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NUCLEAR POWER PLANTS

Mechanisms Governing Fine Fragmentation of Hot Melt Immersed in Cold Water

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Abstract—Hypotheses about the mechanisms governing fragmentation of superheated liquid metal droplets falling into cold water are analyzed. It is shown that a physical model based on the cavitation–acoustic mechanism governing fine fragmentation of melt under steam explosion conditions is likely the most suitable one for consistently describing the fragmentation of both low-melting and refractory metals. For checking this conjecture, special experiments for studying the processes triggered when cold (20°C) water comes into contact with a heated surface and for measuring the pressure impulses (arising both in coolant and in the hot body) accompanying the coolant flashing were carried out using liquid metal (tin and steel) droplets and superheated solid steel bodies. The working substance temperatures were varied in the range from 200 to 1600°C. The results obtained from the performed experiments are not in contradiction with the melt fine fragmentation process represented by the cavitation–acoustic model. It is shown that the acoustic waves generated during explosive growth of bubbles on a hot surface propagate in the solid body and are alternating in nature. Their intensity (including that at negative pressure values) differs only slightly in the modulus from the pressure impulses measured in the coolant and is sufficient for finely fragmenting the droplets. It is experimentally found—with the use of a conductance measuring technique—that the transition from the coolant film to bubble boiling mode is preceded by a short-term (lasting a few milliseconds) process involving intense interaction of waves at the steam–liquid boundary with the heated surface. The signal from the conductance measuring transducer was subjected to a wavelet analysis for different values of the heated surface temperature. The study results testify that high-frequency (several tens of kilohertz) pulsations of electric current are generated in the preburnout region with their characteristics varying (toward increasing the amplitude and intensity) with time as the heating and heated media come closer into contact with each other. A probabilistic process development scenario is suggested.

Keywords: steam explosion, fragmentation, liquid metal, pressure impulse

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Vapor explosions occupy a special place among the thermal physics phenomena that are observed in nature and occur during operation of various technical devices in terms of dangerous consequences they may entail [1]. Such explosions may occur when a low-boiling coolant characterized by essential subcooling to the saturation temperature comes into contact with hot melt. These explosions entail very intense pressure impulses caused by drastically growing rates of coolant vaporization and pressure in the apparatus under the conditions of explosion-like fragmentation of hot liquid. Such phenomena were observed, e.g., during severe accidents at nuclear power plants (NPPs), in melting metals, during technological operations for boiling cellulose and liquefying gases, and also during eruption of underwater volcanoes [2, 3].

As far as the safety of NPPs and the metallurgical industry is concerned, the vapor explosion process is usually subdivided into the following four stages [1]. At the first stage, a hot corium jet premixes with the metal falling into a low-boiling coolant. In this stage, numerous melt droplets are generated. These droplets have characteristic sizes from a few to a few tens of millimeters and are surrounded by vapor films (cavities) of cooling liquid in the state of film boiling. At the second stage, vapor explosion is triggered. At the third stage, melt droplets are divided into fine fragments, entailing a drastic growth of the heat transfer surface area and intense generation of vapor. At the fourth stage, the generated vapor phase expands in an explosion-like manner into the surrounding space.

At present, all vapor explosion stages need a more in-depth study using both experimental and theoretical methods. In particular, there is still lack of a clear and fully consistent description of the processes causing fine fragmentation of hot droplets as the vapor shells surrounding them collapse (the second and third stages). In the literature, e.g., [1, 4–14], one can find a few tens of hypotheses describing this phenomenon, a circumstance that points, in all likelihood, not only to the fact that this problem has not yet been fully understood but also that there is no commonly shared idea about the mechanism of this phenomenon. It can be conjectured that there may be a few such mechanisms depending on the physical characteristics of a droplet and cold liquid surrounding it (the droplet substance, its wettability, the extent to which the liquid is saturated with gases, etc.), the operating conditions under which the hot and cold media interact with each other, and the apparatus geometry.

At present, a so-called hydrodynamic model [15–20], in which the melt fragmentation phenomenon is attributed to cold water jets of the surrounding liquid that occur as vapor shells are collapsing, has been elaborated to the fullest extent and dominates in the scientific literature [15–20]. These jets penetrate into a hot droplet and flash in it in an explosion-like manner, causing hot liquid to disintegrate into fragments. This theory reproduces the multistage avalanche-like fragmentation process; however, for this theory to be consistent with the experimental data, it is necessary to assume that the cold liquid comes into contact with hot droplets and the subsequent collapse of vapor bubbles entailing generation of liquid jets take place quite synchronously over the entire contacting surface. In our opinion, however, such synchronous behavior is unlikely. What is more, this hypothesis poorly explains numerous experimental facts evidencing to an essential effect the oxidation degree of heated surface has on the fragmentation of liquid metal droplets and some other effects.

Another line in which the fine fragmentation phenomenon is theoretically analyzed involves consideration of thermal stresses occurring in rapidly cooled melt droplets [21–27]. Supposedly, destruction of the vapor shell surrounding an individual droplet causes the coolant to come into intense contact with the hot surface, due to which the melt surface layer is quickly cooled and solidified. As a consequence, tensile mechanical stresses arise in this layer with the solid shell exerting strong uniform compression forces on the droplet liquid core. The above-mentioned processes initiate crack formation in the solidified surface layer and ejection of fragmenting jets of hot liquid into coolant. An essential drawback of this hypothesis is that it fails to describe the multistage avalanche-like mechanism through which the melt undergoes fine fragmentation: the conditions and details of the contact between the hot and cold liquids remain beyond the scope of this hypothesis. In addition, numerical assessments show that the time taken for a droplet to disintegrate according to the thermal–mechanical model may be as long as a few milliseconds, which is an order or two of magnitude more than the hot melt fine fragmentation times recorded in experiments.

