Intensive cooling metallic bodies with low thermal conductivity in film boiling of ethanol

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Abstract. Film boiling regime occurs when temperature of solid surface exceeds the attainable limiting temperature of the cooling liquid. In unsteady conditions, this boiling regime has applications in safety systems of Nuclear Power Plants (NPP) and in metal-processing. Nonsteady film boiling of subcooled water has unresolved issues relating to the conditions when low-intensive stable film boiling regime turns to a high intensive mode. The present paper considers the new experimental results on unsteady film boiling of ethanol over a wide range of subcoolings. On the basis of the experimental data, a hypothesis has been developed to explain appearance of the intensive heat transfer during film boiling.

1. Introduction
Severe nuclear reactor accident with meltdown involves the analysis of interaction between corium with the temperature of 3000K and cooling water, which can lead to steam explosion [1]. Thirty years ago study of this problem resulted in revealing a new heat transfer regime, which was called “micro-bubble boiling” [2]. This term was used for film boiling of water under high subcoolings, when huge cooling rates up to 1000K/s have been achieved. The regime was detected at temperature of the copper sphere surface higher 400ºC that excluded direct liquid-solid contact; emergence of plenty of microscopic bubbles close to the heat transfer surface explains its name. HTCs related to the saturated water temperature were unusually high for film boiling (up to 10 kW/m²K). After the work [2] all the known scientific teams working in this field studied only subcooled water film boiling; the subsequent publications do not concern the micro-bubble boiling as a particular regime and did not mention the above paper. As it is shown in [3], there exist contradictions in interpretation of some experimental results in quenching process and sometimes misunderstanding of the problem content. The detection of micro-bubble boiling with nonaqueous liquids could provide information crucial for of this type boiling mechanism.

2. Experimental facility
The experimental unit created in 2013 allows to conduct experiments in a wide range of coolants temperatures (from -200°C to +200°C) and pressure (up to 1.5 MPa). The experiment consists in heating the sample to a predetermined temperature and then immersing it into the test liquid. As the test section we used metallic spheres of 30-51 mm in diameter. A sphere is equipped with 4 or 5 cable thermocouples (one in the center and 3 or 4 on the surface). Simultaneous measurement of temperature in several points of the sphere gives the opportunity to recover the temperature field inside the sphere at any given time and to calculate heat flux density distribution and heat transfer coefficient by means of solving an inverse heat conduction problem. The experimental facility and technology of test pieces manufacturing are described in detail in our previous work [3].

3. Results and discussion
Earlier we have conducted many series of experiments on cooling high temperature spheres in different liquids. The materials of spheres were copper, nickel and stainless steel, and liquids were water,
perfluorhexane, isopropanol and ethanol. The cooling regime strongly depends on the properties of a cooling liquid, its subcooling value, and partly, on metal properties. The numerous experiments with water as a cooling liquid have revealed that the highly intensive film boiling mode occurs in cooling a sphere from any metal used at subcoolings $\geq 25$-$50$ K independently on absolute pressure. This regime arises at the sphere surface temperature several hundreds degrees higher than the critical water temperature. In the experiments with all the nonaqueous liquids a stable film boiling regime was the predominant one during the spheres cooling. To answer the question why the highly intensive mode of film boiling occurs only in water, an analysis of all the previous experimental results is necessary. During intensive cooling the metal spheres heat transfer intensity is higher than in steady convective film boiling of subcooled water at large flow velocities [4]. The temperature field in a cooled sphere at intensive heat transfer markedly depends on effusivity (thermal activity) of the sample material: the lower the thermal activity, the higher cooling rate of the sphere surface [3].

These observations allow to propose a hypothesis about the conditions of the appearance of intensive film boiling regime. The presence of roughness elements (protrusions) on the cooled surface and waves on the vapor/liquid interface may cause liquid/surface point contacts. The instability of the interface caused by the liquid motion in its boundary layer at the vapor/liquid interface. Since a vapor density is 2-3 orders of magnitude less than a density of liquid in our experiments, there exists an analogy between a free-convective upstream flow of subcooled liquid relative to vapor film and a gravitational liquid film flow. This allows to use the well-known Kapitza results for wavy film flow and to obtain a wave number, frequency and period of waves at the interface. The wave frequency determines duration of liquid/surface point contacts. The protrusions of the surface can partly differ on their chemical composition from the cooled sphere metal; this provides an additional possibility for their earlier cooling in comparison to the other parts of the surface, the protrusions temperature can be below than the attainable limiting temperature of a liquid. The wetted micro-regions of the surface can exist under the conditions when the average surface temperature is much higher than $T_{lim}$; the probability of their appearance is higher in the case of lower values of the metal thermal activity. Highly intensive evaporation inevitably occurs at the boundary of liquid/surface contact (the three-phase contact line). According to [5] heat flux density at the contact line is proportional to product of latent heat of vaporization and surface tension divided on a liquid kinematic viscosity i.e. to the complex $q_{ev} \sim \frac{H \Delta T}{\nu}$. Heat flux due to nonsteady heat conduction at this region is determined as $q_{ns} \sim \frac{\Delta T}{\sqrt{\tau_0}}$, where $\Delta T_0$ is the wall superheat in relation to the liquid attainable temperature $T_{lim}$, $\tau_0$ is the characteristic time of the liquid contact with the protrusions of the surface roughness.

Figure 1. Schematic of the possible contact of a hot surface protrusion with a liquid.

