Experimental study of thermo-hydrodynamic processes related to the film boiling crisis

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Abstract. The thermo-hydrodynamic processes, preceding and accompanying the crisis of the film boiling regime of subcooled water on superheated liquid metal and solid surfaces, were studied by physical modeling. The main models of liquid-metal droplet fragmentation are analyzed. Experiments with liquid metal droplets have been carried out. The results of the experiments indicate a significant dependence of the shape of the fragments formed on the melt temperature, which confirms the assumption of different mechanisms of their fragmentation. It was also found that when the steel droplets are heated in air, intensive sparking is observed, which prevents explosive fragmentation of the melt. It was found that the film boiling regimes of subcooled water on liquid metal drops and metal spheres differ in the cooling rate of heated bodies (for liquid metal drops it is much higher). In experiments with solid metal samples, the process of contact of water with a hot (170-620°C) surface was studied in detail using a conductometric technique. The results of measurements of oscillograms of the electric current in the regimes of film, transition, and bubble boiling are presented and their amplitude-frequency characteristics are investigated with the help of wavelet analysis. It is established that the contact between the cooler and the hot surface is preceded by a short (several millisecond) process, characterized by intense generation of waves at the vapor-liquid interface. The physical nature of waves developing on the phase surface in the film boiling regime and contributing to the pulsation of the electric current is discussed.

1. Introduction
The development of ways to prevent steam explosions and effective methods of controlling this formidable phenomenon is impossible without the creation of original theoretical models based on new information on all stages of its course, including the process of fragmentation of a hot coolant at its interaction with low-boiling liquids under the conditions of a film boiling crisis. In the literature [1-5], several dozen hypotheses devoted to the description of the last of the mentioned processes can be found that to all appearances attests not only to the insufficient study of the question but also with a high probability about the absence of a universal mechanism of the phenomenon under study. At present, the so-called “thermo-hydro-mechanical” (Figure 1a) and “penetrating jets” (Figure 1b) models of fragmentation are most thoroughly developed and dominated in the scientific literature. The first of these models relates the fragmentation of the melt to the appearance of cold water jets of the surrounding cold liquid when the vapor cavities collapse. These jets penetrate into the hot drop and boil explosively in it leading to the fragmentation of the hot liquid. In the second model, it is assumed...
that as a result of the destruction of the vapor shell located around a single drop, intensive contact of the coolant with the hot surface takes place. There is rapid cooling and solidification of the surface layer of the melt, accompanied by the appearance of tensile mechanical stresses and a strong all-round compaction of the liquid core of the droplet by a solid shell in this melt layer. The above processes initiate the formation of cracks in the hardened surface layer and the ejections of crushing jets of hot liquid into the cooler. In our opinion, these two hypotheses do not fully describe the process of fine melt fragmentation, and with a high degree of probability it can be assumed that explosive crushing is caused by the cavitation-acoustic effect associated with generation of high-frequency and intense pressure pulses (Fig. 1c). Such impulses are caused by sound (shock) waves, which are formed during the growth and collapse of steam bubbles as a result of the contact of hot and cold coolants. These waves also propagate in the volume of the droplet, and their reflection from its internal surface leads to appearance of a series of rarefaction pulses in the melt, with amplitude and duration sufficient to create cavitation cavities within the drop of the hot coolant and its fragmentation. The presented research is devoted to obtaining additional experimental information on this not fully studied issue.

![Figure 1](image.png)

**Figure 1.** Basic models of fragmentation (a, b, c) and photographs of the main types of fragments formed (d, e, f). 1 - water; 2 - melt; 3 - vapor; 4 - shock wave; 5 - steam bubble; 6 - jet of melt; 7 - water jet.

2. **Experimental installation and method of measurements**

In the experiments installations with liquid-metal drops (tin, steel) and solid metallic (steel, nickel) samples were used. A detailed description of the experimental stands can be found in [6]. Liquid metal (tin) droplets were either suspended at the end of a stainless steel tube (outer and inner diameters of 6 and 4 mm) with a wire electric heater wound on it, or placed on a special substrate and heated by induced currents. The liquid metal samples had a hemispherical shape with a diameter of 4 mm. Solid metal working areas with a hemispherical end surface were used to study the regularities of film boiling and the stage of initial contact of the cooler with a hot surface, since it can be assumed that similar processes for liquid and solid superheated bodies develop in a similar manner. The experiments were carried out in the following sequence. In the initial state, depending on the task, the working sample was heated in air or argon atmosphere to a temperature both below and above the melting temperature of the metal. Then, the electric heater was switched off, and the sample was immersed in a cooler (distilled water was degassed by a two-hour boil), the temperature of which varied in the range of 15 - 95°C. The initial temperature of the heated sample before immersion varied from 400 to 1600°C. Converging the vapor film around the heated body and melt fragmentation was observed using videocameras. At the same time, the temperature parameters of the process: pressure,
sound effects, the thickness of the vapor film, and the parameters of contact between the cooler and the hot surface, were measured.

