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Visualization of the Processes Occurring during Spontaneous Triggering of a Vapor Explosion

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Abstract

The vapor explosion process is an explosive increase in the volume of vapor, accompanied by a sharp rise in pressure when a hot melt enters a cold liquid medium with a temperature above its limiting superheat temperature. This phenomenon incurs the threat of great destruction and human casualties in certain types of accidents in the nuclear, metallurgical, pulp and paper industries. Nevertheless, there are still many insufficiently studied aspects of this phenomenon, one of which is the initiation (triggering) of the process.

There are a number of logically fairly consistent descriptions of the processes occurring at a given stage of a vapor explosion. However, almost all of them are based on experiments carried out with external (forced) triggering. The article describes the data obtained during spontaneous triggering, i.e. under conditions much closer to reality.

In this paper, using high-speed video recording (with a frame rate of up to 180 kHz and an exposure time of up to 2 μs), the first visualization of the processes occurring during spontaneous triggering of a vapor explosion on molten NaCl salt drops in distilled water subcooled to saturation temperature is presented. It is shown that when several drops of the NaCl melt interact with water, the micro vapor explosion that occurred on one drop, with an interval of several tens of microseconds, causes explosive vaporization on neighboring drops as well. Thus, the logical descriptions of the processes received instrumental confirmation.

Keywords: vapor explosion, subcooled water, molten salt, spontaneous triggering, high-speed video filming.

1. Introduction

The process of a vapor explosion is realized when two liquids with different temperatures come into contact (when the hot liquid is heated above the temperature of the limiting superheating of the cold liquid), as a result of which an explosive boiling of a cold liquid occurs with the formation of large volumes of vapor and an increase in pressure in a space of limited dimensions, in which these events develop. This phenomenon can be observed in the nuclear power industry when corium (core melt) enters the water during a severe accident at a nuclear power plant, in the metallurgical and pulp and paper industries, and occurs during underwater volcanic eruptions. A sufficiently large number of both experimental and computational-theoretical works, reflected in a number of detailed reviews [1–7], are devoted to the study of the vapor explosion process. However, a comprehensive theory of this phenomenon has not been created to date, and this fact is explained by the complexity and variety of forms and situations in which it can be realized.

The vapor explosion process is usually divided into four stages: initial coarse mixing of the melt jet (premixing), explosion initiation (triggering), fine fragmentation of melt droplets (a sharp increase in the area of the hot surface with the explosive generation of a large mass of vapor, often accompanied by the propagation of a powerful shock wave) and expansion of explosion products into the environment. Presently, the least studied stage of the process is its initiation. In particular, there are no experimental data in the literature on the transfer of vapor explosion pulse between individual melt drops.

As to experimental study of the processes occurring during the triggering of a vapor explosion, it is most expedient to conduct the experiments with single drops or with a group of drops (several grams in weight) of a hot substance. As the main tool in such studies, due to a high speed transience of the process (it lasts from \tens to hundreds of μs), visualization using high-speed video filming is used. In our previous work, almost 100% occurrence of a vapor explosion on a single drop of molten NaCl salt (at a temperature of t_{NaCl} = 850–1100°C in water with a temperature of t_{w} = 20–70°C) was shown with spontaneous triggering of the process [8]. In this work, we visualized using high-speed video filming (with a frame rate of up to 180 kHz and an exposure time of up to 2 μs) we visualized the «chain» transfer of a vapor explosion pulse between individual drops of NaCl melt from the site of the initial spontaneous triggering. This method is closer to real conditions than external artificial triggering, which is often used in many studies (sudden movement of the piston, rupture of the diaphragm separating the working volume and the high-pressure vessel, «electrical» explosion of the wire).

2. Experimental setup and research technique

The studies were carried out on an experimental setup, the scheme of which is shown in fig. 1. A stainless steel container having a rectangular cross section of 530×250 mm and a height of 230 mm was filled with distilled water to a level of about 200 mm. A glass window was made on the side wall of the container to visualize the process using high-speed video filming.

