Journal of Zhejiang University SCIENCE
ISSN 1009-3095
http://www.zju.edu.cn/jzus
E-mail: jzus@zju.edu.cn

Experimental investigation of external explosion in the venting process*

DU Zhi-min (杜志敏)[†1], JIN Xin-qiao (晋欣桥)[1], CUI Dong-ming (崔东明)[2], YE Jing-fang (叶经方)[2]

([1]*Department of Mechanical Engineering, Shanghai Jiaotong University, Shanghai 200030, China*)

([2]*School of Powering Engineering, Nanjing University of Science and Technology, Nanjing 210094, China*)

[†]E-mail: duzhimin@sjtu.edu.cn

Received Dec. 21, 2003; revision accepted Mar. 22, 2004

Abstract: Experimental investigations were conducted on the process of combustion and explosion vent in a 200 mm (diameter)×400 mm (length) vertical cylindrical vessel. When CH_4-air mixture gases were used and the vent diameter was 55 mm, conditions of Φ (equivalent ratio)=0.8, Φ=1.0 and Φ=1.3 and two ignition positions (at the cylinder center and bottom) were selected. The venting processes and the correlated factors are discussed in this paper.

Key words: Venting process, CH_4-air, External explosion, Correlated factors

doi:10.1631/jzus.2005.B0357 **Document code:** A **CLC number:** O389; X932

INTRODUCTION

Venting technology provides possible protective measures against the effect of explosions. The essential point is to release the high pressure through proper venting to ensure pressure vessel safety. In a combustion system, when abnormal pressure occurs and the venting orifice is opened, a lot of combustible mixtures venting from the vessel lead to a series of changes inside and outside the vessel, and may result in serious explosion disasters.

During the venting process, the explosion which occurs outside the vessel is called external explosion. The combustible mixtures venting outside of the vessel are ignited by the jet flame and then led to external explosion. External explosion is the abnormal situation during the venting process. According to the study of Harrison and Eyre (1987), external explosions can not only produce explosion disasters outside of the vessel, but also make the inside pressure of the vessel rise. In essence, external explosion is the transit from deflagration to detonation (DDT). So the DDT mechanism has received much attention in recent years.

In order to study the mechanism of external explosions, many investigations (Catlin, 1991; Carnasciali *et al*., 1991; Wu and Swithenbank, 1992) were concentrated on intensified experiment conditions. In those experiments, the venting vessel was connected with another large vessel full of combustible gas mixture, and the combustible mixture vented to the large vessel. The investigations were aimed at studying when and how the external explosions occur by measuring the pressure and displaying the flow field. Catlin (1991)'s study was typical. He found two impulse peaks of super pressure. The second impulse pressure peak was generated by DDT of combustible mixture outside the vessel.

Holbrow *et al*.(1996)'s study on the behavior of dust explosions in linked vented vessel systems revealed that the passage of flame from the primary ignition vessel could result in a secondary explosion producing a much higher pressure than expected from a vented single vessel. They suggested that the effects

* Project (No. 19832030) supported by the National Natural Science Foundation of China

of secondary explosion were dependent on some factors such as the vent area, the pipe diameter, and so on.

Thomas and Jones (2000) employed a conventional wave tube to introduce a pre-ignited flame bubble from a circular pipe into a large vessel full of CH_4-O_2 mixture. They used Schlieren photography to shoot the venting process, and the occurring process of explosion could be clearly observed from the pictures.

Razus and Krause (2001) suggested that the key problem in venting is the appropriate design of the vent area necessary for effective release of the material. They presented a review of different calculation methods, their ranges of validity, their physical background and applicability.

Hu and Pu (2001) conducted experimental investigations on explosion occurring at the vent in a 0.025 m^3 vertical cylindrical vessel. They used 4.1% propane and 9.5% methane air mixtures with central bottom spark ignition. When vent explosions occurred at different failure pressure through different vent areas, pressure histories were obtained and possible mechanisms for vent explosions were discussed.