Hypotheses attributing the melt droplet fragmentation phenomenon to an intense growth of gas bubble volumes in the droplet can also be found in the literature. The mechanisms through which such phenomenon occurs may differ from one another in their details. Thus, the authors of [28] suggested a hypothesis according to which a rapid growth in the number of gas bubbles and their total volume inside a hot liquid droplet may be due to drastic cooling of the melt when a fast transition from the film to bubble boiling mode takes place. The results of numerical assessments carried out for silver droplets containing dissolved oxygen confirm such a possibility. Another fragmentation model [29], which has much in common with the previous one, considers an external pressure impulse. This impulse gives rise to tensile mechanical stresses inside the droplet volume (thus causing the pressure in the liquid to decrease) as it propagates inside the melt and reflects from the droplet inner boundaries, and it is particularly these stresses that stimulate an explosion-like growth of gas bubble volumes and fragmentation of the droplet.

In [30, 31], a similar fragmentation mechanism is described; however, the suggested model does not assume the presence of dissolved gases in the melt. In brief, the basic idea of this so-called cavitation–acoustic fragmentation model is as follows. The flashing of coolant at the hot liquid metal droplet surface is accompanied by a growth and collapse of steam bubbles, due to which high-intense acoustic or shock waves are generated. These waves propagate, in particular, also in the droplet volume, and a sequence of rarefaction impulses emerges in the melt as these waves reflect from the droplet surface inside of it. The amplitude and duration of these negative pressure impulses may reach values sufficient for the occurrence of cavitation voids inside the hot coolant droplet and its fragmentation as these voids are collapsing. Dissolved gases in the droplet can intensify this process.

In [30], the parameters characterizing the acoustic pressure induced by a single external impulse with an amplitude of approximately 0.7 MPa and duration of 2 μs are numerically estimated. The results from these estimations testify that such external impact can give rise to alternating pressure pulsations at the droplet center with an amplitude of ±1.56 MPa and a frequency of 50 kHz that are sufficient to cause melt fragmentation. It should be noted that the most reliable and well-repeatable results of experiments on fragmenting melt droplets were obtained particularly under the conditions of the impact produced by an external pressure impulse with an amplitude of around 0.4 MPa or higher generated by explosion of a wire, diaphragm rupture, strong impingement of a droplet against the vessel body, etc. [32, 33]. The obtained data are described well enough using the cavitation–acoustic model of the hot droplet fragmentation phenomenon. These data also prompt one to search for phenomena spontaneously occurring in the system and phenomena causing a noticeable pressure impulse to occur in it. Collapse of the vapor shell surrounding the droplet is most frequently considered as the primary cause of this process. In this regard, a very interesting (from the methodical point of view) publication [33] should be pointed out, the authors of which used conventional photographing to observe the evolution of vapor film around a hot droplet (tin with $t \approx$ 1000°C) falling in water and used X-ray photographing to observe how the fragmentation of this liquid metal droplet develops.

The process was triggered by an external pressure impulse generated at the vessel bottom. It is interesting to note that the fragmentation of liquid metal droplet that took place under the conditions of its being triggered from outside was also preceded by advancing powerful generation of the vapor phase; that is, cold liquid came in intense thermal interaction with the droplet surface, and, only after that, fragmentation of the droplet itself was observed after some delay (a few hundred microseconds). It can be assumed that, if there is no external pressure impulse, the vapor shell disintegrates, and the cold liquid and hot droplet come into contact as a result of hydrodynamic effects spontaneously on individual droplets, thus giving rise, first, to an initial and then to an avalanche-like growing pressure impulse, which is external with respect to the other droplets participating in the process.

The possibility of melts being fragmented according to the cavitation–acoustic mechanism is also confirmed by the results of experimental [34] and numerical [35] investigations aimed at studying the fragmentation of single water droplets under the effect of an external pressure impulse. In particular, the authors of [35] determined, using a so-called smoothed particle hydrodynamics (SPH) numerical analysis method, that the focusing of a shock wave reflected from the droplet free surface results in the fact that a cavitation cluster emerges in the droplet center, the rapid expansion of which causes explosion-like fragmentation of the liquid.

Summarizing what was said above, we should point out that, for certain reasons, in particular, due to an insufficient body of available experimental data, it is now difficult to give absolute preference to any of the available theories explaining fine fragmentation of melt, which is an important and the most intricate stage of vapor explosion. In addition, one cannot exclude the possibility of combination of a few effects. In our opinion, the cavitation–acoustic model may turn out to be the most acceptable one. In this context, we carried out additional experiments aimed at clarifying the mechanism governing fragmentation of hot liquid metal droplets. In so doing, we studied details of the following processes: the occurrence of alternating pressure pulsations in a hot droplet or in a solid metal body modeling this droplet, spontaneous occurrence of an initial pressure impulse with a sufficiently high amplitude in the considered system, and the coolant coming into contact with the heated body surface after destruction of the vapor shell as a possible source of this initial impulse.

EXPERIMENTAL SETUPS AND MEASUREMENT PROCEDURES

The most comprehensive and repeatable information about melt fragmentation and accompanying processes can be obtained with the use of experiments in which a hot sample surrounded by a vapor shell is immobile with respect to the observer. It is namely under similar conditions that the additional experiments on droplet fragmentation were carried out (mainly by means of video recording) at the setups whose detailed description can be found in [36]. Experiments carried out with liquid metal droplets yield poorly repeatable results, which is mainly because the hot liquid metal surface oxidation process that has an effect on the surface temperature state in unsteady (transient) modes and on its wetting conditions [36], is poorly amenable to monitoring during the experiments. Samples made of solid metallic material, the surface state of which is amenable to certain monitoring (with the properly selected sample material and experiment conducting procedure), are essentially free from this drawback. By carrying out experiments under such conditions, it becomes possible to obtain additional information about the vapor explosion generation mechanism in the subcooled water transient boiling mode. Here, it can be assumed that the processes associated with the coolant coming into initial contact with liquid and solid superheated samples develop in an almost identical manner.