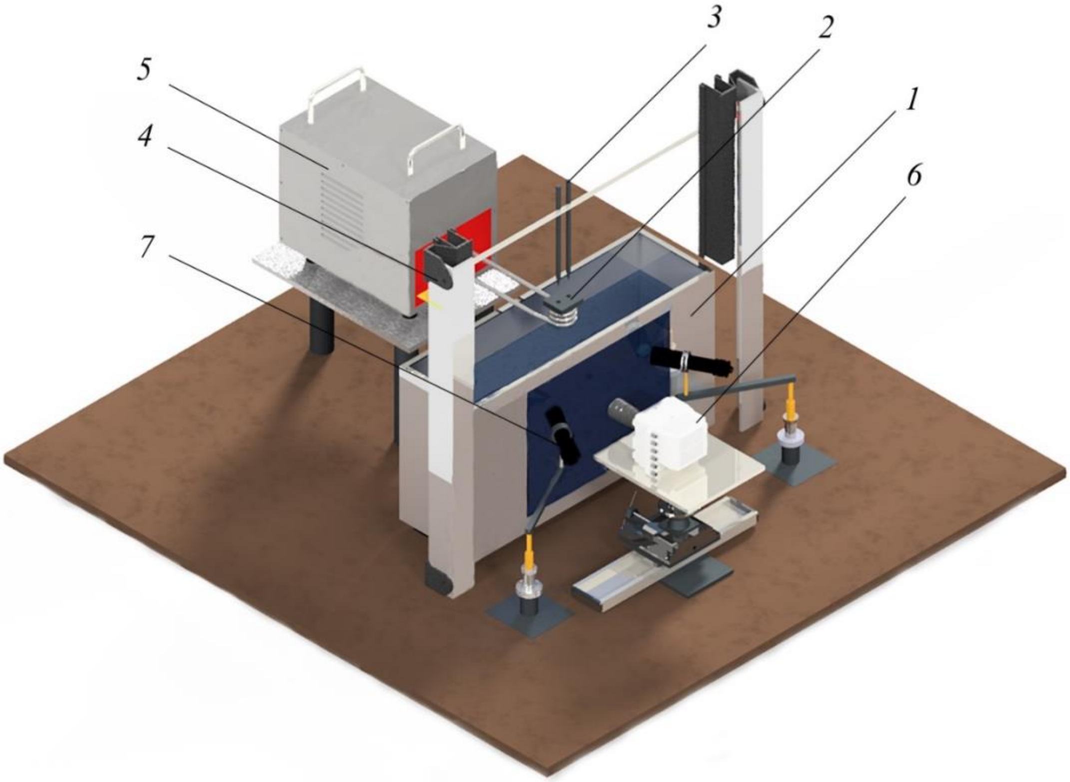


Fig. 1. Scheme-model of the experimental setup: *1* – container with distilled water; *2* – graphite crucible-generator of melt drops; *3* – graphite rods; *4* – vertical linear moving device; *5* – inductor; *6* – high-speed video camera; *7* – backlights.

Molten droplets of NaCl salt entered the water from the mouths of a graphite crucible (pos. *2* in fig. 1) located at a distance of 60–80 mm above the free water surface. The use of a graphite crucible made it possible to significantly reduce the probability of oxidation of the melted medium during heating. The crucible had the shape of a rectangular parallelepiped, 35 mm high, 33 mm wide, and 23 mm thick. Inside the crucible, two cylindrical cavities 10 mm in diameter were drilled to a depth of 30 mm, the distance between the axes of which was 13 mm. Through holes 4 mm in diameter were made in the lower part of both cavities, which were closed by graphite cylindrical rods with conical ends (pos. *3* in fig. 1) until the molten drops were fed into the water container. Drops were supplied by lifting graphite rods using a special automated mechanism in the form of a linear movable device (pos. *4* in fig. 1) operating from a source with a voltage of 12 V DC.

The crucible was heated to a temperature of 850–1150°C to melt the salt in it (the melting point of NaCl is 801°C) using a VCh-15AV high-frequency induction heater (inductor) (pos. *5* in fig. 1). The temperature in the body of the crucible and water in the container was measured by chromel-alumel thermocouples. The mass of salt loaded into each mouth of the crucible varied from 1 to 2 g.

To measure the pressure rise during the vapor explosion, a PCB 113B24 high-frequency piezoelectric transducer was used, with a resonance frequency of ≥ 500 kHz. The sensor was placed on the wall of the container with water at a distance of ~2–3 cm from the expected place of the explosion of the melt drop.

Visualization of the process under study was carried out using high-speed video cameras – monochrome Phantom v2012 or color Phantom VEO 410s (pos. *6* in fig. 1) with a frame rate of up to 180 kHz and a minimum exposure time of 2 μs. The camera was installed on a special movable along two axes (horizontally and vertically) laboratory table. The lens used was Sigma DC 18–125 mm 1:3.8–5.6 HSM. The illumination was provided by two powerful Fenix TK20R LED flashlights with a maximum brightness of 1000 lumens each (pos. *7* in fig. 1). In separate experiments, additional lights immersed in a water container were used to improve illumination.

