Study of the features of behaviour of overheated liquid-metal drops in gas media, water and electromagnetic field of the inductor

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Abstract. A modern experimental setup designed for the melting of liquid-metal samples by the eddy current is described. A new experimental material about the behaviour of drops of the melts in gas atmospheres (argon, air) and distilled water of room temperature is obtained. It was confirmed that during the heating of a steel drop, that is the main component of corium in case of crashes at the nuclear power plants, in air an intensive spark generation of metal (drop erosion) are observed. The latter prevents the occurrence of the film boiling regime of the coolant and contributes to the prevention of explosive fragmentation of the melt. It is shown that in an inert argon atmosphere such regime does not take place but there is another physical effect that requires additional study and which is behind the ejection of the streams (or departure of drops) of liquid metal from its surface into the surrounding space. The relation between was determined the frequency of departure of coolant (distilled water) vapour bubbles and external pressure and temperature of the heated ball. It was stated that the regime of film boiling with the departure of vapor bubbles is observed only at temperatures over 350 °C. A figure with the changing form of the inter-phase vapor-liquid surface depending on the temperature of the heated body was obtained.

1. Introduction
The investigation of the behavior of the hot liquid-metal drops that are laying at a surface or are levitating in an electro-magnetic field is important for many areas of modern technology including the design of new materials and modern cooling systems [1, 2]. Besides that, such investigations make it possible to study in a more detailed way the mechanisms of many wide-spread but still sufficiently studied physical processes that take place during the contact of heated bodies and hot drops with different coaling media, for example during the vapor explosion [3,4]. Most of the experiments regarding the mechanisms of vapor explosions including the first stage of its initiation were conducted for the situation when the melted metal or heated bodies are falling in a cold liquid (water) [5]. Such approach, when the hot samples are moving with the respect to the measurement systems is not perfect and does not allow to monitor a lot of important parameters including the temperature of the working models. Contactless induction heating makes it possible to relatively simply overcome these experimental difficulties without using additional devices (different handles) that distort the experimental conditions [6]. The
goal of the presented investigation is to study the specific behavior of heated (up to 1600 °C and higher) balls and liquid-metal drops in water, air and argon. The experiments were conducted using a modern method with a specially designed setup that includes the induction heater. The short description of the experimental setup and method is presented below.

2. Experimental installation and method of measurements
The experiments were conducted at a specially constructed setup with the induction heating (Figure 1). The solid samples produced from different metals (tin, zinc, copper, steel, melt of nickel and Lanthanum NiLa5) were put into gaseous environment (air, argon) and were heated in a levitation or semi-levitation (sample lies at a non-electroconducting high temperature substrate) regimes of the inductor. Then in case of the levitating drop the melt was falling in a cuvette filled with distilled water of room temperature. In other experiments the heated balls and drops that lied on the substrate surface were immersed in a cooling media by step-wise increase of water level in the working chamber. During the experiments the temperature of the melting sample was controlled. Also the video recording of the sample behavior in the processes of induction heating and fragmentation was performed.

The power supply of the inductor included an inverter. Construction of the inverter was improved with additional devices of phase auto-tuning system and high speed protection of the power transistors from the current excess. A special pulsed regulator allowed controlling the power of the inverter via personal computer. Such changes ensured a stable operation of the inductor with the current frequency of power supply of 250 kHz and investigating the melting process of different metal (tin, zinc, aluminum, nickel, and stainless steel) samples heated in laboratory conditions to temperatures above 1600 °C.

3. Experimental results and discussion
The results of the experiments conducted with the usage of video recording in air environment are shown at Figure 2 and Figure 3a. It was confirmed that during the steel drop heating in such conditions an intensive generation of sparks (drop erosion) takes place. During the dispersion of the initial drops (characteristic speed of the dispersion is about several m/s) some of them can be intensively fragmented to finer fragments in an explosive way (Fig 2 e, f). If the fragmentation takes place but is not intensive enough, then this process can only lead to a distortion of the particle movement trajectory. In this case, the angle of turn of the particle can reach 90 degrees (Fig. 2c). The particles generated during the initial dispersion from the heated surface have the form of balls with a characteristic size of 1 mm.

