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Boiling liquid expanding vapor explosion: Experimental research in the evolution of the two-phase flow and over-pressure

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Abstract

In a boiling liquid expanding vapor explosion (BLEVE), the superheating and boiling of the liquefied gas inside the vessel as it fails is important information necessary to understand the mechanism of this type of disaster. In this paper, a small-scale experiment was developed to investigate the possible processes that could lead to a BLEVE. Water was used as the test fluid. High-speed video was utilized to observe the two-phase flow swelling which occurred immediately following the partial loss of containment through a simulated crack. The velocity of the two-phase swelling was measured along with pressure and temperature. It was observed that initially a mist-like two-phase layer was rapidly formed on the liquid surface (∼3–4 ms) after the vessel opened. The superheated liquid rapidly boiled and this accelerated upwards the two-phase layer, the whole liquid boiled after about 17 ms form opening. It was supposed that the swelling of the two-phase layer was the possible reason for the first over-pressure measured at the top and bottom of the vessel.

From 38 ms to 168 ms, the boiling of the superheated liquid weakened. And from 170 ms, the original drop/mist-like two-phase flow turned into a churn-turbulent bubbly two-phase flow, rose quickly in the field of the camera and eventually impacted the vessel top wall. The force of its impact and "cavitation" and "choke" following with the two-phase ejection were maybe main reasons for the second obvious pressure increasing.

Keywords: BLEVE; High-speed photography; Two-phase flow; Over-pressure

1. Introduction

A boiling liquid expanding vapor explosion (BLEVE) is a type of physical explosion that can cause severe damage in the modern chemical plant. The BLEVE has been defined as 'an explosion resulting from the failure of a vessel containing a liquid at a temperature significantly above its boiling point at normal atmospheric pressure' [1]. In general, 48% of the BLEVE can be classified as transport accidents and most of them being caused as a result of fire [2]. The direct hazards of a BLEVE are blast, the ejection of tank fragments and fireballs if the contents are flammable. If the contents are flammable, the fireball may ignite immediately with intense thermal radiation. Any liquid that does not flash into the aerosol forming the fireball will remain in the form of a pool fire. Fragments from the tank can be projected over large distances. Such events can cause great harm to the public, plant and the environment.

Significant efforts have been made to study BLEVE explosions and some researchers have published articles concerning the diverse aspects of these accidents. In the research dealing with the mechanism of the BLEVE, one dealing with liquid superheating has been substantiated by a series experiments with different scales [3–7]. In this the superheated liquid boils violently after the vessel is suddenly partially opened and the resulting internal over-pressure is given as the main reason that the vessel can be totally destroyed [8–10]. The influence of thermal stratification on the force of such events has also been analyzed [11]. The accidents damage has been quantified by some researchers and new methods of the calculation of the accident after effects have been published [12–14]. In numerical simulations, several models have been evaluated and the results compared to experiments [15,16].

After the initial partial failure of the high-pressure vessel wall, the phase change and the resulting development and movement

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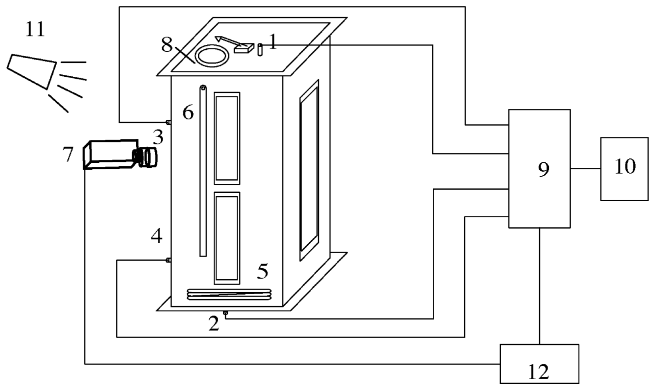

1, 2—pressure sensor;
3, 4—thermocouple;
5—heater;
6—rule;
7—the high-speed photography system;
8—the orifice covered with rupture disc;
9—the data acquisition system;
10—computer;
11—the lighting system;
12—the synchronous control.

Fig. 1. The schematic of the experimental setups.

of the two-phase swell are key elements in determining the mechanism of a BLEVE. Some works have been done about this area [17–19], but there are still wide gaps in our knowledge; such as how the two-phase flow forms and how the corresponding pressure changes inside vessel during the rapid boiling process within the bulk superheated fluid?