The simplified schematic diagram of the experimental setup in which solid-state metallic elements are used as test samples is shown in Fig. 1.

The experiments on studying pressure impulses in liquid and the process through which a superheated surface comes into contact with coolant were carried out on the copper test section (Fig. 2) having the shape of a cylindrical rod. Replaceable samples with thermally insulated lateral surfaces and with a noninsulated semispherical end immersed in water were screwed into the rod end-face part. Samples 10 mm in diameter made of Grade Kh18N10T stainless steel were used in the majority of experiments. The pressure in the liquid was measured using a PCB-type piezoelectric sensor (the HSM 113A28 model), which was placed in a bath at the semispherical end face axis at a distance of 5 mm from its lower end.

The experimental sample and cooling liquid temperatures and also the estimated heat flux values were determined from the readings of Chromel–Alumel thermocouples made of insulated wires 0.2 mm in diameter. Thermocouple wires were placed in capillaries made in the form of sleeves with an outer diam-

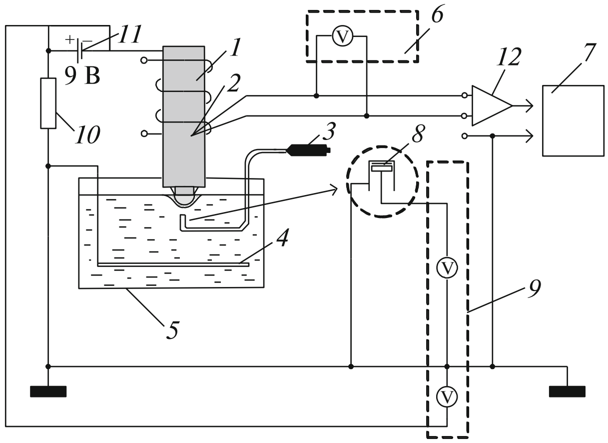

Fig. 1. Experimental setup with a solid-state test section and the general scheme of main measurements. *1*—Test sample with a heater; *2*—thermocouples; *3*—pressure sensor arranged in water along the test section axis at a distance of 5 mm from the test section lower end face; *4*—electrode immersed in water; *5*—vessel with water; *6*—type NI PXI-4275 multimeter; *7*—type NI PXI-6070E analog-to-digital converter; *8*—pressure sensor sensing element; *9*—type NI PXI-5122 oscillograph; *10*—reference resistor; *11*—power supply; and *12*—thermocouple signal amplifier.

eter of 0.7 mm, which were tightly embedded (using mechanical techniques) into radial holes drilled in the sample and in the copper segment (see Fig. 2). The thermocouple beads welded from inside to the capillary end-face surface were arranged at the test section axis. The time constants of the used thermocouples estimated according the experimental procedure set out in [37] did not exceed 100 ms.

The heat flux was determined in the stable film boiling mode (with a cooling rate of around 0.3 K/s) according to the Fourier law based on the readings from thermocouples nos. 5 and 6 installed in the sample cylindrical part (see Fig. 2). The amount of heat transferred to the surrounding medium from the cooling semispherical part of the sample was estimated numerically; its value did not exceed 5% of the entire heat flux removed from the test section's lower end face surface. The heat flux density varied from its maximal value equal to around 8×10^4 W/m^2 at the cooling initial stage to approximately 7×10^4 W/m^2 at the moment before the steam film went off.

The characteristic sample cooling time τ from the moment it is immersed into coolant to the moment at which transition to the bubble boiling mode occurs depends on the semispherical end face initial temperature t_{ss}. For t_{ss} = 450°C with the initial water temperature equal to 20°C, the time $\tau \approx 300$ s. The temperature signals were measured using the following instruments: a multichannel thermocouple signal amplifier developed by the authors (with an amplification factor of up to 1000 and with the frequency ranges 0–120 kHz and

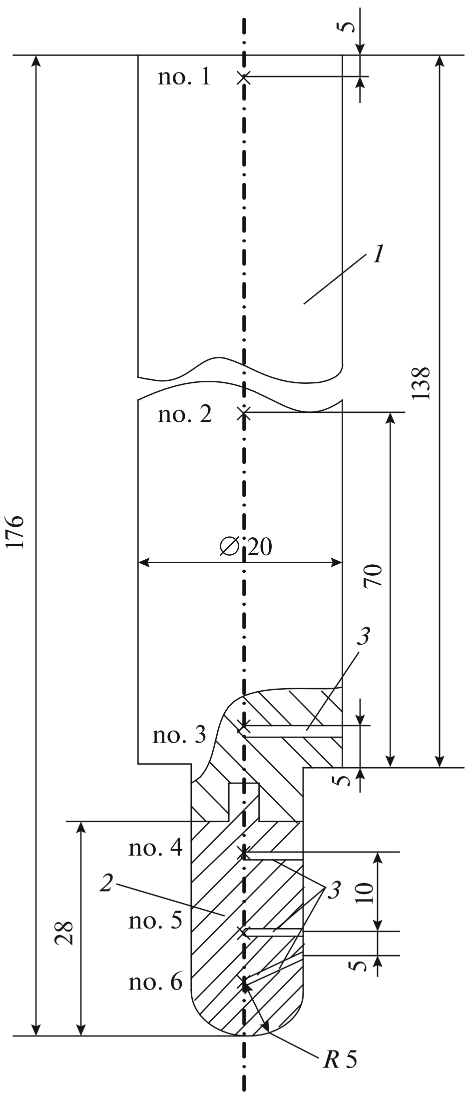

Fig. 2. Test section with a solid-state tip (heat insulation is not shown in the drawing). *1*—Copper unit; *2*—interchangeable cylindrical sample with a semispherical end; *3*—six thermocouple holes 0.75 mm in diameter. The crosses indicate the thermocouple installation places.