If $q_{ev}$ is equal to or exceeds the heat flux entering the intense cooling zone from adjacent areas of the body $q_{ns}$, then this zone will exist (or expand), creating conditions for high average heat transfer rate. The equality of these heat fluxes determines the conditions for appearance of intensive heat transfer regime during film boiling of subcooled liquid:

$$q_{ev} = q_{ns}$$
As a zero approximation, the corresponding criterion can be written as

$$K_0 = \frac{\alpha h_{AG}}{v \Delta T_s} \sqrt{\frac{\eta}{(\alpha h_{AG})_s}},$$

where $\rho$, $c$, $\lambda$ - the density, specific heat and thermal conductivity of a metal.

Although this hypothesis can be regarded as a qualitative one, two experimental observations serve as arguments in its favor. First, it implies that significantly higher values of latent heat of evaporation and surface tension are those specific properties of water that distinguish it from the investigated alcohols and perfluorohexane. Second, sharper cooling the surface of spheres with lower thermal conductivity is explained by dependence of heat flux from the sphere volume to the area of intensive cooling ($q_{ns}$) on the metal effusivity. The average superheat of the surface in relation to the liquid attainable limiting temperature affects the process in the same direction.

Most recently, we have carried out series of experiments with a new test pattern, a 40 mm stainless steel sphere cooled in subcooled ethanol. Pressure and liquid bulk temperature were constant during quenching. Assuming (in the frames of the zero approximation) that the characteristic time $t_0$ slightly depends on the properties both of a sphere metal and of a coolant, it is possible on the basis of (1) to estimate that cooling stainless steel sphere in ethanol at high subcooling can give the values of $K_0$, which are close to those for the copper sphere cooling in subcooled water. This means a possibility of obtaining intensive heat transfer regime with ethanol as a coolant. Under high pressure it is possible to provide high subcoolings without entering the temperature range where ethanol becomes too viscous.

![Figure 2](image.jpg)

**Figure 2.** Averaged surface thermograms of cooling stainless steel sphere in ethanol at 0°C and different pressures: 1-0.1, 2-0.3, 3-0.5, 4-0.7, 5-0.8 and 6-0.9 MPa.

Fig. 2 presents the averaged surface thermograms of cooling the stainless steel sphere in ethanol at temperature 0°C. The experiments were conducted at pressures from atmospheric up to 1.0 MPa. One can see that the cooling intensity grows with pressure increasing. At pressures 0.7-0.9 MPa the stable film boiling changes into the intensive heat transfer regime at the surface temperature 285-300°C (for ethanol
\[ T_{cr} = 243.1\, ^\circ C, \quad T_{lim} \approx 186^\circ C \] at 0.9 MPa. As is seen, the steady film boiling lasts about 20 s, during which the surface temperature decreases by \( \sim 140 \, K \). The intensive film boiling regime smoothly transforms into transient and nucleate boiling regimes; at pressure 0.9 MPa during these regimes the surface temperature decreases from \( \sim 312^\circ C \) to \( \sim 150^\circ C \) for 3 s. It should be noted that in the experiments with water, transition from intensive film boiling heat transfer to the transient and nucleate boiling regimes is also smooth. However, in those experiments the thermograms demonstrate more dramatic variation of the surface temperature, because the initial sphere temperature is much higher, when water is a coolant (>700°C). Besides, incipience of intensive cooling in water occurs at very high surface temperature, for stainless steel spheres practically at the initial surface temperature.

In any case, the new experimental results essentially widen the data domain on intensive heat transfer in film boiling of subcooled liquids. This gives a hope for success in theoretical modelling this intricate process. Although the local wetted spots can exist at the cooled surface of the sphere, when its average temperature exceeds \( T_{lim} \), variation of the average temperature in cooling process presents self-sufficient interest. The thermograms in Fig. 2 show, what value of this temperature corresponds to transition to the intensive heat transfer regime of cooling. At atmospheric pressure the sharp increase of the averaged surface temperature inclination occurs at \( T_c \approx 225^\circ C \) that is lower than \( T_{cr} \), but markedly higher than \( T_{lim} \approx 174^\circ C \). The experimental results on cooling the copper sphere in subcooled ethanol [6] differ slightly: transition to intensive heat transfer occurs at \( T_c \approx 180^\circ C \), practically at \( T_{lim} \). This difference reflects influence of effusivity of the metals on the minimal temperature of film boiling and has well-known explanation. Hence, one can confidently relate the cooling regimes at atmospheric pressure to stable film boiling regimes.

Beginning with 0.3 MPa transition to intensive heat transfer occurs at the wall temperatures higher the critical one. Probably, this cooling run and the similar one at 0.5 MPa can be considered as examples of intensive heat transfer regime in film boiling. One can see that the temperature of transition to the intensive heat transfer mode increases with pressure, but the growth continues till pressure 0.7MPa only, and then remains at a constant level of \( \sim 290^\circ C \). At this stage of our studies we suppose that only the regimes at \( p=0.7\text{-}0.9 \) MPa can be with a confidence classified as related to the intensive ones in subcooled film boiling. Subcoolings in this regimes are higher 137 K; calculated values of HTC and \( q \) reach the maximum values of 15 kW/m²K and 1.8 MW/m², respectively, at the surface temperature 220-230°C. Today, this is the first recorded case of achieving the regime of intensive heat transfer during film boiling of a subcooled non-aqueous liquid.

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