3. Research results

Fig. 2 shows typical visualization frames of vapor explosion pulse transfer between molten NaCl droplets. The video was filmed with a Phantom VEO 410s color video camera at a frame rate of 50 kHz (20 μs between successive frames) and an exposure time of 10 μs. After entering the water, the droplets could split into several parts that existed independently, or re-merged together (in fig. 2a one can see four separate drops ranging in size from 3 to 8 mm). The time interval from the fall of drops into the water to the onset of spontaneous triggering ranged from several tens to hundreds of ms. Triggering began with local perturbations of the vapor film around one of the melted droplets (the trigger point is indicated by the white arrow in fig. 2a). After a short period of time (several tens of μs), these perturbations propagated over the entire surface of the drop (figs. 2b–2c). The picture to a large extent resembled those observed in [9] on solid heated spheres. Then, a characteristic short-lived (during one frame of video recording, i.e., in this case, no more than 20 μs) local luminous spot with a characteristic size of approximately 1 mm appeared, which could be associated with cavitation luminescence (the spot indicated by the black arrow in fig. 2d), and followed by the beginning of a vapor explosion, accompanied by an intensive increase in the volume of vapor. A luminous spot was observed by us in a fairly large number of experiments on NaCl drops. It is also mentioned in review [3]. Then the process of explosive vaporization spread to neighboring drops (fig. 2e). The time interval between micro explosions on adjacent drops (pressure pulse transmission time) correlates reasonably with the sound velocity in water.