In this paper, a small-scale experiment was developed to investigate the possible processes that could lead to a BLEVE. High-speed photography was utilized to observe the two-phase flow swell which occurs immediately following the partial loss of containment through a simulated crack, and the velocity of the two-phase flow swell was measured. The corresponding pressure and temperature changes were also recorded.

2. Experimental apparatus

As there is some danger in the experiments using LPG, and so water was used as the test fluid instead.

Fig. 1 shows the schematic of the experimental setup which consists of a vertical rectangular cross-section pressure container, a rupture unit, a data acquisition system, a high-speed photography system, thermocouples and pressure sensors, computer and other auxiliary equipments (e.g. lighting system and synchronous control).

The vessel which was made of stainless steel was 880 mm high and 160 mm × 160 mm in cross-section. The thickness of the vessel wall was 5 mm. At the top of the vessel a circular opening was made with a vent diameter of 80 mm. In the experiment, the opening was covered with a rupture disc, and then sealed. The rupture unit was designed to break the disc. At the bottom of the vessel, there was a heater inside the vessel; the power of the heater was 5 kW. In the liquid and vapor region of the vessel, pressure sensors (piezoelectricity crystal pressure sensor; mode of installation: M10 × 1; working temperature: −40 °C to +250 °C) and thermocouples (K-type sheathed thermocouples with 1.0 mm diameter wire) were installed (two pressure sensors were installed one at the top and another at the bottom). In the wall which faced to the camera, two glass windows (60 mm × 300 mm) were fitted. A ruler set beside the window could be used to determine the velocity of the medium movement. For the high-speed photography a high intensity lighting system was necessary. The high-speed video and the data acquisition system were started at the same time through the synchronous control.

The high-speed photography system is manufactured by the Photron Limited Company (Japan). The model is Ultima Fast-Cam APX. This System offers extremely high-speed recording at 60 to 2000 frames per second (fps) at full mega pixel image resolution (1024 × 1024) and up to 120,000 fps at reduced resolutions to capture the fastest events. The data could be recorded a 3 s period at full resolution.

In the experiment, water in the airtight vessel was heated until the temperature exceeded 100 °C, the degree of superheating could be adjusted based on the requirement of necessary for each experiment. The pressure inside the vessel was decided by the temperature of the liquid (the phenomenon of liquid temperature stratification in actual externally heated LPG tanks was not obvious in this experiment due to its internal heating). When the temperature and pressure in the vessel reached the required values, the disc used to seal the opening was broken. This was used to simulate the occurrence of cracks or tears that could possibly lead to a BLEVE. The data acquisition (YE6262 dynamic data acquisition system with 16 channels per PCMCIA gather card; the highest date acquisition frequency is 500 kHz/s; YE5850 electric charge amplifier linked between the data acquisition system and the pressure sensor) recorded the pressure and temperature changes during the experiment.

3. Results and discussions

With the device mentioned above, the details of the experiment are shown in Table 1. With an initial fill of about 60% (H = 530 mm) and a data acquisition rate of 2 kHz the water was heated until its temperature reached 125 °C, at this point

Table 1
The experimental conditions of the test

Experiment devices	Experimental conditions
Fill level	60% (H = 530 mm)
The initial temperature (water)	125 °C
The initial pressure inside vessel	2.3 bar (kg/cm^2)
Frequency of data acquisition	2 kHz
Height of the visual field of the high-speed video	118 mm (the original liquid level was about 1/3 lens view in height)
Frequency of the high-speed video	2000 fps

the pressure was about 2.3 bar (kg/cm^2). The high-speed video camera was adjusted to observe the boiling and gasifying of the liquid directly after the disc was broken at 0 ms. The height of the visual field was about 118 mm and the original liquid level was about 1/3 lens view in height.

Fig. 2 shows a series of typical photos captured by the high-speed video camera with time set to 0 the instant the rupture disk is opened. The frequency of the photography was 2000 fps. Then the rupture disc was broken to simulate the occurrence of crack in vessel wall. These photos revealed the boiling process and the evolution of the resulting two-phase flow. The pressure traces during the evolution process of the two-phase flow measured at the top and bottom positions are shown in Figs. 3 and 4. Fig. 5 is the temperature curves measured by the top and bottom thermocouples inside the vessel.

