Investigation by electrocontact method of interaction of water with hot surface in film and transition boiling regimes

Y P Ivochkin¹, K G Kubrikov¹, O A Sinkevich² and Y A Zeigarnik¹

¹Joint Institute of High Temperature, RAS
Russia, 124412, Moscow, Izhorskaya, 13 Bd. 2
²National Research University ”Moscow Power Engineering Institute”
Russia, 111250 Moscow, Krasnokazarmennaya, 14

Abstract. Using the conductometric technique, the process of contact of subcooled distilled water with a hot surface was studied. The results of measurements of the parameters of the contact made in the range of the temperature change of the heated surface $170 \pm 620 \, ^\circ \text{C}$ are given. An experimental fact has been revealed, which indicates that a transition from film to bubble boiling is preceded by a short (several millisecond) hydrodynamic process that is characterized by intense interaction of waves at the vapour - liquid interface with the heated surface. With the help of wavelet analysis, the amplitude-frequency characteristics of this process are investigated and a qualitative physical model of its flow

1. Introduction

Among the thermophysical phenomena observed in nature and technology, steam explosions occupy a special place in their dangerous consequences. PV can be formed when the low-boiling coolant is in contact with the hot melt and is characterized by high-intensity pressure pulses, caused by a sharp increase in vaporization under conditions of explosive fragmentation of the hot liquid. Similar processes took place, for example, in severe accidents at nuclear power plants and in the smelting of metals [1].

To date, almost all stages of a steam explosion, including the stage of its initiation, associated with the fragmentation of a single drop under the abrupt transition from film to bubble boiling mode of the cooler have not been fully studied. In the literature, you can find several dozen different hypotheses on the mechanism of such a process of fragmentation, which, in our opinion, is indicative not only of the lack of study of the question, but also, with a high probability, the absence of a single universal mechanism of the phenomenon under study. It is especially difficult (in part, due to the lack of available experimental data) to give unconditional preference to any of the available theories of the process of fine melt fragmentation - an important and difficult to understand stage of the steam explosion. It can be assumed that for this purpose the cavitation-acoustic model of crushing [2], which is based on the generation of pressure pulses with the boiling of the coolant, may be most productive. In this context, we conducted additional experiments aimed at clarifying the mechanism of contact between the cooler and the surface of the heated body during the spontaneous destruction of the vapor shell. Below are descriptions of the methods and results of the experiments.
2. Experimental installation and method of measurements

The most complete reliable information on the mechanisms of fragmentation of the melt and its accompanying processes can be obtained by experiments in which a hot sample with a vapor shell is immobile relative to the observer. It is precisely under these conditions that experiments on installations, the description of which can be found in [3], have been carried out (mainly video shooting) on the fragmentation of drops. However, experiments conducted with drops of liquid metal are characterized by a weak reproducibility of the results obtained. This circumstance is mainly due to the degree of oxidation of the hot liquid metal surface that is difficult to control in experiments and which affects the value of its temperature and the wetting level in a determinative way [3]. This deficiency is largely deprived of samples made of solid metallic material, the surface state of which is subject to certain control. Such samples allow to obtain additional information on the mechanism of the steam explosion in the boiling regime with underheating, since it can be assumed that the primary contact of the coolant with liquid and solid superheated surfaces develops in a similar way.

A simplified diagram of the installation is shown in Fig. La. The experiments were carried out on a copper working section in the form of a cylindrical rod, with removable specimens with a hemispherical or flat end screwed into the end part of which. In the experiments we used samples with a diameter of 10 mm, made of stainless steel (grade X18H10T). The temperatures of the prototype and the cooling liquid, as well as the values of the heat flux, were determined from the indications of chromel-alumel type thermocouples made of insulated wires with a diameter of 0.2 mm.

To study the process of contact of water with a hot surface, a conductometric measurement procedure was used in which the contact parameters were determined from the change in the magnitude of the electric current flowing between two electrodes, one of which was a heated sample. The second electrode was a flat copper plate placed in water. A more detailed description of the conductometric technique used to measure the contact can be found in [3]. Previously, before the experiments, numerical and experimental estimates of the possible effect of displacement currents on the value of the output signal were made, the results of which indicate a small magnitude of such an effect.

