Features of cooling bodies with a high coefficient of thermal effusivity in subcooled mixtures

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Abstract. The paper focuses on the study a special type of boiling, "microbubble boiling". Experiments are carried out on water-ethanol mixtures of different concentrations. The pressure varies from 0.1 to 0.3 MPa; and copper and stainless-steel samples are used as working samples. The purpose of the experiments is to investigate the effect of such parameters as solid and liquid properties and subcooling on the transition temperature from the stable film boiling to “microbubble” boiling regime. In the course of direct comparison of the results obtained by cooling the samples with different thermal effusivity under the same conditions, a strong influence of the properties of the cooled body on the quenching process has been revealed.

1. Introduction
Understanding the laws governing the cooling of high-temperature bodies in liquids is critical in the issues of heat treatment and nuclear power plant safety. If the initial temperature of the hot body exceeds the homogeneous nucleation temperature of the coolant (or the attainable limiting temperature), then the cooling process begins with the film boiling. As the body temperature decreases, contacts between the liquid and the wall become possible and film boiling is replaced by transition and, then, nucleate boiling. Predicting the temperature of transition from film boiling to more intensive boiling mode is an important practical task. For cooling in a saturated liquid, the temperature of the transition from the film to the transition boiling lies in the range from the attainable limiting temperature ($T_{lim}$) up to the critical temperature of the liquid ($T_c$). However, under certain conditions, the process becomes much more complicated, since a special boiling mode, the so-called "microbubble" boiling, arises. This boiling regime, first described in articles [1, 2], is characterized by high values of the removed heat fluxes (10 MW/m²). It is completely atypical for those wall superheats (up to 700 K) at which this regime is observed. A large number of works, including the authors' own works, indicate that the occurrence of this regime is influenced by a large number of factors, such as:

- liquid properties [3];
- subcooling of the liquid to saturation temperature [4];
- properties of the cooled body;
- condition of the surface of the cooled body [5].
Based on these experimental data, it is possible to create an approximate model of the beginning of an intensive cooling regime \([6, 7]\):

\[
(T_{tr} - T_{lim}) = C \left( \frac{h_{LG} \sigma}{\nu} \right) \sqrt{\frac{t}{\rho c \lambda}}
\]

(1)

where \(T_{tr}\) is the surface temperature at the onset of intensive cooling; \(T_{lim}\) is the temperature of the attainable liquid superheat; \(\rho\) is the solid density; \(c\) is the solid heat capacity; \(\lambda\) is the solid thermal conductivity; \(h_{LG}\) is the heat of evaporation; \(\sigma\) is the surface tension; \(\nu\) is the liquid viscosity; \(t\) is the characteristic time; and \(C\) is the constant.

As can be seen from equation (1), the temperature of the appearance of the intensive cooling mode \((T_{tr})\) depends on the properties of the cooled body, namely, the coefficient of thermal effusivity \(\varepsilon = \sqrt{\rho c \lambda}\).

In [8] the effect of coatings with high thermal resistance (low \(\lambda\)) on heat transfer during quenching was investigated. The studies were carried out on water and liquid nitrogen at atmospheric pressure. The authors confirmed the presence of liquid-solid contacts when applying low-thermal conductivity coatings. This led to a significant destabilization of the vapor film and transition from the stable film boiling regime to the intensive one. The authors [9] also found an intensification of the process when using low-thermal conductivity coatings. They quenched copper cylinders in saturated and subcooled nitrogen. The samples were coated with epoxy resin coatings with a thickness from 50 to 500 \(\mu\)m. In [10] a series of experiments on cryoliquids were performed. Spheres of different diameters, made from bismuth, zinc, aluminum, brass and copper, were used. The boiling curve was found to depend on the properties of metal. The lower was the thermal conductivity of the cooled body, the higher was the \(T_{tr}\).

The work [11] described studies on unsteady heat transfer of high temperature cylindrical samples in water. Samples were made from zircaloy, stainless steel, niobium, copper, and niobium and chrome plated steel. The authors explained the difference in quenching of samples from different metals in saturated water by the complex \((\rho c)\). The authors of [12] used cylinders made of FeCrAl, SiC and Zry-4 in their quenching experiments. Subcooling of water reduced the duration of quenching and increased \(T_{tr}\), while for each material by a different value, which depended on the thermal diffusivity of the sample.

In this paper, to confirm the influence of the properties of the cooling liquid and the cooled surface, experimental results on cooling spheres made of different metals in water-ethanol mixtures are presented.