Because of the pressure gradients between the interior and the exterior of the container after the rupture disc broken, the medium in the vapor region discharged. Then the pressure in the

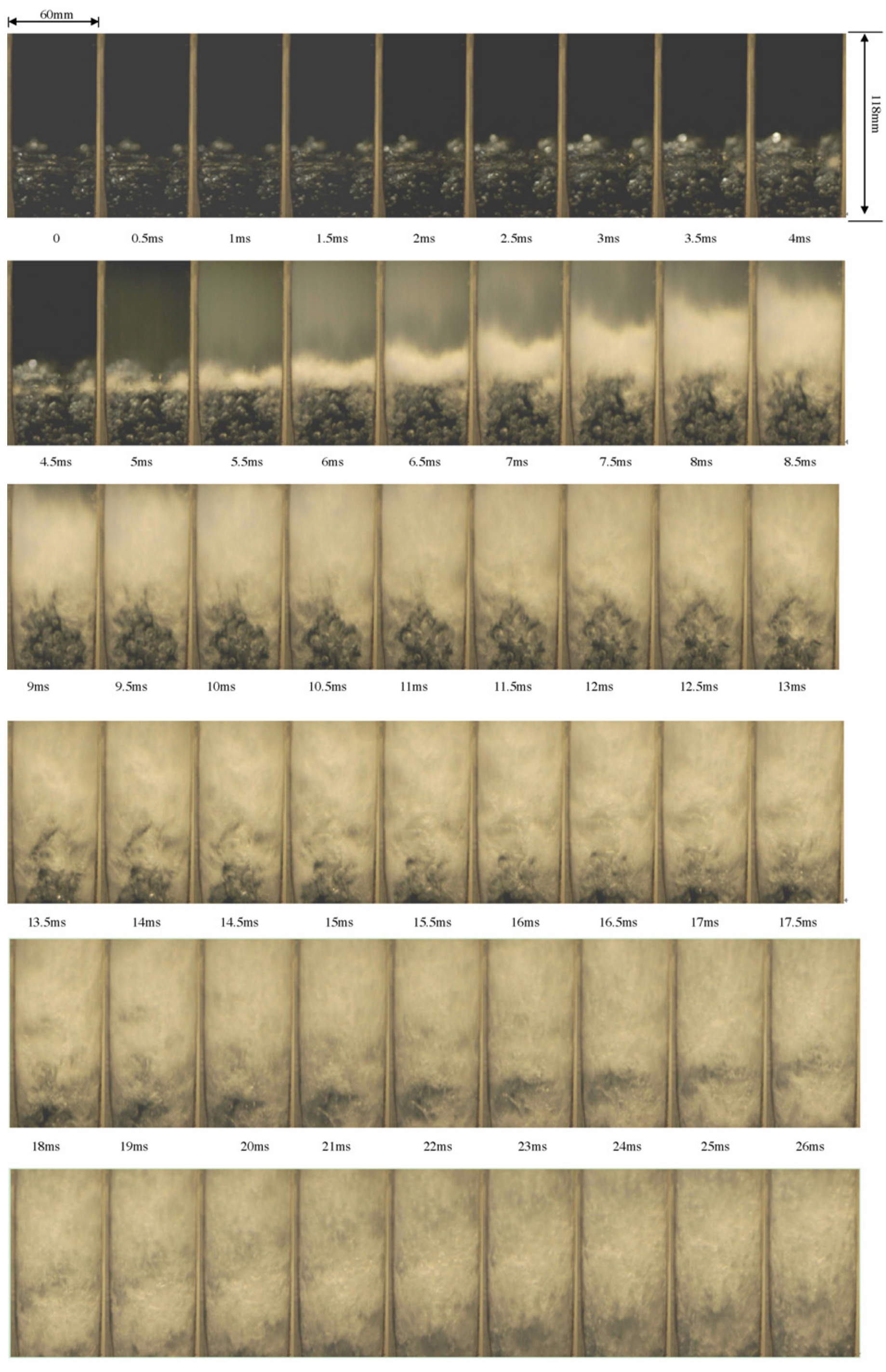

Fig. 2. The boiling process and the evolution of the resulting two-phase flow after opening the orifice.