Since external explosion is a typical explosion disaster, it is necessary to study its mechanism. In this work, during the venting process of the experiment, external explosion was observed and its mechanism was studied. For a reactive system, however, the venting process is very complicated and is affected by many correlated factors such as Φ, ignition position, venting orifice diameter and failure pressure. These correlated factors are discussed below.

EXPERIMENT SYSTEM

The experiment system (Fig.1) includes venting vessel, gases mixing system, ignition device, pressure measurement and flow field display systems. The length of the vessel was 400 mm and its diameter was 200 mm. There was a series of orifices on the vessel for fitting sensors. One of the ends of the vessel was closed, while the other end was open with various area circular flanges where various thickness films were used to obturate the vessel. The methane and air in the mixing system were mixed in proportion in advance. The main measuring methods of the venting process experiment were pressure measurement and flow field measurement. A series of Kistler pressure sensors were used in the experiment (Table 1). And the deviation angle between all these sensors and the axis of the cylinder was 30° (Du, 2003). The first sensor above the venting orifice was used as datum mark. The sensor signals were amplified and input to the JV5200 transient register. YA-16 high speed spark photograph system was used to get the images of the flow field.

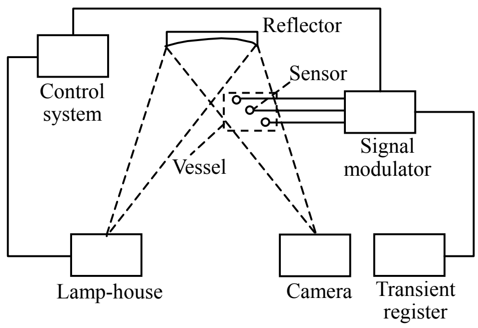


Fig.1 Diagram of experiment system

Table 1 Pressure sensors schedule

Number	Position*	Model	Scale
1	Orifice	211M	500 PSI
2	100 mm	211B	50 PSI
3	200 mm	211B	50 PSI
4	300 mm	211B	50 PSI
5	400 mm	211B	50 PSI
6	Bottom	211M	1000 PSI
7	Foreside	211M	1000 PSI

*The position refers to the distance between the sensor and the vessel orifice

After the venting vessel was vacuumed, the methane and air mixture were introduced into the vessel. The initial pressure was set to the pressure of the environment. Then the combustible gases mixture was ignited. During the venting process, the pressure measurement system records the various pressure processes inside and outside the vessel, while the YA-16 photographic system shoots the images of the flow field.

RESULTS AND DISCUSS

Normal venting process

The normal venting process without abnormal pressure should prevail during the venting process. The method to judge whether the venting process was normal was to examine whether there was only one pressure peak in the *P*-*t* curves and one wave in the pictures. For example, when Φ=0.8, initial pressure was 0.101325 MPa, venting diameter was 55 mm, ignition position was at the center of the vessel, and the failure pressure of the film was 0.3 MPa, external explosion did not occur as proven by comparing the *P*-*t* curves with the photos. The normal venting process is shown in Fig.2.

External explosion

The typical external explosion process is different from the normal venting one. Fig.3 shows that there are two pressure peaks in the *P*-*t* curves and two waves in the pictures. The first wave was the initial wave P_1 caused by the breaking of the orifice film. The second was the external explosion wave P_2 generated after venting. The experiment conditions of Fig.3 were selected as follows: Φ=1.0, failure pressure=0.101325 MPa, the diameter of the venting orifice was set at 55 mm, and the ignition position was set at the vessel bottom.

Next, the growing process of the explosion waves P_1 and P_2 was analyzed. The initial wave P_1 moved from the venting orifice to the outside space and reached the second, third, fourth and fifth sensor in 320 μs, 520 μs, 740 μs and 940 μs respectively. The external explosion wave P_2 that followed the initial explosion wave P_1 reached the second, third, fourth and fifth sensor in 400 μs, 580 μs, 820 μs and 1020 μs respectively. At the same time, the pressure of the external explosion wave P_2 was about 19.7 kPa, 21.5 kPa, 16.8 kPa and 10.6 kPa respectively. Different from the rapid attenuation of P_1, the pressure of P_2 increased at first, and then began to attenuate after a few microseconds. This means that during the venting process, the reigniting outside the vessel may not only compensate for the energy attenuation, but also increase the pressure inside and outside the vessel.