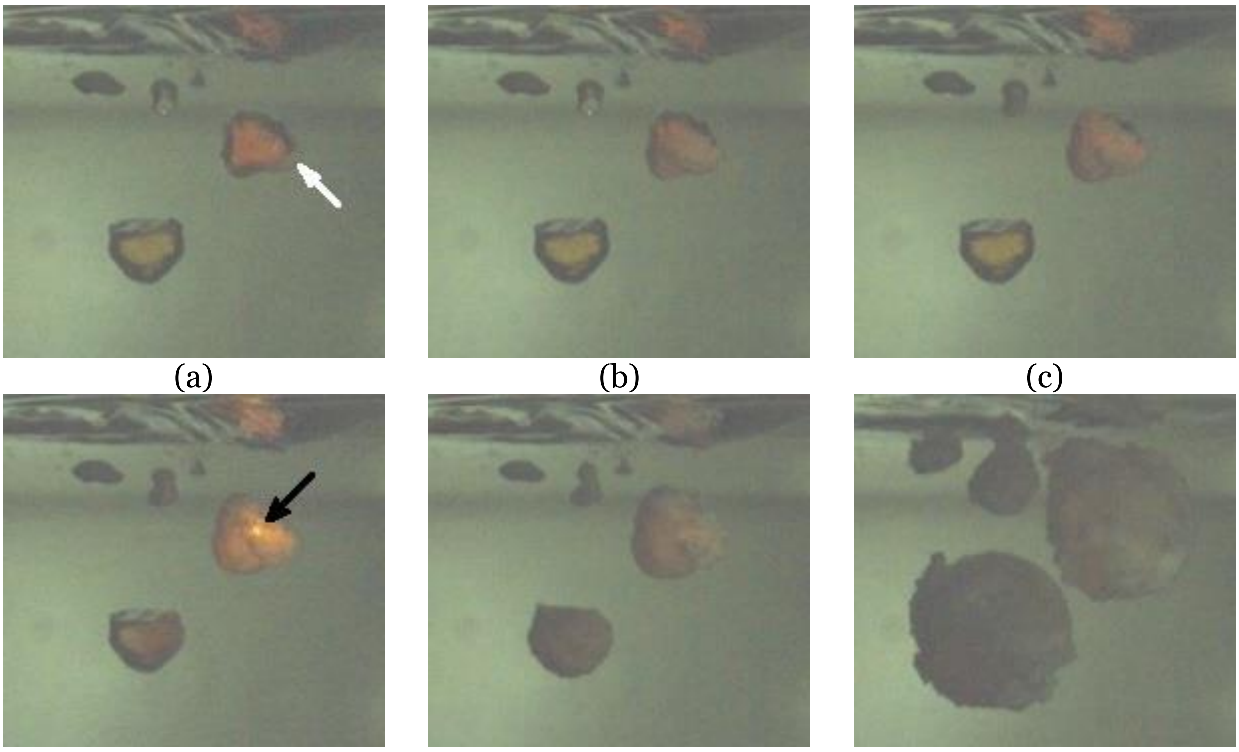
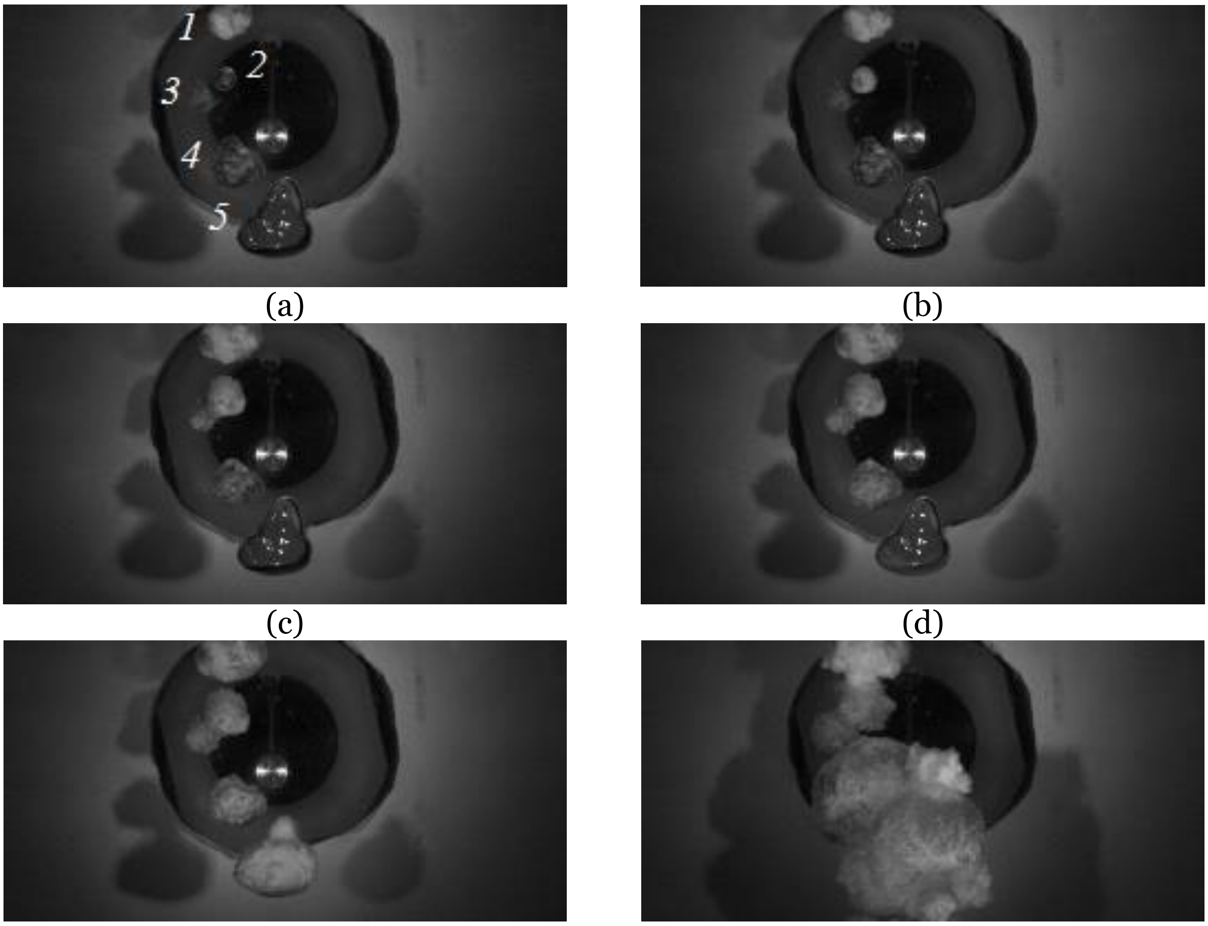

(a) (b) (c)
(d) (e) (f)

Fig. 2. Propagation of a vapor explosion between NaCl drops (t_w = 23°C, t_{NaCl} = 910°C in a crucible). The exposure time is 10 μs. Frame size is 44 x 40.5 mm. Time from frame (a) – the beginning of triggering on the first drop: (b) – 20 μs; (c) – 40 μs; (d) – 60 μs; (e) – 100 μs; (e) – 380 μs. The white arrow marks the point of triggering (local perturbations of the vapor film), the black arrow marks the short-term light flash.

According to fig. 2, it is worth noting an important point, which consists in the fact that explosive vaporization on the first drop occurred several frames after the onset of local perturbations of the vapor film (figs. 2a–2d), while this process on neighboring drops occurred within one frame (the interval up to 20 μs) after the explosion on the first drop (fig. 2e). Apparently, the acceleration of the process on subsequent drops was the result of a pressure wave propagating in the liquid after the explosion on the first drop, which forces the water to contact with the hot melt.