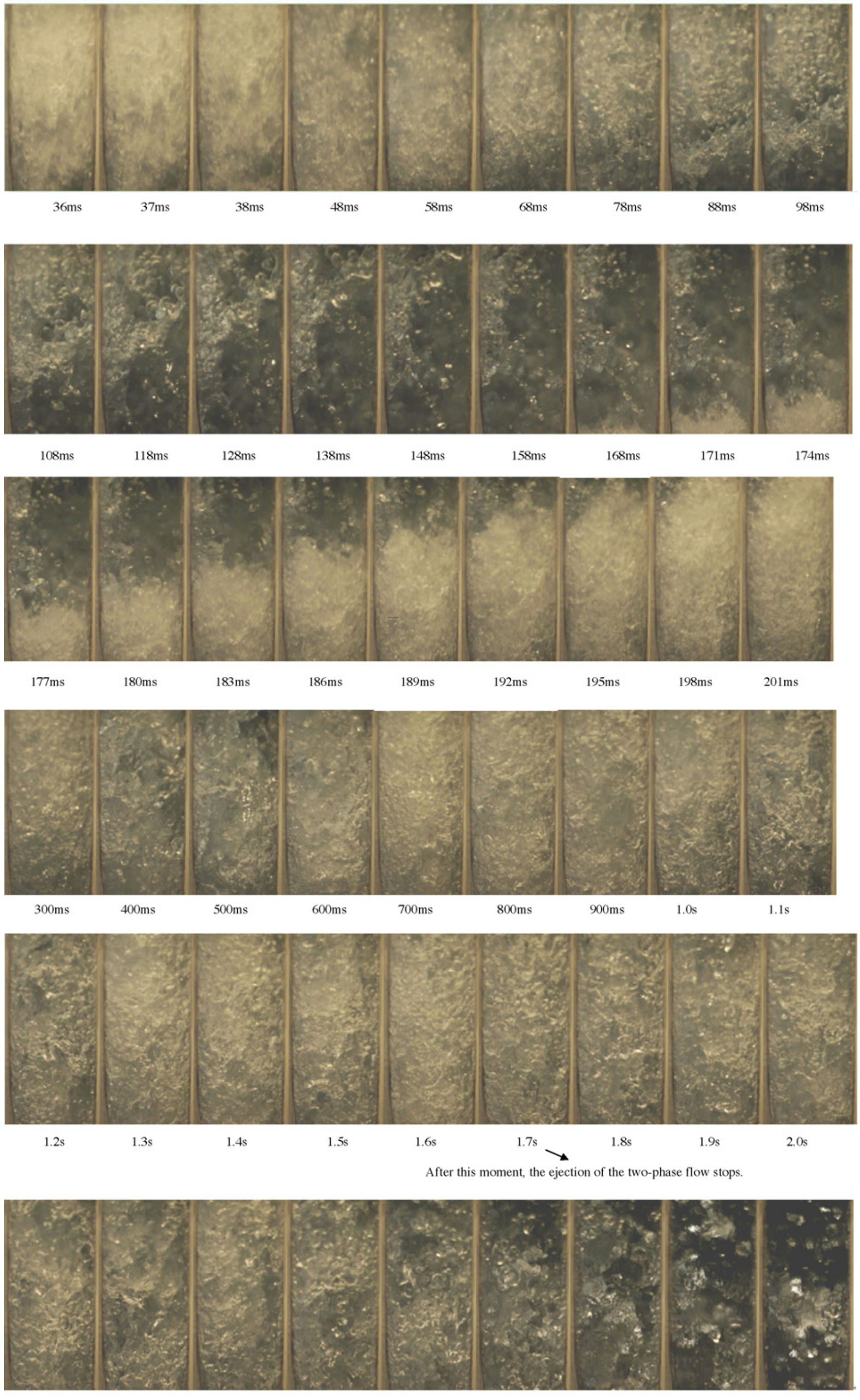

Fig. 2. (*Continued*)

container began to descend, and the depressurized wave propagated from the opening towards the bottom of the vessel at the local speed of sound.

In Fig. 3 the pressure descended immediately after the disc broken, which made a portion of the liquid retain in its saturated state and the depressurized liquid above became superheated. The duration of the pressure decreasing was about several milliseconds.

From Fig. 2 it could be seen that the boiling of superheating liquid, which differed from the common boiling mode (heated from internal or external), was a step-by-step process progressing upwards from the surface with time.