The curves and the pictures show that the time interval for the two explosion waves passing the same sensor was shortened, and was about 300 μs, 250 μs, 200 μs and 100 μs respectively when the explosion waves P_1 and P_2 passed by the second, third, fourth and fifth sensor. So it can be concluded that P_2 was chasing after P_1. According to this trend, it is expected that the wave P_2 may possibly catch up on the initial

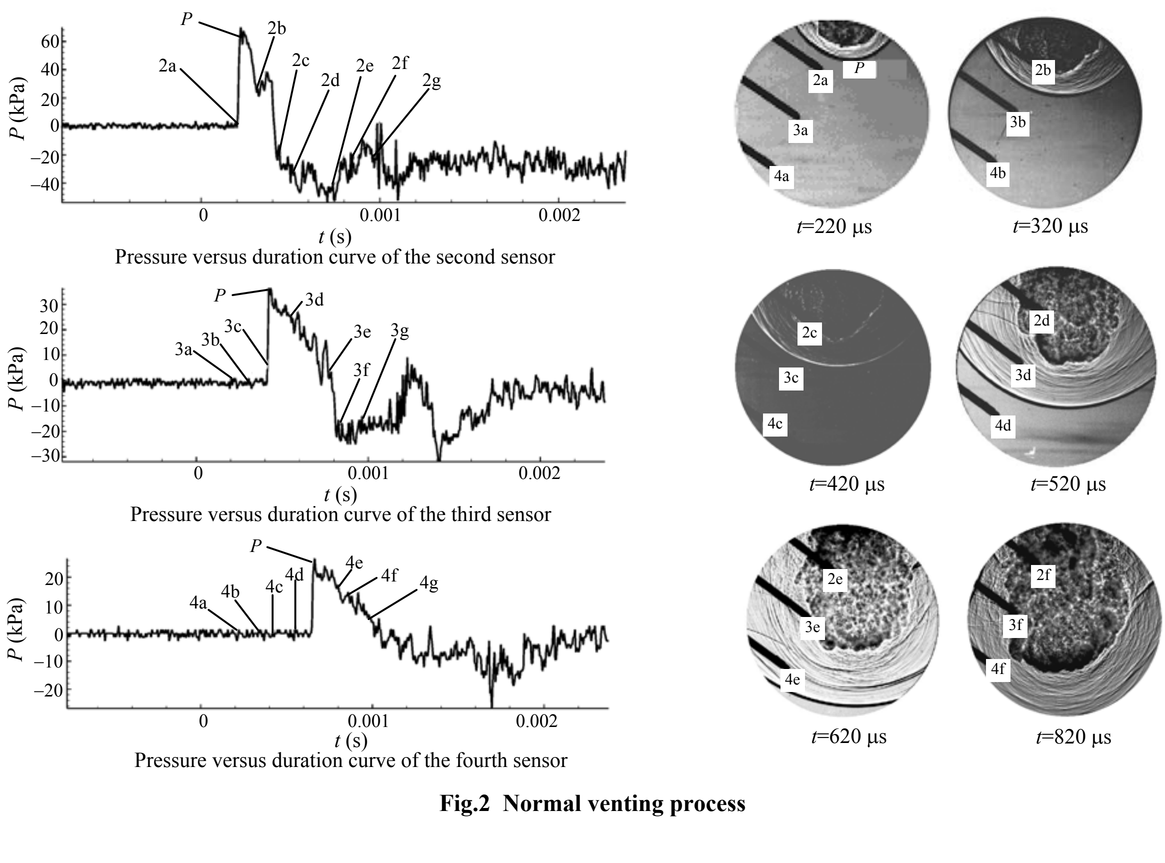


Fig.2 Normal venting process

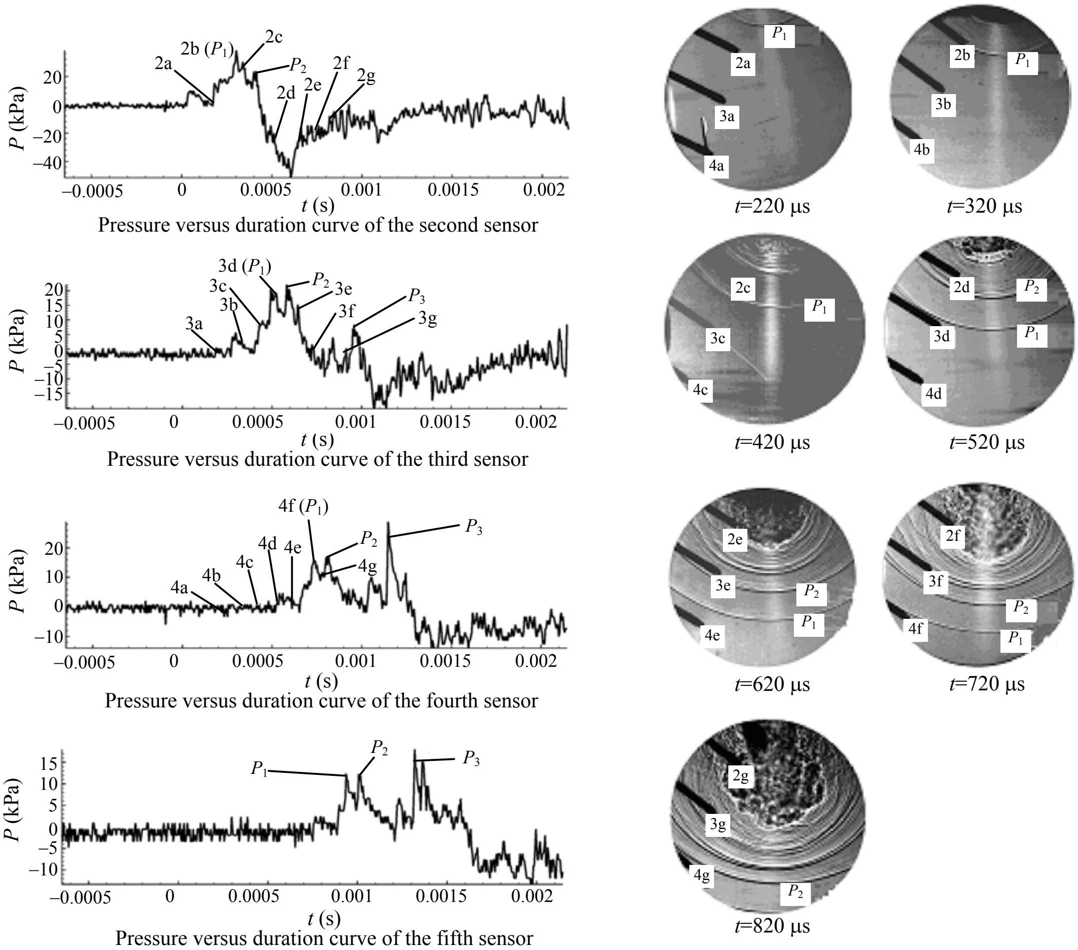


Fig.3 External explosion

wave P_1 to some extent.

In addition, it can be concluded from the images and the curves that the third explosion wave can be found. Comparison of the second sensor *P-t* curve with the third, fourth and fifth sensor *P-t* curves showed the occurring process of the third external explosion P_3. The second *P-t* curve showed that P_3 had not emerged, while the third sensor *P-t* curve showed that P_3 had formed clearly. So it can be concluded that P_3 was generated at the location between the second sensor and the third one. What was more, the pressure value of P_3 was only about 8 kPa when it reached the third sensor (shortly after its occurring), while it was about 30 kPa when it reached the fourth sensor. The pressure value of P_3 was increased by about four times. And then, P_3 began to attenuate. When it reached the fifth sensor, the pressure value of the explosion wave P_3 was 17 kPa.