0–350 Hz with and without using a fourth order Butterworth filter) and the secondary measurement devices produced by the National Instrument company, which allows the signals to be digitized at a rate of 10^7 measurements per second.

The test section having the shape of a dripping droplet made of nickel (Fig. 3) was used in special experiments while simultaneously measuring the pressure impulses in the liquid and in solid body. Pressure impulses in a solid body were measured with a Kistler sensor (model 601), which was installed in the upper cooled end-face part of the test section (see Fig. 3).

In their major part, the experiments were carried out according to the following procedure. In its initial state, the test section with the solid end-face surface

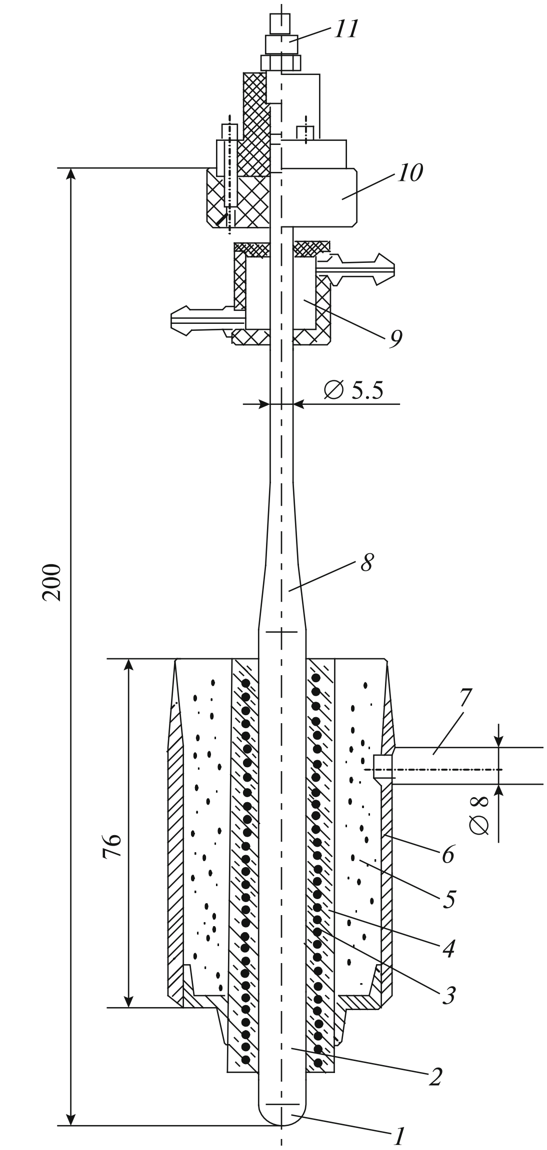

Fig. 3. Test section: a waveguide made in the form of a dripping droplet. *1*—Semispherical tip; *2*—cylindrical body; *3*—heater; *4*—electric insulator; *5*—heat insulator; *6*—casing; *7*—holder; *8*—waveguide; *9*—cooling system; *10*—pressure sensor attachment device; and *11*—pressure sensor.

having a semispherical shape was heated in air or in argon atmosphere. After that, the electric heater was disconnected, and the sample together with the test section was immersed, by means of a special coordinate device, with a velocity of a few millimeters per second into a bath filled with distilled water to the depth equal to the semisphere radius. During the experiments, the steam shell destruction process was recorded by a video camera with simultaneously measuring the parameters of pressure impulses and the electric contact between water and the heated body surface. The rectangular bath made of organic glass was 300 × 100 × 110 mm. The initial semispherical end face temperature was varied in the range 300–700°C and was selected from the condition of setting up a fortiori stable film boiling mode at its surface being immersed into water. All of the presented experiments were carried out with the cooling distilled water temperature equal to 20°C.

EXPERIMENTAL INVESTIGATIONS INTO FRAGMENTATION OF LIQUID METAL DROPLETS AND AN ANALYSIS OF THE RESULTS

To obtain additional useful qualitative information, the experiments on solid metal surfaces were combined with experiments carried out with heated liquid metal droplets of different metals. These experiments are described in detail in [36]. The results of the performed experiments on fragmentation of liquid metal droplets are described in a fairly good manner according to the cavitation–acoustic mechanism. It has been positively determined that oxidation of the liquid metal surface has a determining effect on the fragmentation process [36]. Oxidized surfaces with the oxide film thickness equal to approximately 1 μm or more always see a smooth (nonexplosive) transition from the film to bubble boiling mode without melt fragmentation. Explosive destruction of the steam shell accompanied by finely dispersed fragmentation of the droplet (Fig. 4a) or by the formation of a porous structure (Fig. 4d) occurred on a fresh liquid metal surface that was generated immediately after the liquid metal (tin) melt was extruded from a capillary into the environment. Fragmentation of such a sort is typical for the heated tin temperature range 400–700°C. At higher temperatures, no fragmentation was observed in the experiments—in all likelihood, because a thick layer of oxides appeared on the droplet surface in the course of its rather long (for a few minutes) cooling. It should be emphasized that the liquid droplet fragmentation process is statistical in nature. Fragmentation is observed by no means in every experiment.