![Figure 1](image1.png)

**Figure 1.** A simplified scheme of the experimental setup and basic measurements is (a). 1 - working sample; 2 - steam film; 3 - electrode in water, 4 - a vessel with water; 5 - power supply; 6 - standard resistance; 7 - ADC NI PXI-6070E; 8 - PC with built-in NI PXI-4275 multimeter card.

![Figure 2](image2.png)

**Figure 2.** A schematic electrical diagram of the method of measuring the integral contact area under a film boiling regime (Rut is the leakage resistance).
Two types of experiments were conducted to study the contact of water with an overheated surface. In one of them, the process of contact of water with a cooling hemisphere under the second boiling crisis was observed, which was observed on a heated surface in the temperature range $T_w$ 170-350 °C. The experiments were carried out in the following sequence. In the initial state, the working region with a hemispherical end face was heated in air or in an argon atmosphere. Then the electric heater was switched off, and the sample, together with the working area, was immersed in a bath filled with distilled water to a depth of the radius of the hemisphere with a special coordinate device at a speed of several millimeters per second. The dimensions of the rectangular bath made of plexiglass are 300 x 100 x 110 mm. The initial value of the temperature of the hemisphere varied in the range 300-700 °C and was chosen from the condition for obtaining a regime of deliberately stable film boiling on immersion in water. In the second type of experiments, the interaction of a superheated flat end surface of a cylindrical specimen with a free surface of cold water was studied during its slow (at a few millimeters per second) immersion in a liquid. In such experiments it was possible to ensure a condition in which the temperature of the working sample during the destruction of the vapor shell could exceed 600 °C. All the experiments were carried out at a temperature of cooling distilled water of 200 °C. The sampling rate in the experiments performed with the use of the measuring equipment of National Instruments was $5 \times 10^5$ measurements per second. When processing oscillograms of electric current pulsations, the Marlet wavelet was applied.

![Figure 3](image-url) **Figure 3.** Oscillogram of the relative value of electric current ripple before the moment of contact of water with a hot surface. $I_{\text{max}}$ – maximum value of electric current in the bubbling boiling mode. The sidebar shows the complete implementation of the signal. $T_w=266^\circ \text{C}$.

![Figure 4](image-url) **Figure 4.** Wavelet analysis of the signal (the region before the contact) in Figure 3. $T_w=266^\circ \text{C}$. 
3. Experimental results
The characteristic results of measuring the oscillograms of the electric current (in terms of the voltage drop at the reference resistance 10 (see Fig. 1)) under the conditions of different temperatures of the heated surface are shown in Figures 3, 5, and 7. It is seen from the graphs that the process preceding the contact of the cooler with hot surface, has, at least, several important features. First, in most cases, at a wall temperature $T_w > 230 \, ^\circ C$, an insignificant increase in the average value of the current flowing in the measuring circuit before direct contact is observed. As can be seen from the figures above, the lifetime of such a regime preceding the second boiling crisis ($T_w < 300 \, ^\circ C$) is slightly more than two milliseconds for the case $T_w = 266 \, ^\circ C$ and increases with the temperature of the hot surface. Secondly, this regime is characterized by a significant level of intensity of electric current pulsations, the amplitude and frequency of which increases with time.