Explosion occurs at the orifice

During the venting experiments, besides the external explosion, another abnormal phenomenon that was observed was the explosion at the vessel orifice. The *P-t* curve of the first sensor (Fig.4) showed that the value of the pressure at the venting orifice was about 5000 kPa. This condition was different from the normal venting condition and the external explosion condition.

Correlated factors

1. Influence of Φ

There was no doubt that Φ affected the venting process. And various value of Φ may lead to different venting results. When the venting diameter was 55 mm, conditions (Φ=1.0, Φ=0.8 and Φ=1.3) were investigated and the results are shown in Table 2. For Φ=1.0, external explosions occurred 17 times (among

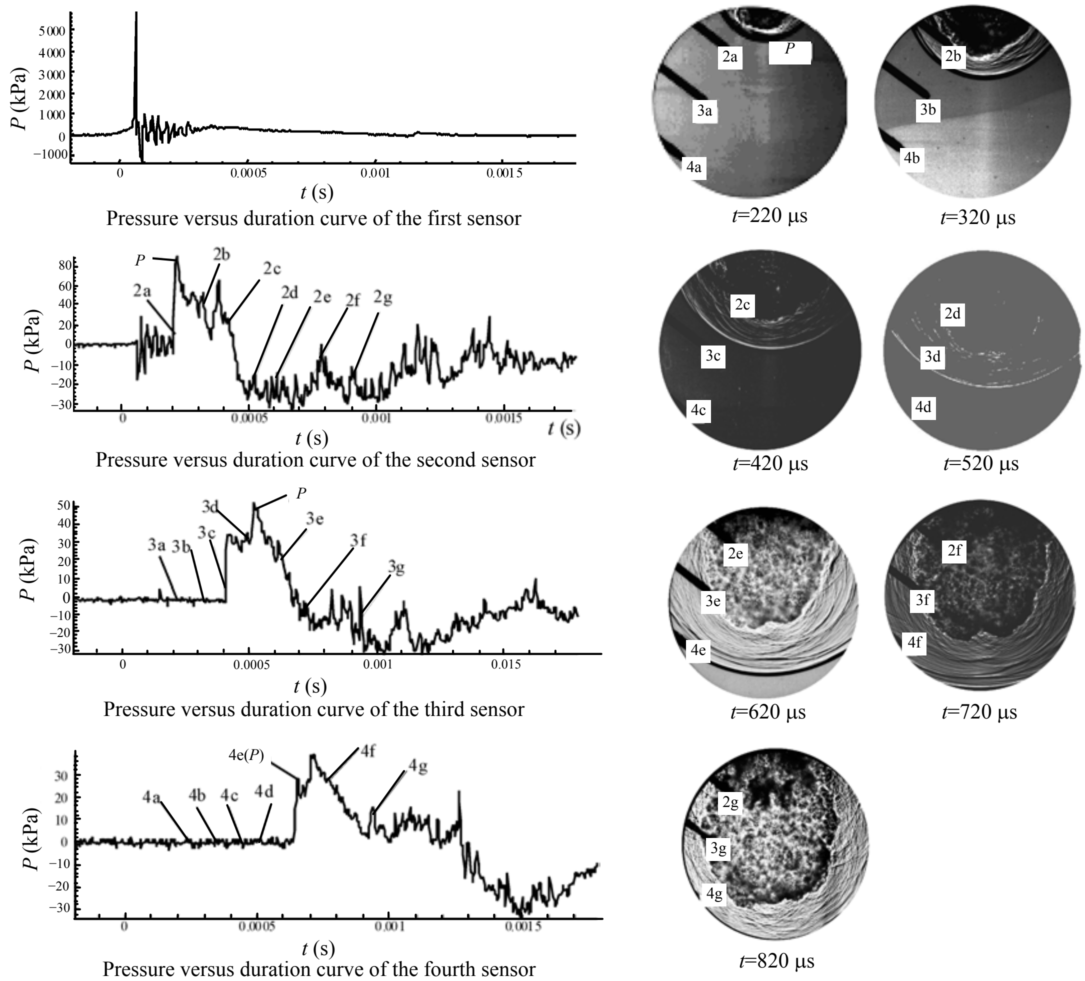


Fig.4 Explosion occurs at orifice

Table 2 Results of various Φ

Φ	Experiment (times)	Normal venting (times)	External explosion (times)	Orifice explosion (times)	Others (times)
1.0	46	16	17	6	7
0.8	7	4	1	2	0
1.3	5	4	0	1	0