With water coming into contact with tin having a temperature below 400°C, a bubble boiling mode was always observed on the melt surface, which hindered generation of high intense pressure impulses. Under such conditions, the disintegrated droplet fragments had quite large sizes commensurable with the sizes of the initial droplet and took odd shapes of "hedgehogs" (Fig. 4b) or hollow fragments (Fig. 4c). It can be conjectured that this type of droplet fragmentation is due to the thermal–mechanical stresses described at the beginning of the article, which result from fast hardening of the droplet accompanied by compressing its liquid metal core. Such mechanical stresses occurring when the entire droplet surface hardens may give rise to cracks in the hardened layer, and melt can relatively slowly flow out from them into the surrounding coolant. Under certain conditions, in which only part of

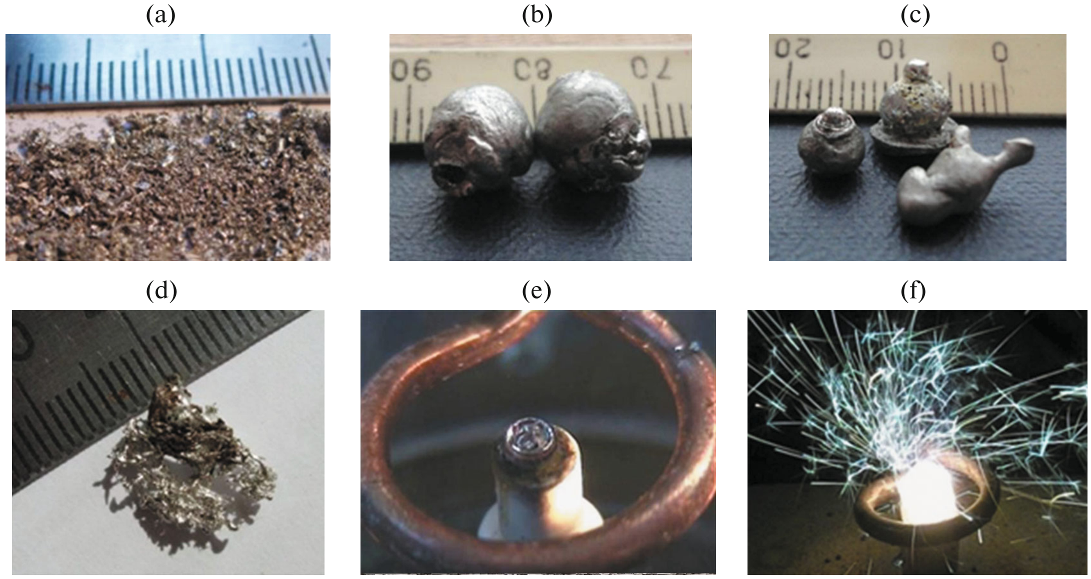

Fig. 4. Photographs of droplet fragments. Rule small division value is 1 mm. Tin droplet: (a) Fine fragmentation, (b, e) hollow fragments, (c) hardened jets, (d) porous structure, and (f) ball bearing steel droplet burning in air (1600°C).

the droplet surface hardens, a jet may be ejected due to an abrupt compression of the shell. In this case, the velocity of liquid metal jets ejected from the droplet may reach quite high values (up to 4 m/s), and the fragmented parts may have the shape of a crater (Fig. 4e).

It has also been found that the droplet heating processes in air differ considerably from those in the inert atmosphere of argon. In particular, intense droplet erosion of liquid metal (in the form of liquid metal droplets appearing as sparks escaping from the heated body surface as shown in Fig. 4f) is observed in the course of melting steel samples in air. With this phenomenon, the development of film boiling mode on the hot droplet surface is ruled out, thus preventing steam explosion to occur.

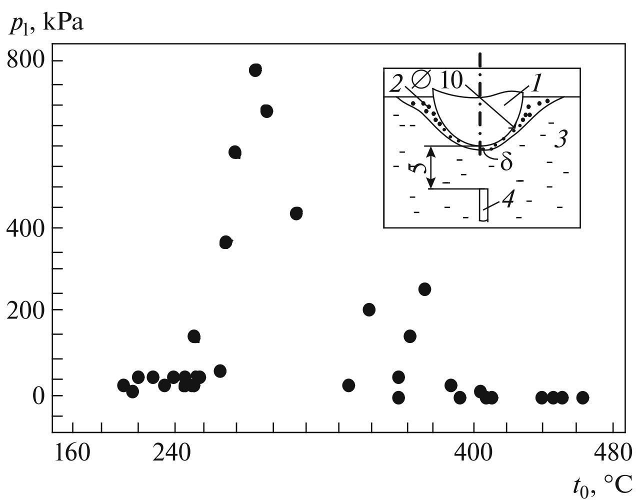

Fig. 5. Maximal amplitude of pressure impulses in liquid p_l as a function of temperature t_0 at the center of a semisphere with a radius of 5 mm. *1*—Heated semisphere; *2*—steam interlayer; *3*—water (t = 20°C); *4*—pressure sensor; δ—steam film thickness in the semisphere lower part (the value of δ before the steam film destruction is a few tens of micrometers and its value is 200 μm at $t_0 \approx 500$°C).

EXPERIMENTS WITH SUPERHEATED SOLID SURFACES

To check the conjecture according to which a melt can undergo fine fragmentation under the effect of the cavitation–acoustic mechanism, we carried out special tests on measuring the characteristics of pressure impulses developing in water and in a solid heated body modeling a hot droplet as well as tests on studying the local parameters characterizing water coming into contact with a superheated surface (Figs. 5, 6).