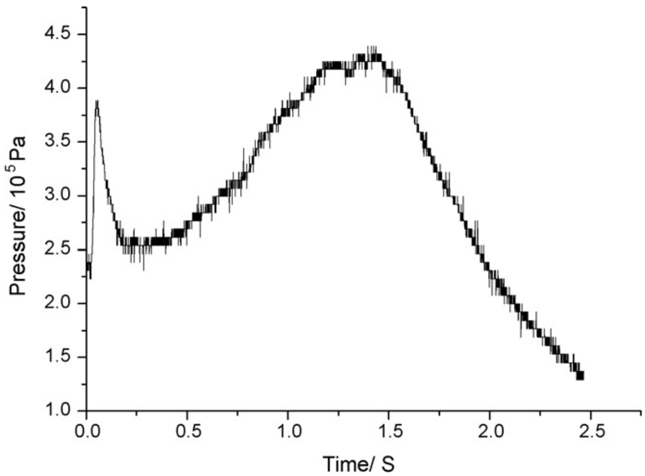

Fig. 3. The whole pressure curve measured by the pressure sensor installed on the top of the vessel (60% liquid height; 125 °C; 19.6% orifice area).

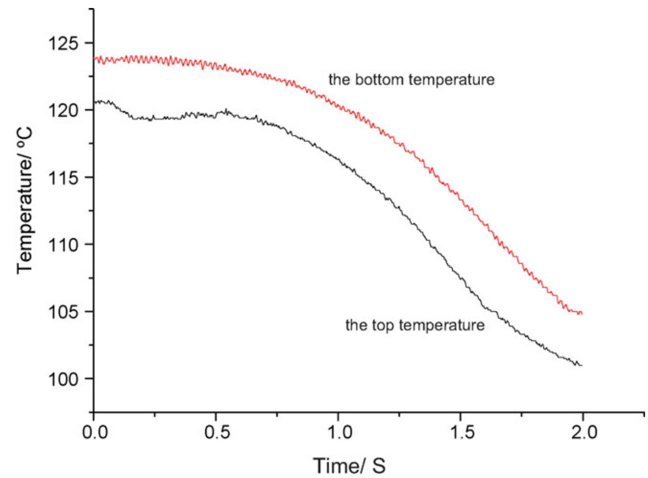

Fig. 5. The temperature curve measured by top and bottom thermocouples inside the vessel.

From 0 ms to 3.5 ms, there was not a distinct change on the liquid surface, and the original bubbles in the liquid rose only slowly. From 4.0 ms onwards the surface of the superheated liquid began to boil fiercely, and energy and saturated vapor were released. The released saturated vapor swelled and brimmed the vapor region in the container, and its concentration increased with the boiling continuously progressed. Compared the pictures at the different moments of 4.5 ms, 5 ms and 5.5 ms, the color of the area above the boiling surface became whiter and thicker. From 5.0 ms on the liquid surface the boiling became violent and bubbles broke continually, which first formed a swelling two-phase mist-like layer. From 5 ms to 38 ms, the mist-like two-phase layer swelled and its density also increased gradually.

Fig. 6 shows the change of the thickness of this two-phase layer with time (start time in Fig. 6 corresponds to the disc broken time). As shown in Fig. 6, the thickness of the two-phase layer increased with time, and in the period when the two-phase layer firstly occurred (from 4.0 ms to 5.5 ms) the flow expanded upward and downward synchronously, centered about the previous relatively steady-state liquid surface(the location of origin point of *y*-axis). Subsequently, the total thickness of the two-phase layer increased and its position ascended, which may be caused by that the volume of the bubbles and nucleus which previously existed in the liquid increased and made the total volume of the liquid expanded because of the decrease of the liquid surface pressure (It is known that free gas is always present in a real liquid as small bubbles or nuclei. There are usually 10^4 to 10^8 bubbles contained in a cubic centimeter for most liquids [20,21]. When pressure is suddenly reduced these bubbles grow rapidly. In addition some new bubbles will also be initiated as a result of the local liquid superheat.). From 8.0 ms, the boiling of the inner liquid intensified, which made the boundary of the two-phase layer blur gradually. The thickness of the two-phase layer increased, and its lower boundary expanded downward rapidly.