46 times) comprising thirty-seven percent. While for *Φ*=0.8, only one (among 7 times) external explosion occurred. Moreover, none (among 5 times) occurred when *Φ*=1.3. The statistic results showed that when *Φ*=1.0, the external explosion occurred easily, while for *Φ*=0.8/1.3, it was more difficult.

Fig.5 and Fig.6 are two examples of external explosion phenomenon when *Φ*=1.0. The curves and pictures in Fig.5 showing two pressure peaks and two waves indicate occurrence of external explosion. Especially from Fig.6, the developing process of the external explosion wave can be observed clearly.

2. Influence of ignition position

Our experiments showed that the ignition position affected the venting process; and that various ignition positions led to different venting results. When *Φ*=1.0 and venting diameter was 55 mm, two kinds of conditions (vessel center ignition and bottom ignition) were investigated and the results are shown in Table 3. For center ignition, external explosions occurred 6 times (among 30 times) comprising twenty percent. For bottom ignition, external explosions occurred 12 times (among 28 times) comprising forty-three percent. The statistical results showed that

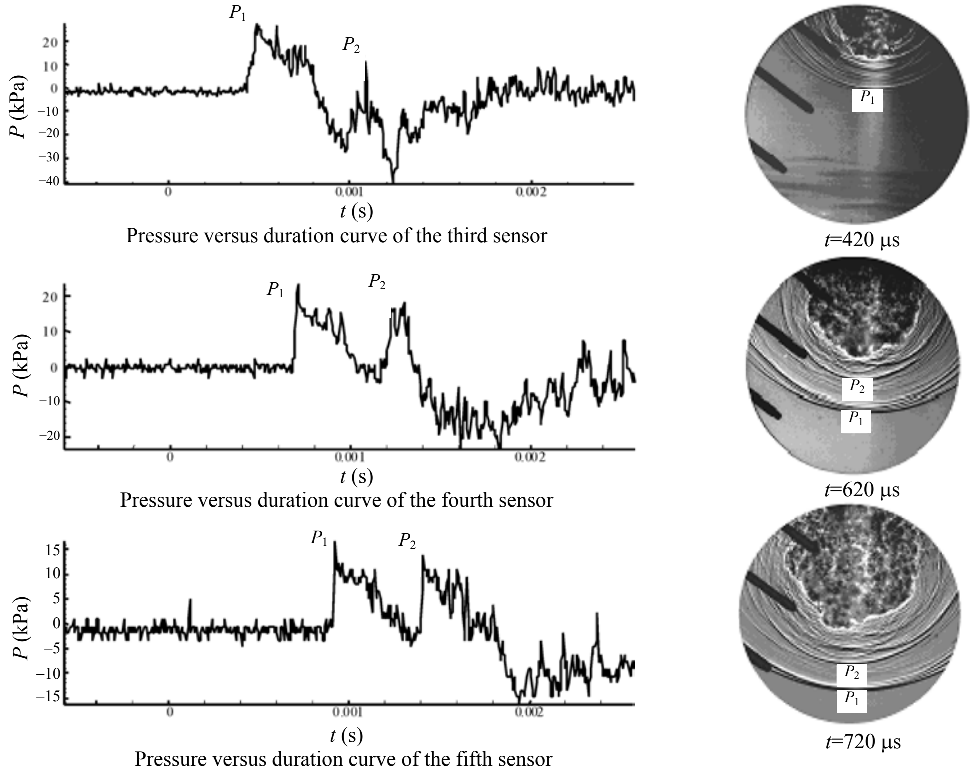


Fig.5 Example 1 of external explosion (Φ=1.0)