It can be seen from Fig. 5 that the maximal pressure impulses generated in the cooling liquid arise spontaneously at semisphere temperatures somewhat below the ultimate water superheating temperature (around 300°C at atmospheric pressure). The intensity of such impulses is approximately equal to 1 MPa (the level characteristic for external triggering), and their duration is around 10 μs. According to [32], a pressure impulse having such parameters is able to cause fragmentation of an iron oxide droplet; i.e., it can initiate steam explosion. At the same time, the results of our experiments indicate that the steam film is stable with relatively high temperatures of a sample, and the piezoelectric sensor does not record pressure impulses with values sufficient to cause fragmentation according to the cavitation–acoustic mechanism.

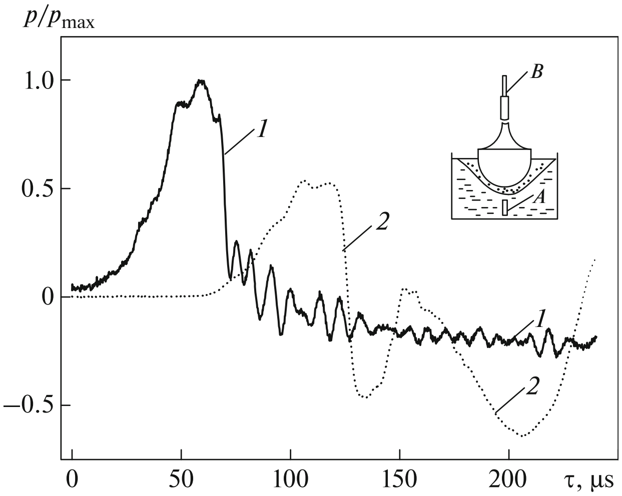

Fig. 6. Oscillograms of pressure pulsations during simultaneous measurements in water (sensor *A*) and at the remote (cold) end face of the droplet-shaped heated sample (sensor *B*); $p_{max} \approx 1$ MPa. The sample temperature at the initial moment ($\tau = 0$) is $t \approx 270$°C. *1*—Sensor *A*; *2*—sensor *B*.

The obvious discrepancy between the described experiments carried out on the modeling solid semisphere and the integral experiments on fragmentation of metal droplets can be removed by carrying out additional experiments. It is not excluded that the cavitation model itself of the fragmentation phenomenon needs certain additions, refinement, and further sophistication. This is important for describing the fragmentation of droplets of not only liquid metals with high melting temperature (copper, steel, etc.) but also of pure tin, metal that is able to produce, with a sufficiently high probability, fragments at lower temperatures, as was pointed out above.

The growth and collapse of steam bubbles cannot give rise to intense pressure impulses under the conditions of such high heated surface temperature.

Synchronous measurements carried out by means of two pressure sensors (see Fig. 6) were expected to confirm that a pulsing pressure initiated by the pressure impulse in the liquid existed in the solid body modeling a hot droplet. The obtained results speak in favor of the cavitation–acoustic theory and confirm that intense pressure pulsations are observed in the solid sample like in water, which are caused by an abrupt change in the steam interlayer volume as a result of coolant coming into contact with the hot surface with its subsequent flashing. The acoustic waves generated in the solid body are alternating, and their intensity (also in case of their negative values) are only slightly different in modulus from the pressure impulse intensity measured in the coolant. The duration of these negative impulses makes several tens of microseconds, which, according to [30], is sufficient to initiate fine fragmentation of a droplet according to the cavitation–acoustic mechanism.

For correctly constructing the cavitation–acoustic model for liquid metal droplets with a high melting temperature, experimental data on the hot and cold media coming into initial contact with each other are necessary. There are two ways in which such contact can take place: (i) when the media come into direct short-term contact followed by explosion-like boiling of cold liquid and (ii) when the hot surface is locally cooled (through a thin steam gap) by closely approaching waves of cold liquid, the amplitude of which is commensurable with the steam film thickness. We carried out additional experiments on measuring the initial contact.

A conduction-measuring procedure was used in the experiments (see Fig. 1a). A copper cylindrical sample with a flat end-face surface 10 mm in diameter heated to 600°C or higher was descended into water at room temperature with a velocity of 2 mm/s. The experiment procedure and the corresponding check calibrations are described in detail in [36]. The experiment results are shown in Fig. 7. A drastic (within a few tens of microseconds) change of current through the reference resistor indicated the onset of direct contact between the liquid and the sample. A spike of pressure in the liquid was recorded with a delay of a few tens of milliseconds with respect to the contact onset moment.

Figures 8a and 8c show the oscillograms of electric current flowing through the reference resistor at the temperatures in the semispherical sample center equal to 265–300°C. It can be seen from the presented graphs that the process preceding the moment at which the coolant comes into contact with the hot surface has two specific features in this temperature range. The first one is that the measured electric signal shows an insignificant growth (equal to approximately 5% of the maximal value) before the media come into direct contact with each other, during which the electric current shows a drastic growth. Such mode precedes the steam film collapse and lasts a few milliseconds. The second specific feature is that the electric current contains pulsations. It should be pointed out that the above-mentioned specific features in the electric signal behavior are not observed if the sample temperature is below 170°C, and the liquid comes into direct contact with the hot surface immediately without any preliminary oscillatory processes.