At the Figure 3a there is a plot of the relative change in time of the drop area (full face) shown at Figure 2 during its intensive heating and spark generation. The area of the full-face surface was determined with the computer video processing (frame frequency 25 f/s) using a self-designed software.
and freely available software product IpSquare that is intended for the calculation of the flat figure surface.

As it can be seen from the graph at Figure 3a, during the processing of the experimental data, a rather unexpected result was obtained – indication of the linear increase of the melted sample area during the heating process despite the drop erosion of metal. It should be mentioned that the graph was plotted using a limited number of experimental points (14) and only demonstrates the average tendency of the process development. It can be supposed that with the increase of the video recording speed and taking into account all video material this tendency will remain and the final experimental curve will have pulsed shape.

The increase of the area and the volume of the drop hardly can be explained by the inaccuracy resulted from the loss of axis symmetry of the sample during the melting. The problem requires further study. It looks like that the observed effect is connected to the generation of the porous structure in the sample volume initiated by the gas emission during melting and burning of steel. It should be noted that the process of the drop erosion of metal is observed in several technological processes, for example during the electric welding. A distinctive feature of our experiments is a possibility to model sophisticated physical processes related, for example, to explosive fragmentation of moving bodies like meteors in quite an easy way. The mechanisms of this phenomena have not been studied fully enough and the theories described in the literature are debatable.

![Figure 2. Photographs of melting a metal sample (ball bearing steel) in air.](image)

(a) – the last frame in the absence of sparking (time \( t = 0 \)); (b) – 3 s; (c) – 12 s; (d) – 22 s; (e) – 15 s; (f) – 17 s. Inductor diameter 20 mm; the characteristic value of the current in the inductor \( I \approx 400 \) A; temperature of the drop \( T \approx 1500 \) °C (photographs a, b, c, e, f); \( T \approx 1450 \) °C (photograph c).

Initial diameter of sample (ball) 10 mm.

![Figure 3.](image)

(a) — the relative change in the full-face area \( S \) of a liquid-metal droplet in the process of its dropping erosion, \( S_0 \) is the area at time \( t = 0 \); (b) – photographs of fragments formed from metallic splashes. The drop material - ball bearing steel.

Temperature of the drop \( T \approx 1450 – 1500 \) °C

The results of the experiments carried out by heating samples in argon show the absence of the intensive drop erosion regime. Under high-frequency electro-magnetic field a drop deformation (stretch)
and its intensive volume vibrations were observed. In the regime of steel drop cooling in argon when the inductor is turned off an uncommon physical effect related to liquid streams (or separate drops) ejection from the surface of the overheated drop into ambient environment was discovered (Figure 4). The following temporal pattern of the process takes place. Just after turning off the electrical current in the inductor ($t=0$ at Fig. 4) the steel liquid sample shapes into a form of a spherical drop and remains in this configuration for one or two seconds. Then with the cooling of frequent sample at the drop surface and obviously in its volume a melt flow arises that deforms the drop shape. This deformation is followed by an ejection of liquid jets and drops of small size. The physical nature of the observed phenomenon is not quite clear and requires additional investigations. It is just possible to suggest that the found phenomenon is related to different gases which are dissolved in the melt and are emitted during its cooling. It is known that the solubility of gases in liquid metals decreases with the temperature decrease.

![Figure 4. Photos of a steel sample melted in argon. Below the photos there is a time interval from the time $t = 0$, corresponding to switching off the inductor.](image)

Experiments regarding the behavior of overheated bodies in water with temperature lower than the boiling temperature (subcooling-80°C) were conducted with metal balls (steel type SHCH15, 96CH18, diameter 5-10 mm) heated up to 1400°C as well as with liquid metal drops of the same material. The results of the study of the liquid-vapor border form during heating and cooling of the studied sample in water have shown that it is possible to distinguish three regimes of behavior of the liquid shell. The first regime that is observed at temperatures above 350°C is marked by the separation of bubbles from the
upper part of the sample. It is possible to imagine the following simplified scheme of the process which is presented in Figure 5 ($t = 0 – 0.12$). For relatively high temperatures of the ball an intensive vaporization over the whole vapor-liquid phase boarder takes place. The generated vapor moves to the upper part of vapor cavity where it is accumulated and partially condensed. The bubble separation takes place at the same value of the separation diameter $d \approx 3.3$ mm. The regime of the second type takes place without separation of vapor bubbles but with low-frequency vibrations of the vapor shell. Such vibrations are caused by the waves originated by the bubble separation process as well as by the rising movement of vapor in the vapor shell. In the third regime (Figure 6 ($t=0, 0.24, 2.6$ s)) the vapor layer is motionless and its thickness is almost constant. This regime is stable to the disturbances and can exist for a long time up to the destruction of the vapor shell (second crisis of boiling). The explosive destruction of the vapor cavity is followed by a dramatic detachment bubble (Figure 6, $t=2.64$ s) that leads in case of the steel drop to the formation of a through hole in it (Figure 6a) and to the ejection of liquid fragments of spherical form into the cooling media (Figure 3b). At the surface of all balls semi-spherical caverns were observed. A possible formation mechanism of such cavities related to the shrinkage of the material of the particles during its cooling is described in [5, 6]. The obtained data also confirm (Figure 6, $t=2.76$ s) the existence of the “golf boiling” regime after the explosive vapor shell destruction described in [3].