![Figure 5. Oscillogram of the relative value of electric current ripple before the moment of contact of water with a hot surface. $I_{\text{max}}$ - maximum value of electric current in the bubbling boiling mode. The sidebar shows the complete implementation of the signal. $T_w=293^\circ C$.](image)

More detailed information on the nature of the detected oscillations can be obtained by means of a wavelet analysis of these pulsations (see Figures 4, 6 and 8). It can be seen from this graphical material that for pulsations obtained in the first type of experiments (surface temperature $T_w < 305 \, ^\circ C$) two periodic components can be distinguished. In particular, for the mode $T_w = 393 \, ^\circ C$, the frequency of one of them (low oscillation frequency) practically does not change with time and has a value of $\approx 12 \, kHz$. Another component of the pulsations is characterized by a steady growth in time of
this magnitude up to ~ 16 kHz. The intensity of both modes of oscillation increases with time and reaches the maximum values before the destruction of the vapor shell. Under conditions of high temperatures of the heated surface (Tw> 305 °C), a slightly different type of observed pulsations takes place, the specific feature of which is the presence of sharp periodic pulses of the signal, possibly connected with the formation of solitary waves-solitons at the vapor-liquid interface.

4. Discussion

Based on the results obtained, supplemented by wavelet analysis of the electric current oscillograms, the following qualitative physical model of the process of contact between the cooler and the heated surface can be assumed (see Figure 8). Under conditions of a thick vapor layer waves at the vapor-liquid interface (for example, capillary nature, which practically always take place) do not lead to any appreciable change in the value of the electric current flowing in the measuring system. As the working sample cools down, accompanied by thinning of the vapor shell, i.e. the approach of a liquid

![Figure 7. Wavelet analysis of the signal (the region before the contact) in Figure 5. Tw=620°C](image)

![Figure 8. Wavelet analysis of the signal (the region before the contact) in Figure 6. Tw=620°C](image)
sufficiently close to the hot wall, it becomes possible to boil water in the wave crests. Such an effect leads to an increase in the intensity of the oscillations and the propagation of local perturbations along the vapor layer. In addition, there is an introduction of liquid droplets into the volume of the vapor layer and, consequently, the transition of dry water vapor to a wet state. The latter circumstance causes a decrease in the electrical resistance of the vapor layer and an increase in the value of the electric current. At the same time, there is a process of decreasing the local temperature of the hot wall (this is confirmed by the results of [4], where in the Leidenfrost regime, the temperature of the hot plate surface was measured with a microthermocouple under the water drop located on it). These circumstances lead to direct contact of the hot wall with the cooler, its heating and subsequent explosive boiling.

Based on the described scheme, it can be assumed that additional important factors determining the process of contact, in addition to the oxide layer, are: the intensity of the disturbances at the vapor-liquid interface; Thickness of the vapor shell; the boiling point of the liquid, depending on the external pressure.

![Figure 9](image.png)

**Figure 9.** Dependence of the relative contact radius on time 1 - hot surface; 2 - steam; 3 - water. Explanation of the physical model of contact.

5. Conclusion
The literature analysis showed that the cavitation-acoustic model of melt fragmentation proposed in the early studies of the steam explosion, in our opinion, was undeservedly forgotten and can be used to describe the process of its fine fragmentation. The presented experimental data on the primary contact of cold water with an overheated surface during the transition from the film boiling to transition regime, obtained with the conductometric technique, do not contradict this statement. The results of the measurements indicate that the second-stage boiling crisis is preceded by a short (several millisecond) process characterized by intense interaction of waves at the interface of vapor-liquid phases with a heated surface. This process leads to a decrease in the temperature (cooling down) of the hot wall and direct contact of the cooler with the cooling surface. The latter circumstance makes it possible to apply the cavitation-acoustic theory of fragmentation of droplets to explain the fine fragmentation of a melt of highly heated droplets during a steam explosion.

**References**

[1] Berthoud G 2000 *Annu. Rev. Fluid Mech.* **32** 573-611.

[2] Kazimi M S and Autruffe M I 1978 *T. Am. Nucl. Soc.* **27** 321–322.

[3] Zhilin V G, Zeiharnik Y F, Ivochkin Y P, Oksman A A, Belov K I 2009 *High Temp.* **47** 856-863.

[4] Cokmez-Tuzla A F, Tuzla K, Chen J C 1993 *Nucl. Eng. Des.* **139** 97-103.

**Acknowledgments**
This work was supported by the Russian Foundation for Basic Research (Project No. 15-08-06145-a)