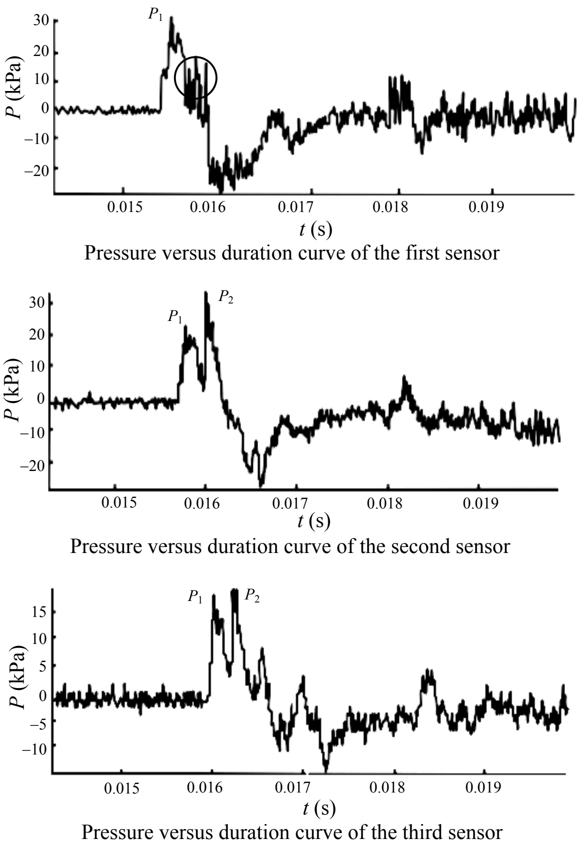


Fig.6 Example 2 of external explosion (Φ=1.0)

igniting at the vessel bottom, rather vessel center, led to external explosion easily.

Fig.7 is an example when the ignition position was selected at the vessel bottom. The curves and pictures showing two pressure peaks and waves indicate external explosion occurred.

3. Influence of failure pressure

Failure pressure would also affect the venting process. When Φ=1.0 and venting diameter was 55 mm, two kinds of conditions (low failure pressure and high failure pressure) were investigated and the results are shown in Table 4. In the former condition, there were 6 times (among 17 times) when external explosion occurred, comprising thirty-five percent. In the latter condition, however, there was only one time (among 14 times) when external explosion occurred, comprising seven percent. The statistical results showed that low failure pressure, rather than high failure pressure, easily led to external explosion.

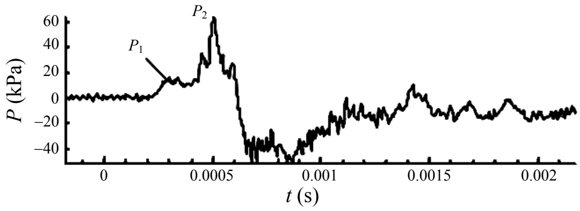
Fig.8 is an example when failure pressure was low. From the curves and pictures with two pressure peaks and waves, it can be concluded that external explosion occurred.

Table 3 Results of various ignition positions

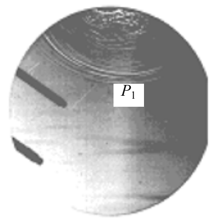
Ignition position	Experiment (times)	Normal venting (times)	External explosion (times)	Orifice explosion (times)	Others (times)
Vessel center	30	15	6	4	5
Vessel bottom	28	9	12	5	2

Table 4 Results of various failure pressures

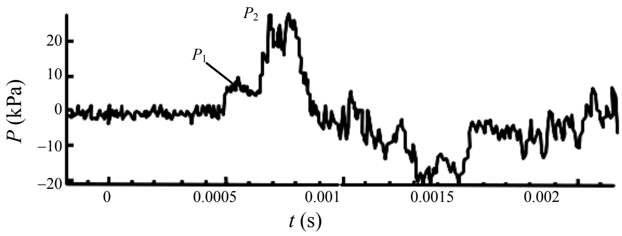
Failure pressure	Experiment (times)	Normal venting (times)	External explosion (times)	Others (times)
Low	17	8	6	3
High	14	7	1	6