For this purpose, based on the equipment of the National Instruments company, a measuring complex was created that allows simultaneous measurements of signals from several transducers, including temperature and pressure sensors, with a sampling rate of up to $10^6$ s$^{-1}$. Finally, we used piezoelectric sensors Kistler (Switzerland) and PCB (USA). This article focuses on describing the results of video observations of the process of fragmentation and measurements using the conductometric technique of the parameters of contact between the cooler and the superheated wall.

In the latter case, the measuring electric circuit consisted of a direct current source, two electrodes - one of which is a working section, and the other - a copper plate placed in water, connecting wires, water and water vapor layer. In the film boiling mode, the electric current in the circuit is practically absent due to the high electrical resistance of the vapor film. When the vapor film is destroyed, water moistens the heating surface, i.e. there is an electrical contact of the coolant with the hot wall. An electric current appears in the circuit, the value of which increases in proportion to the area of the wetted surface, which makes it possible to establish one-to-one correspondence between the current and the integral contact surface.

![Figure 2. Calibration curve and measuring scheme of the area of the contact spot.](image)

To obtain a quantitative dependence of the signal in the measuring circuit from the area of the wetted surface, calibration experiments were carried out in which the contact spot was modeled by the area of the end surface of the copper wire insulated from the sides (see the inset in Figure 2).

One end of the wire (rod), whose diameter varied from 30 μm to 15 mm in experiments, was soldered to the hemispherical surface of the working area, and the other was submerged several millimeters into water. The typical form of the obtained calibration dependence, which is in satisfactory agreement with the theoretical estimates, is shown in Fig. 2, where the relative value of the electric current flowing along the measuring circuit is plotted on the ordinate axis, and the wire diameter $d$ is shown along the abscissa axis.

The calculations were carried out basing on an analytical expression of the $J/J_{\text{max}} = U/(Kd^{-1} + R)$ where the reference resistance is $R = 24.3$ kΩ, $U$ is the voltage drop at the reference resistance, $K$ is the constant of the installation, depending on the electrical conductivity of the water, the diameters of the wire and the electrode. All experiments, the results of which are presented below, were carried out at the temperature of distilled water of 20°C. A wavelet of the "Mexican hat" type with a basic wavelet function of the form $\psi(t) = \frac{2}{\sqrt{3}} \pi^{-\frac{1}{4}}(1 - t^2) \exp\left(-\frac{t^2}{2}\right)$ was used when processing oscillograms of electric current pulsations. Sample rate of the electrical signal digitization was $5 \times 10^5$ s$^{-1}$.

3. Experimental results

Explosive destruction of the vapor shell, accompanied by fine-dispersed droplet crushing (Figure 1f) or formation of a porous structure (Figure 1e), occurred on a fresh liquid metal surface, which was
obtained immediately after extrusion into the external environment of hot melt (tin) from the capillary. Such types of fragmentation, which mechanism requires refinement, were of a statistical nature of the realization in the temperature range of heated tin $T \sim (400 - 700)^\circ C$. When water contacted tin with a temperature below 400°C, a bubble boiling regime was always observed on the surface of the melt, which prevented generation of high-intensity pressure pulses. Under such conditions, the fragments of the disintegrated droplet were large in size, commensurate with the size of the initial drop, and took the bizarre forms of “hedgehogs” (Figure 1d) or fragments of bodies of a hollow shape. It can be assumed with a high degree of probability that this type of droplet fragmentation is due to the thermomechanical stresses described in the introduction, related to the rapid solidification of the droplet, which is accompanied by squeezing its liquid metal core.

The results of experiments with liquid-metal drops (tin, steel stainless) clearly indicate that the oxidation of the liquid metal surface has a decisive influence on the fragmentation process. Experimental explanation of this effect is associated with great technical difficulties. We do not know how to control the thickness of the oxide film during the experiments. The thicknesses of oxide films obtained after the experiments do not provide reliable information on this question [7].

![Figure 3](image.png)

**Figure 3.** (a) - photos of a steel drop heated in argon and immersed into water. 1 - detached vapor bubble; 2 - the vapor envelope around the drop; 3 - fragments of the melt; 4 - inductor; 5 - water. Temperature of the droplet $\approx 1500^\circ C$. (b) - cooling curves for 1 - the ball (diameter $d = 10 \text{ mm}$, initial temperature $T_0 \approx 1300^\circ C$) of a ball bearing and 2 - drop ($d = 10 \text{ mm}$, $T_0 \approx 1500^\circ C$) from a ball bearing steel.

It was also found that there is a significant difference in the droplet behavior when heated in air and inert atmosphere of argon. In particular, when steel specimens are melted in air, intense liquid metal droplet erosion is observed. This phenomenon makes it difficult to develop a stable film boiling mode on the surface of a hot drop and prevents the occurrence of steam explosion. The regime of film boiling on a liquid metal drop is characterized by a similar feature associated with the ejection of small metal particles into the surrounding water (Figure 3a). Perhaps, it is this effect that results in the fact that the rate of cooling of liquid metal droplets in water is much higher than when cooling steel balls in a solid state (Figure 3b).