Fig. 3 shows frames from a video of the propagation of a vapor explosion filmed with a Phantom v2012 video camera at a frame rate of 30 kHz (33 μs between successive frames) and an exposure time of 10 μs. As seen in the frame of fig. 3a, after falling into the water, five separate drops of NaCl were formed, each separated by a vapor layer from the liquid. The time interval between the fall of the first and last drops (the numbering of drops is shown in fig. 3a) into water was approximately 100 ms. Fig. 3a shows the moment of spontaneous vapor explosion on this first drop of salt. Six frames before that, local perturbations of the vapor film appeared on the first drop, i.e., the time interval from the start of triggering to the explosion on the first drop took approximately 200 μs. The frame fig. 3b shows the moment of transfer of the explosion to the nearby second drop and the beginning of the perturbations of the vapor film on the third drop. The next two frames illustrate the moments of explosion transfer to the third (fig. 3c) and fourth (fig. 3d) drops and the beginning of vapor film disturbances on the fourth (fig. 3c) and fifth (fig. 3d) drops, respectively. On the frame fig. 3e explosion process extends to the farthest fifth drop. Time interval between frames fig. 3a and fig. 3e is only about 165 μs.



(a) (b) (c) (d) (e) (f)

Fig. 3. Propagation of a vapor explosion between NaCl drops (t_w = 23°C, t_{NaCl} = 1150°C in a crucible). The exposure time is 10 µs. Frame size is 87 x 43.5 mm. Time from frame (a) – steam explosion on the first drop: (b) – 33 µs; (c) – 99 µs; (d) – 132 µs; (e) – 165 µs; (e) – 495 µs. In the background, a pressure sensor with a fastening element on the wall is visible. Drops are numbered in frame (a).

In fig. 3 in the same way as in fig. 2, there is an «instantaneous» transmission of a vapor explosion from the first drop to neighboring ones in 1–2 frames, while explosive vaporization on the first drop occurs after local perturbations of the vapor film propagate over the entire surface of the drop during 6 frames (approximately 200 µs). When using external artificial triggering, the process will develop similarly to those occurring on drops 2–5 in fig. 3. That is, the use of the method of external triggering of the process moves the experiment away from real conditions, since it does not allow tracking the stage of local disturbances of the vapor film in it, which occur during spontaneous triggering on the first drop

4. Conclusions

The processes occurring during spontaneous triggering of a vapor explosion on molten drops of NaCl salt in distilled water were visualized using high-speed video filming. A «chain» of vapor explosion pulse transmission between separate drops of NaCl melt from the place of initial spontaneous triggering was instrumentally registered.

Instrumental (visual) confirmation of logical constructions obtained under conditions of spontaneous triggering, which are much closer to reality than experiments with external (artificial) triggering, is very important for developing phenomenological models of the phenomenon adequate to reality.

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References

1. Reid R.C. Rapid phase transitions from liquid to water // Advances in Chemical Engineering. 1983. V. 12. P. 105–208.
2. Stepanov E.V. Physical aspects of the vapor explosion phenomenon // IAE Preprint. 1991. № 54503/3. [in Russian]
3. Fletcher D.F., Theofanous T.G. Heat Transfer and Fluid Dynamic Aspects of Explosive Melt–Water Interactions // Advances in heat transfer. 1997. V. 29. P. 129–213.
4. Berthoud G. Vapor explosions // Annu. Rev. Fluid Mech. 2000. V. 32. № 1. P. 573–611.
5. Melikhov V.I., Melikhov O.I., Yakush S.E. Thermal interaction of high-temperature melts with liquids. High Temperature. 2022. V. 60.
6. Shen P., Zhou W., Cassiaut-Louis N., Journeau C., Piluso P., Liao Y. Corium behavior and steam explosion risks: A review of experiments // Annals of Nuclear Energy. 2018. V. 121. P. 162–176.
7. Simons A., Bellemans I., Crivits T., Verbeken K. Heat Transfer Considerations on the Spontaneous Triggering of Vapor Explosions – A Review // Metals. 2021. V. 11. № 55.
8. Vavilov S.N., Vasil’ev N.V., Zeigarnik Yu.A. Vapor Explosion: Experimental Observations // Thermal Engineering. 2022. V. 69. № 1. P. 66–71.
9. Grigor’ev V.S., Zhilin V.G., Zeigarnik Yu.A., Ivochkin Yu.P., Glazkov V.V., Sinkevich O.A. The behavior of a vapor film on a highly superheated surface immersed in subcooled water. High Temperature. 2005. V. 43. № 1. P. 103–118.