Additional information about the revealed electric current pulsations was obtained using the Morlet wavelet analysis method [39]. The corresponding spectra are shown in Figs. 8b, 8d, and 8f. It can be seen that the pulsations obtained with the sample temperatures equal to 266 and 293°C contain, along with relatively low-frequency components (a few kilohertz) (Figs. 8a, 8c), two high-frequency periodic components (see Figs. 8b, 8d). In particular, for the mode with a temperature of 293°C, one of the components has a frequency that remains almost unchanged with time and is approximately equal to 12 kHz. The second

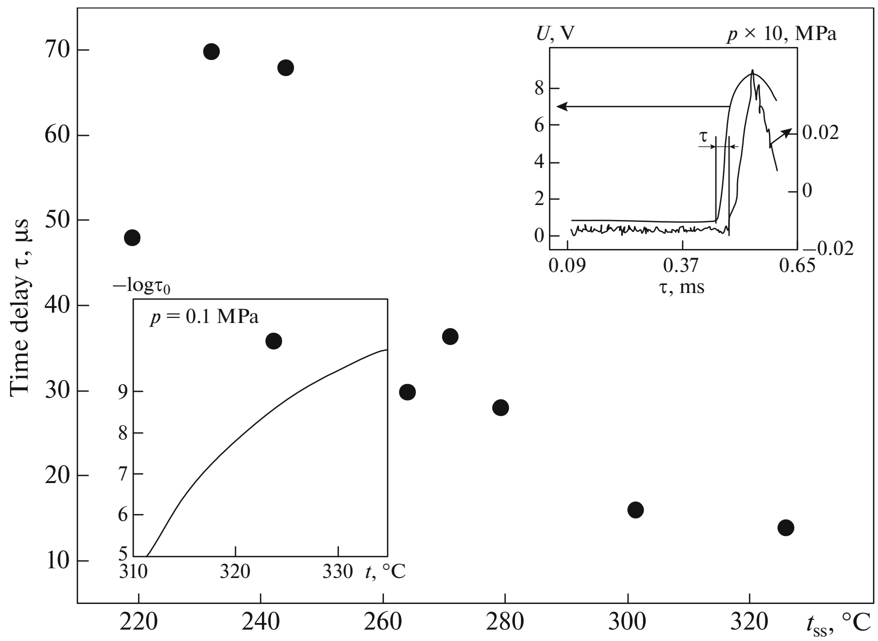

Fig. 7. Cold water heating time (the initial water temperature is 20°C) before its flashing as it comes into contact with the hot surface versus the semisphere temperature. The graph's lower left corner contains the calculated data from [38], in which the ordinate axis is the heating time logarithm (the time delay before flashing). The graph shown in the right upper corner explains the procedure (described in [36]) for determining the delay time based on the readings obtained from the pressure sensors and contact electric resistance sensors (a conductometric sensor for measuring the contact parameters).

pulsation component shows a stable increase of its frequency with time to approximately 16 kHz. The intensity of both these kinds of pulsations grows with time and reaches the maximal values before the steam shell is destructed.

The process observed in the experiments with the semispherical test section heated to very high temperatures shows a somewhat different behavior (Figs. 8e, 8f). In particular, sharp periodic impulses with a period of 250 μs in the signal are observed, which are possibly related to the occurrence of soliton waves at the steam–liquid interface boundary.

The obtained results allow us to suggest the following qualitative scheme of the process through which a coolant comes into contact with a heated surface.

If there is a thick steam layer, the waves occurring at the steam–liquid interface boundary (e.g., waves of a capillary nature, which are observed almost in all cases) do not generally cause any noticeable change in the film thickness and, consequently, in the value of electric current flowing through the measurement circuit in the experiments on studying how the media come into contact with each other. As the sample cools down, which is accompanied by the steam shell becoming thinner (i.e., as the liquid approaches the hot wall quite closely), it becomes possible that water can boil either in the wave crests or after they come into short-term contact with the heated surface. According to the theoretical assessments presented in [38], which are confirmed to a certain degree by the experimental results presented in [36], the time for which cold (20°C) water comes into contact at atmospheric pressure with a hot wall heated to a temperature of 310–330°C is in the range 10^{-5}–10^{-10} s. In both cases, such effects entail a growth in the intensity of film surface oscillations and propagation of local disturbances along the steam shell. Along with this, a decrease in the hot wall local temperature is observed (this statement is confirmed by the results of study [40], in which the hot plate surface temperature was measured—by means of a microthermocouple—under the water droplet lying on it). Owing to the combined effect of these circumstances, the hot wall remains in relatively long contact with the coolant, as a result of which the latter is heated with subsequent explosion-like boiling, due to which pressure impulses having different amplitudes are stochastically generated in the liquid.

Besides an oxide layer and the size of hot droplets, the intensity of disturbances at the steam–liquid phase interface boundary, steam shell thickness, and liquid boiling temperature are the additional important factors governing the process through which hot and cold liquids come into contact with each other and determining the possibility of droplets to undergo fine fragmentation according to the cavitation–acoustic mechanism.

Thus, the obtained experimental data confirm that pressure impulses with an amplitude of up to 1 MPa can be generated within a certain range of temperatures in a melt droplet as a result of its coming into