With the spray of the medium in the previous vapor region, the pressure above the two-phase flow descended gradually and the intensity of the liquid boiling increased continuously, and this made the two-phase layer rise with a high acceleration. Fig. 7 shows the velocities of the lower and upper boundaries of the two-phase flow, and the positive direction is straight upward. The thickness of the two-phase flow increased with time and

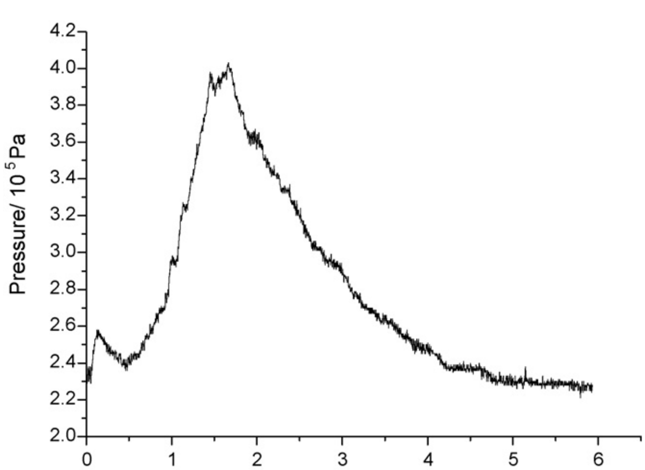

Fig. 4. The whole pressure curve measured by the pressure sensor installed at the vessel bottom (60% liquid height; 125 °C; 19.6% orifice area).

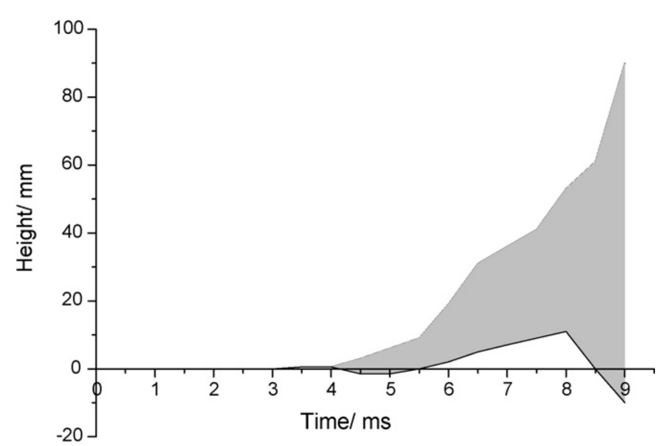

Fig. 6. The changing of the two-phase layer height vs. time.

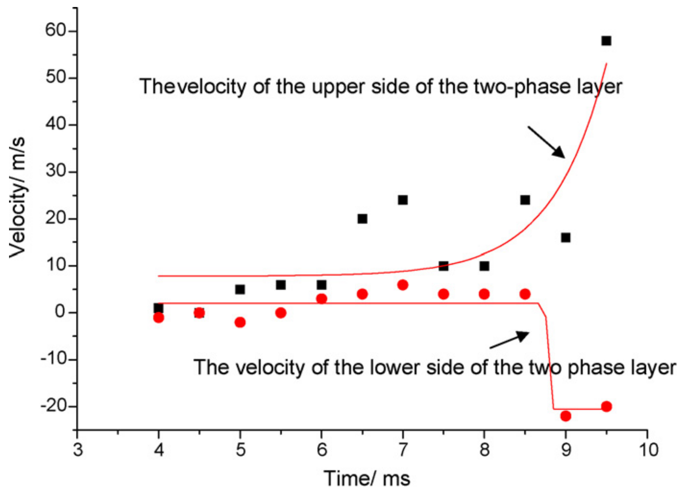

Fig. 7. The velocity of the upper and lower sides of the two-phase layer.

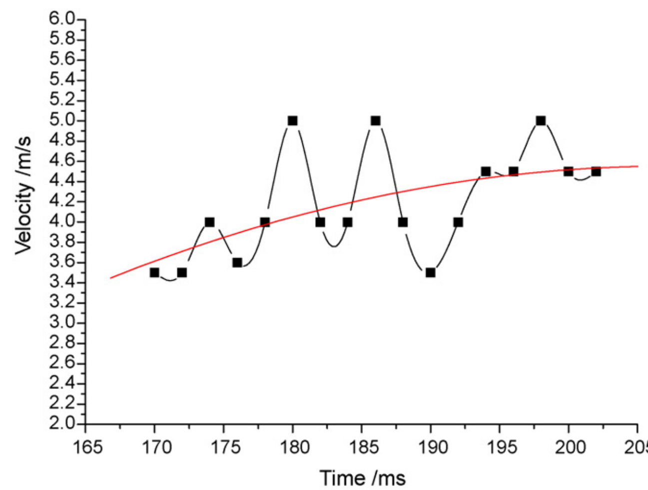

Fig. 9. The velocity of this bubbly two-phase flow.

the velocity of the lower boundary reversed becoming blurred gradually because of the boiling of liquid and bubbles rupture until finally the visual field of video camera was filled with an apparent two-phase space.

