. However, during cooling in water with large subcooling, such coating had a stronger effect.
Conclusions
Despite the fact that nickel is the high thermal conductivity coating for stainless steel, the increase in the transition temperature for cooling the cylinder with nickel electroplating coating was observed. Apparently, in this case, the method of coating deposition was influenced by the resulting structure of the coating. In addition, nickel was oxidized at high temperatures. Thus, we obtained a developed rough structure of nickel oxide, instead of the initially smooth stainless steel surface, which led to an increase in the transition temperature. Experiments carried out on the nickel-coated cylinder after oxidation test at high temperatures and air cooling have confirmed that the transition temperature also increases with the growth of the oxide layer. This is more noticeable for cooling in subcooled water due to the higher intensity of cooling processes. Under these conditions, the vapor film is thinner than for cooling in alcohols or saturated water. It increases the possibility of the local liquid/solid contacts, according to the approximate model of the incipience of high intensive boiling regime in subcooled liquids.

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