![Figure 5](image5.png)

**Figure 5.** Photographs of the oscillations of the vapor shell near a heated ball during the departure of the vapor bubble. Temperature of the ball $T=1000$ °C.

![Figure 6](image6.png)

**Figure 6.** (a) – Photographs of the vapor film in the absence departure of bubble ($t=0–0.2.6$ sec, stable (no oscillation) vapor film) and at its explosive destruction ($t=2.64–3.0$ sec); (b) – a photograph of a stiffened steel droplet after the vapor film has disappeared. Temperature of the ball at $t=0$ $T=350$ °C.

![Figure 7](image7.png)

**Figure 7.** The dependence of the separation frequency on:
(a) – sample temperature;
(b) – external pressure.

The temperature of the heated surface almost does not influence the values of thickness of the vapor film and the separation diameter of the vapor forms ($D_0 \approx 3.3$ mm). However, as it is seen from Figure
7a, it considerably affects the vapor separation frequency. The frequency of bubble detachment was determined by analyzing video frames in the conditions of constant temperature of the heated sample and external pressure. With the increase of temperature, the separation frequency is increased. This result contradicts the known formula [7] that was obtained in the regime of film boiling of saturated nitrogen and which describes the separation frequency $f$ of the bubbles with the equivalent bubble diameter $D_0$: $f = 0.56 \left( g (\rho_l - \rho_v) \right)^{1/2}$ Here $g$ is the standard gravity and $\rho_l$, $\rho_v$ is the density of liquid and its vapor. The question of the possible reasons for such deviations requires additional detailed investigations. With the increase of the hydrostatic pressure (from 20 to 180 mm water column) the separation frequency is decreased by an order of magnitude (Fig. 7b).

**Conclusions**

The results of the experimental study of the behavior of heated balls and drops of the melted steel during the induction heating in argon, air and distilled water of room temperature are presented. The experiments were carried out at a specially designed setup in which a modern scheme of the inductor power-supply stabilization was used. It made possible to perform melting investigations with high-temperature materials under laboratory conditions with temperatures up to ~2000°C.

The experiments resulted in a confirmation that the process of melting of the steel samples in air environment is followed by the drop erosion (spark-generation) of metal. With the immersion of the melted samples in water, this effect does not allow the formation of the film boiling regime at the heated surfaces. This fact prevents the explosive fragmentation of the melt and the appearance of the spontaneous vapor explosion. Besides that, the observed in the experiments the phenomena of generation of porous structure during the burning and hardening of liquid-metal drop can be used for the development of a new technology of obtaining metal coating with special properties. Carrying out the experiments in the inert gas environment (argon) an effect of streams and small drops of melt ejection from the surface of the cooling melted sample – steel drop has been found out. The mechanism of this effect is not clear enough. Clarification of reasons of its origin can be useful for explanation of several “strange” and difficult for understanding phenomena in astrophysics and electro-metallurgy.

The results of the experiments with the heated balls immersed in a cooling media (distilled water with temperature less than the boiling temperature) have confirmed the expediency of the usage of developed method with the induction heating for the investigations of the boiling specificities of the under-heated liquid also including the vapor explosion. The experiments carried out in such conditions made it possible to prevent the undesired disturbances introduced by the sample holder hanging in a cooling liquid (hanging samples are used in traditional experimental methods) and obtain new data about the form of the vapor film, dynamics of its formation and the size of the departure bubble.

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