The lower and upper boundaries movement accelerations of the two-phase layer are shown in Fig. 8. As seen from figure the swelling of the two-phase layer was an accelerated process. As the pressure rose this recompressed the bubbles and could result in a process of coherent bubble collapse and thus potentially provide a further opportunity for energy release. It was supposed that more and more rapid bubbles nucleation and growth occurred with the liquid superheating which further accelerated the swelling of the two-phase fluid. As seen from Fig. 2, the upward swelling of the two-phase layer was greater than downward swelling when the vessel cracked at the top. This maybe one factor which influenced the destroy intensity in different vessel position.

The two-phase layer swelled so rapidly that the force from expansion of the two-phase flow could cause the vapor and the liquid to be propelled violently in all directions and the pressure in the vessel increased sharply. After the disc opened 34 ms, the first pressure peak was measured by the pressure sensor as indicated in Fig. 3.

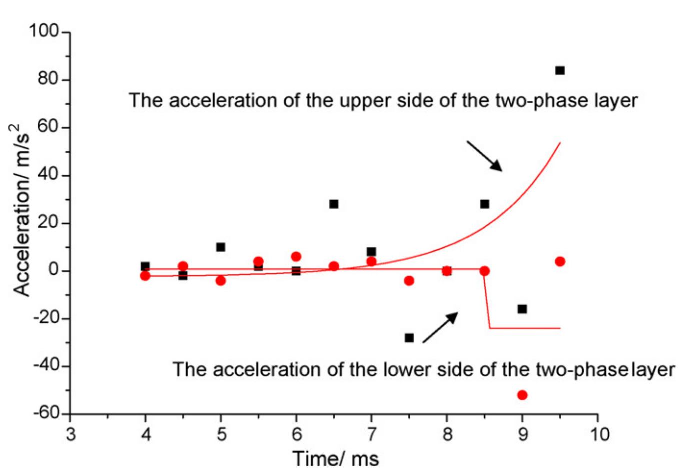

Fig. 8. The acceleration of the upper and lower sides of the two-phase layer.

In Fig. 4, the appearance time of the first pressure peak measured in the vessel bottom was about 100 ms, which is about 30 ms later than the appearance of the first pressure peak measured at the vessel top. It was supposed that because of the asymmetry development of the two-phase layer in different directions and the different spread velocities of the compression waves which determined by the different medium densities (where the region lengths of liquid and vapor are also different) so that the occurrence times of the first pressure peak are different.

As the pressure increased, the boiling of the superheated liquid and the collapse of the bubbles may be restrained, and the development of the two-phase fluid weakened. In pictures of Fig. 2, the mist-like two-phase layer turned into a vapor–liquid mixed bubbly two-phase fluid. From 38 ms to 168 ms, the density of the two-phase fluid diminished and the rose velocity became slow gradually in the visual of lens.

For the weakness of the impetus of the two-phase flow, the inner vessel pressure decreased from 3.9 bar (the first pressure peak) down to 2.5 bar. It could be supposed that the boiling of the remaining superheated liquid became violent again after the pressure decreased into a certain range. It was observed that a churn-turbulent bubbly two-phase flow rose with high velocity from 171 ms, which impelled the two-phase layer that created by the surface boiling and later liquid entrainment with a large amount of dynamic energy. In the subsequent 30 ms this bubbly two-phase flow rose and brimmed the visual field of video camera. The velocity of this two-phase flow is shown in Fig. 9.

The movement of this two-phase flow was an even accelerative process; the acceleration was about 20 m/s^2. After 170 ms, the movement state of the two-phase fluid in video camera visual field had no obvious change. It could be supposed that the two-phase flow would impact the vessel top at the time of 250 ms based on this velocity. In Fig. 3, the pressure measured at the vessel top rose at nearly 200–300 ms, until 1140 ms the pressure reached the second peak. The pressure peak value was about 4.35 bar.