2. Experimental facility

The experiments were carried out on an experimental stand described in detail in [13]. The sequence of the experiments was as follows. First, a water-ethanol mixture of the required concentration was made. In the present experiments, two concentrations were selected: 40 and 60\% by the content of ethanol in water. Then, the mixture was poured into the lower part of the experimental setup. Temperature of mixture was set in the thermostat to which the coil was connected. Then, an inert gas (Argon) was supplied to the experimental stand to create an excess pressure of up to 0.3 MPa. After the required pressure and temperature of the liquid were established, the sample was heated by a high-frequency inductor to a predetermined temperature (400–700 °C). After that, the heated sample was immersed into a liquid, where it was cooled. At the same time, with the help of thermocouples mounted into the working sample, the temperature curve was recorded on a personal computer. The main working area was a copper ball with a diameter of 40 mm. Copper was chosen because of high \(\varepsilon\), which allowed checking the prediction of the model [7] about a decrease in \(T_{tr}\) for samples with a high thermal effectivity. To protect against high-temperature oxidation of copper, a protective gold coating was applied. Above all, gold, like copper, has a high \(\varepsilon\), and the gold plating will not act as a heat insulator for the base metal. In addition, a sample of Aisi316 stainless steel of the same size was used for direct comparison of the results.
3. Results and discussion
To demonstrate the effect of subcooling on heat transfer during quenching, experiments were carried out on cooling a stainless-steel sphere in the mixture with an ethanol content $X_e=40\%$ by mass (Figure 1). The mixture temperature was set in a wide range from $-17$ to $70\,^\circ C$. It may be seen from the Figure 1 that starting from the temperature of the mixture $T_{liq}=20\,^\circ C$, there is a drop in $T_{tr}$ with an increase in the temperature of the mixture. $T_{tr}$ for subcooling $\Delta T_{sub}=60\,K$ is $475\,^\circ C$, which is $200\,K$ higher than at $\Delta T_{sub}=10\,K$. The mixture temperature range from $-17$ to $+20\,^\circ C$ does not show an increase in the $T_{tr}$ with increasing $\Delta T_{sub}$. $T_{tr}$ practically does not change and a local maximum is observed at subcooling $\Delta T_{sub}=80\,K$. This complex relationship may be explained as follows. $T_{tr}$ from the side of the liquid is affected by its properties ($h_{LG} \sigma/\nu$) and subcooling. However, by increasing the liquid subcooling, the viscosity of the mixture simultaneously increases. It turns out that an increase in subcooling contributes to an increase in $T_{tr}$, while an increase in viscosity acts in the opposite way.

Let us consider the results of quenching the gold-plated copper sphere. Two concentrations $X_e=40$ (Figure 2-a) and $60\%$ (Figure 2-b) were chosen, the mixture temperatures were $30$ and $70\,^\circ C$. The experiments were carried out at both atmospheric and elevated (up to $0.3\,MPa$) pressure. From this figure, the following can be noted. First, the cooling is more intensive for a mixture with a high water concentration. So, at the same temperature of the mixture $T_{liq}=30\,^\circ C$, but for different concentrations (Figure 2-a, curve 1 and Figure 2-b, curve 1), the total cooling time increases by 5 seconds (it is necessary to keep in mind that in this case quenching begins at a surface temperature of $100\,K$ and lower), and $T_{tr}$ drops by more than $100\,K$. Secondly, with an increase in pressure at a fixed $T_{liq}$, the quenching intensity increases. As can be seen from a comparison of curves 1 and 3 (at $T_{liq}=30\,^\circ C$), as well as 2 and 4 (at $T_{liq}=70\,^\circ C$) with increasing pressure, the total cooling time decreases almost 2 times due to the intensification of heat transfer in the regime of stable film boiling and growth of $T_{tr}$.

**Figure 1.** Experimental thermograms of cooling the stainless steel sphere in water-ethanol mixtures with concentrations $X_e=40\%$ and different temperatures: 1 $-17\,^\circ C$, 2 $-10\,^\circ C$, 3 $0\,^\circ C$, 4 $10\,^\circ C$, 5 $20\,^\circ C$, 6 $30\,^\circ C$, 7 $40\,^\circ C$, 8 $50\,^\circ C$, 9 $60\,^\circ C$, 10 $70\,^\circ C$. 
Figure 2. Experimental thermograms of cooling the copper sphere with gold coating in water-ethanol mixtures of different concentrations: a – 40%, 1 – 30°C, P=0.1 MPa, 2 – 70°C and P=0.1 MPa, 3 – 30°C, P=0.3 MPa, 4 – 70°C, P=0.3 MPa, b – 60%, 1 – 30°C, P=0.1 MPa, 2 – 70°C and P=0.1 MPa, 3 – 30°C, P=0.3 MPa, 4 – 70°C, P=0.3 MPa.

Figure 3. The surface temperature of the beginning of the intensive cooling mode for different materials at different mixtures concentration and temperature. SS – stainless-steel, Cop – copper.
It is interesting to directly compare the results obtained on samples with different ε values. For this, we used the results obtained by quenching the stainless steel and copper spheres of the same diameter (40 mm) in mixtures with Xc=40 and 60% at Tlg = 30, 50 and 70°C, i.e. for strong and weak subcooling. Figure 3 presents the diagram for Ti for two metals and the temperature of the limiting superheat of the liquid. Figure 3 shows that at low subcooling (ΔTsub = 10 K), Ti practically coincide and do not differ much from Tlim. However, with increasing subcooling, Ti of stainless steel almost always exceeds Ti for copper and Tlim. Moreover, the larger is subcooling, the stronger is this difference. It is worth noting that for copper with a gold coating, at Xc= 60%, the temperature of the transition to the intensive regime turns out to be tens of degrees lower than Tlim. An increase in the concentration of water in water-ethanol mixture also leads to an increase in the transition temperature. It is especially noticeable at large subcooling.

Conclusions
Unique experiments were carried out on water-ethanol mixtures on samples with very different values of the ε (ε = 36000 Ws/°m·°K−1 for copper, versus ε =7600 Ws/°m·°K−1 for stainless steel) both at atmospheric and at elevated pressures (up to 0.3 MPa). Experiments have shown that:
- Ti behaves in a complex way: Ti practically does not change at large subcooling, but from a certain subcooling Ti drops sharply for all concentrations and materials of the working sample;
- Ti depends on the thermophysical properties of the coolant, namely the complex (hLGσ/ν). The value of this complex is lower for a mixture with a high ethanol concentration. Therefore, Ti on a mixture with a mass content of 40% alcohol is higher than Ti on a mixture of 60% at the same subcooling;
- there is a strong influence of the thermophysical properties of the cooled body on Ti. With an increase in the ε, Ti decreases and approaches the temperature of the attainable limiting temperature.

The formulated conclusions confirm the main ideas on the theory of the approximate model of the incipience of the intensive cooling regime, namely, about the influence of the thermophysical properties of a liquid and a material.

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