Experiments carried out on solid metallic samples made it possible, in particular, to substantiate in more detail the possibility of using a cavitation-acoustic hypothesis for describing fine fragmentation of a melt. The presented experiments were performed with hemispherical samples with a diameter of 10 mm. Earlier in [6] it was shown that the size of the hemisphere determines the temperature range of the appearance of a special oscillating regime for the existence of the vapor film.

A typical form of an oscillogram of electric current, clearly demonstrating the different modes of interaction of water with a heated wall, is shown in Figure 4. From the analysis of this oscillogram it can be concluded that in the time interval of 0 - 8.5 ms there is a film boiling regime, in which, due to the large thickness of the vapor shell, there is practically no interaction of water with the hot surface.
Then, before the contact, a jump of a current with stabilization at some new quasistationary value is observed.

The duration of this mode is several milliseconds (interval of 8.5 to 10.5 ms in Fig. 5), and its distinctive feature is the pulsating nature of the electric current (pulsation frequency is up to tens of kHz). Then, at \( t > 10.5 \) ms, the liquid boils and generation of steam bubbles takes place, the frequency of occurrence of which can be assumed to correspond to the frequency of electrical current pulsations.

![Figure 4. Oscillogram of the electric current pulsations. \( T = 334^\circ\text{C}. \)](image)

![Figure 5. Dependence of the "jump" of the electric current on the temperature of the heated sample.](image)

Figure 5 shows the dependence of the "jump" of the electric current on the temperature of the heated sample. It can be seen from the graph that at temperatures \( T < 250^\circ\text{C} \) the above-described regime was not observed, this can be explained by the instantaneous contact of the cooler with the heated surface.

At \( T \geq 250^\circ\text{C} \), there is a "jump" in the electric current and the accompanying pulsations. The form of these pulsations differs in variety. In particular, in addition to pulsations of "related" harmonic oscillations in their structure (the inset in Figure 4), individual pulses of electric current were also observed in the experiment (Figure 6), the intensity of which increased as the moment of direct contact between water and the heated surface approached. The obtained oscillograms of the electric current can be conveniently investigated using wavelet analysis. The wavelet images of the oscillograms, which are presented in the report, are shown in the graphs depicted in Figures 6 and 7. The scale of the wavelet ("Mexican hat") is plotted along the ordinate axis, which is related to the frequency \( F \) by relation \( F = 1.25 \times 10^5 / a \) Hz. It is important to note that the characteristic frequencies in these two different modes of contact are several hundred (Figure 6) and Hz \( \approx 25 \) kHz (Figure 7).

![Figure 6. Oscillogram of electric current pulsations and its wavelet image. \( T = 242^\circ\text{C}. \)](image)

![Figure 7. The wavelet image of the part of oscillogram presented in the inset in Fig. 4.](image)
4. Discussion
The question of the physical nature of waves developing on the interphase surface and generating the pulsation of an electric current caused by changes in the resistance of a layer between the main volume of liquid and solid wall requires more detailed analysis. Along with the capillary waves, the main role can be played by a wave of a new type, studied in detail in [8, 9]. The frequency of oscillations of a new type of wave, which value reaches tens of kHz, is connected to the dependence of the vapor pressure on the temperature at the phase boundary and is proportional to the square root of the heat flux from the hot body. The physical mechanism of wave generation at the interface under the influence of heat flow is explained by the fact that a random displacement of the phase boundary to a heated surface reduces the thickness of the vapor layer, causes an increase in temperature and vapor pressure. Increasing the saturated vapor pressure leads to a return motion of the phase surface - away from the heating surface. When the phase surface is removed from the heated body, the thickness of the vapor layer increases, temperature decreases and saturation pressure decreases. Lowering the pressure of the saturated vapor leads to a shift in the interface in the opposite direction - towards the heating surface. The changes in the heat flux that occur when the phase surface shifts cause additional evaporation of liquid and lead to damping of the interface oscillations, since a part of energy is spent for evaporation.

5. Conclusions
The obtained experimental data on the primary contact of cold water with a superheated surface indicate that a film-boiling crisis, characterized by the destruction of the vapor shell and boiling of the coolant, can be preceded by a short (several millisecond) thermohydrodynamic process associated with intense generation of waves at the vapor-liquid interface.

This process, observed at sample temperatures $T > 220^\circ$C, can lead to local "cooling down" of the hot melt surface to a temperature below the temperature of the superheat limit temperature of coolant.

This circumstance increases the probability of contact between hot metal and cold liquid accompanying with the explosive effervescence of the coolant and allows one to justify the application of an undeservedly forgotten cavitation-acoustic theory of crushing for reliably explanation of fine fragmentation of the highly superheated melt drops during spontaneous vapor explosion. The results of the wavelet analysis do not contradict the statement that periodic oscillations of the electrical resistance (current in the circuit) can be caused by waves of a new type [8, 9], related to the dependence of saturation pressure on temperatures at the phase boundary.

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