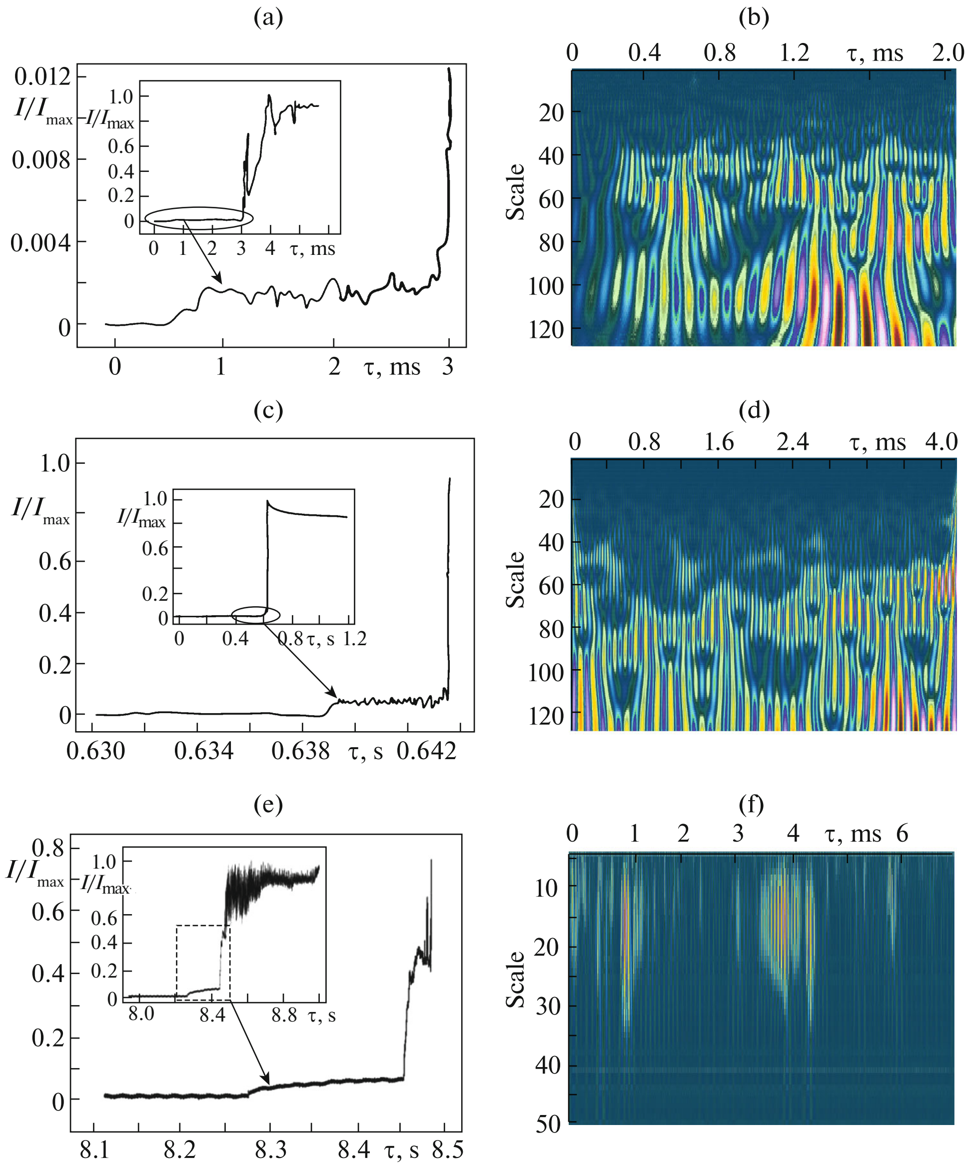

Fig. 8. Oscillograms of the (a, c, e) relative value of electric current pulsations through the reference resistor before the moment at which the steam shell on the semisphere made of stainless steel disintegrates and the (b, d, f) signal wavelet image (the region before the contact). Sample temperature, °C: (a, b) 266; (c, d) 293, and (e, f) 620; the moment $\tau = 0$ in Figs. 8b, 8d, and 8f corresponds to the values $\tau = 0.9$ ms, 0.6395 s, and 8.448 s in Figs. 8a, 8c, and 8e.

contact with cold liquid and that cavitation–acoustic effects causing the droplet to be disintegrated into fine fragments can develop in the droplet volume. These phenomena, which occur spontaneously in the hot droplets–cold liquid system, are similar to those during a steam explosion externally triggered by an applied pressure impulse of approximately the same amplitude. The main difference is that the external impulse synchronously affects the entire mass of hot droplets, thus resulting in close to 100% probability of the fine fragmentation phenomenon to occur, whereas the naturally triggered processes are to a certain degree random in nature. It should be noted that the probability of spontaneous triggering decreases with increasing the hot droplet temperature but still remains different from zero. The synchronized powerful external acoustic impact is replaced by the avalanche-like growing totality of low-power individual pressure impulses. The probability of such cumulative effect to occur is not only essentially less than 100% but also depends on many parameters of the system, and attempts to duly predict and model them in an experiment have hitherto not been met with success.

CONCLUSIONS

(1) The performed analysis of published data has shown that, at present, there are more than a dozen

various physical hypotheses in regard to the fragmentation phenomenon. However, none of them is able to fully explain the available experimental data. The fragmentation models that have been elaborated in the greatest detail and dominate in the scientific literature are based on the assumptions according to which a droplet undergoes dispersion either as a result of cooling medium jets penetrating into the droplet and subsequently boiling in it in an explosion manner (the penetrating jet theory) or as a result of the hot droplet surface layer being drastically cooled (the thermal–mechanical destruction model). In our opinion, the cavitation–acoustic model describing fine fragmentation of a melt that was proposed in early works on studying the steam explosion phenomenon has been unduly forgotten; moreover, it is particularly this model with which this intricate process can be described in the most consistent manner.

(2) The results obtained from additional investigations of pressure impulses generated in the course of destructing the steam shells near superheated surfaces confirm that the melts of low-melting materials (with the melting temperature lower than 250°C) may undergo spontaneous disintegration into fine fragments according to the cavitation–acoustic mechanism. For superheated samples having a high melting temperature, this process can also be observed but with a certain degree of probability. The process may take place both under the effect of intense external hydrodynamic disturbances (e.g., acoustic waves generated when a liquid metal jet impinges against the reservoir bottom during real steam explosions) and according to a scenario involving pressure impulses cumulatively generated in the totality of droplets after the hot and cold liquids come into contact developing in an avalanche-like manner.

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