In this process, the vessel was filled with a quasi-homogeneous two-phase fluid; and this would cause a 'choke' at the orifice when the churn-turbulent bubbly two-phase flow exited. The choke velocity of the mixture was smaller than that for the preceding vapor flow. It could be that at the inner surface of the top wall that bubbles collapse in something like cavitation releasing dynamic energy and impulse to increase the local pressure, while the two-phase fluid continues its ejection. The combination of "impact", "choke" and "cavitation" could possibly result in the second pressure rising phase.

The substance density in the vessel decreased gradually and the ejecting speed of the two-phase flow also decreased. The duration of this ejection was about 1.7 s. Nearly at 1.7 s the pressure measured by the top sensor decreased from the second pressure peak. In Fig. 2, the direction of the two-phase fluid changed and the bubbles departed from the saturated water. After most of the superheated liquid was ejected from the vessel, a fraction of the superheated liquid without sufficient ascend kinetic energy to discharge remained in the vessel. The height of this residual liquid was about 120 mm.

As shown in Fig. 4, the change of the first pressure peak at the bottom was similar to that of the pressure change at top. After the disc broken, the initial formation and swelling of the two-phase layer seemed to make the pressure in liquid region impelled. The value of first pressure peak in Fig. 4 was about 2.6 bar. It was 1.13 times of the original pressure insides vessel. This value was smaller than the first pressure peak in Fig. 3, which may be caused by the difference of impulse intensity of two-phase layer swell in different direction. The second pressure peak reached 4.1 bar in Fig. 4 and 0.25 bar lower than that in Fig. 3.

Fig. 5 shows the temperature changes in liquid and vapor. Because the diameter of the thermocouple is thicker (1 mm), the response time of thermocouple exist delay. The liquid temperature was 3 °C higher than vapor temperature because of the heat model. As shown in Fig. 5, the liquid temperature had no obvious change until 0.3 s after the vessel broken. One reason is the response delay of thermocouple; the other reason is the temperature of superheated liquid changes slowly. With the discharge of two-phase flow, the temperature measured at the bottom decreased gradually.

The temperature measured at the top did not decrease with the same trend. It decreased firstly because the vapor vented. And when the rising mist-like two-phase fluid filled the vapor region, the rapid decrease in temperature was terminated. After 0.5 s, the temperature measured in different position showed the same decrease trend with the medium ejection.

4. Conclusions

In this paper, high-speed photography was utilized to observe the evolution of the two-phase flow which occurred immediately following the partial loss of small-scale containment through a simulated crack in a water filled pressure vessel. The velocity of the two-phase layer swelling was measured. By comparing the pressure response curves with the photographic record of the superheating liquid boiling process, it was discovered that:

(1) the superheating and boiling in the liquid phase was not a uniform process in the simulated BLEVE process reported here. The surface of the liquid first boiled after the disc was broken and then about 3.5 ms later a two-phase mist/droplet layer swell rapidly developed on the liquid surface. The expansion of this two-phase layer was an accelerated process, and its impulse may result from the energy released by bubbles broken on the surface. In the visual field of the video camera the whole liquid boiled and developed into a two-phase fluid at about 17 ms. It was supposed that the occurrence and development of this two-phase layer was the direct reason for the first pressure increase.
(2) 170 ms after the vessel was opened, a rising bubbly two-phase flow was captured by the high-speed video camera. This two-phase flow rose at high speed and then impacted the top wall of vessel. The force of its impact and perhaps a cavitation-like collapse of the bubbles due to impact along with the "choke" following with the two-phase liquid ejection maybe sufficient to cause the pressure increased again.

These experiments mentioned above are implemented under the condition that the water is test fluid and the heater is installed inside the vessel. It may have differences with the experiment results that completed by actual LPG and external fire engulfment. The over-pressure is significant in this paper because the experiment started at only 2.5 bar pressure. In a typical propane tank the rupture pressure may be 20 bar or higher and the vessel scale is bigger, so this two-phase impact effect may have a much smaller relative effect. But the mechanism of the superheated liquid explosive boiling may have considerable similarity, and the different cause of the two-phase pressure impulse may provide different idea for prevent this disaster. It need further research in this field combined with different experiment details.

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