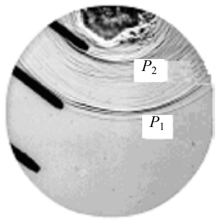
Pressure versus duration curve of the second sensor



t=420 μs

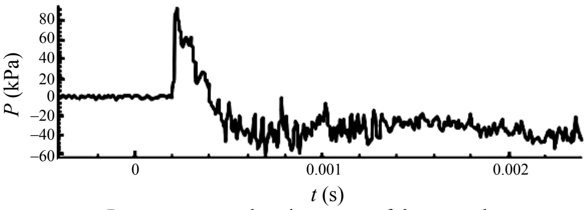


Pressure versus duration curve of the third sensor

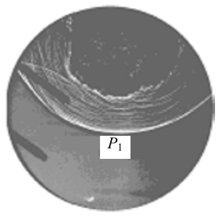


t=520 μs

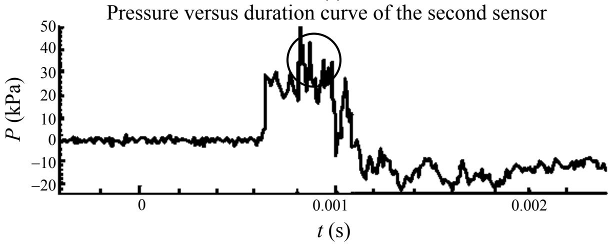
Fig.7 External explosion (bottom ignition)



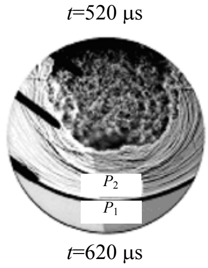
Pressure versus duration curve of the second sensor



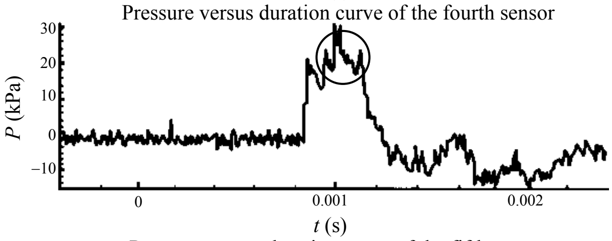
t=520 μs



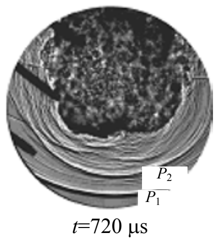
Pressure versus duration curve of the fourth sensor



t=620 μs



Pressure versus duration curve of the fifth sensor



t=720 μs

Fig.8 External explosion (low failure pressure)

CONCLUSION

External explosion is the abnormal condition during the venting process. The method to judge whether external explosion occurred is to examine whether there are two pressure peaks in the *P*-*t* curves and two explosion waves in the figures. The external explosion process observed in this experiment is discussed in this paper. Another abnormal phenomenon found was that the explosion occurred at the venting orifice. Some correlated factors (such as Φ, ignition position and failure pressure) affecting the venting process are discussed in this paper. Three conclusions were drawn:

First, the venting process was remarkably influenced by Φ. When Φ equals 1.0, the external explosion would easily occur, but when Φ equals 0.8 and 1.3, the external explosion does not easily occur.

Second, the ignition position influences the venting process. When the ignition point is at the bottom of the vessel, external explosion easily occurs. However, when the explosion is ignited at the center of the vessel, external explosion becomes relatively difficult.

Finally, failure pressure affects the venting process. Experiments confirmed that low failure pressure, as compared with what was found for high failure pressure, would more easily lead to external explosion. In essence, when the failure pressure is low, as compared with the condition when failure pressure is high, more combustible mixture vents from the vessel to the outside space because the venting orifice is opened earlier. And the unburned combustible mixture can be reignited more easily and then leads to external explosion.

References

Carnasciali, F., Lee, J.H.S., Knystautas, R., Fineschi, F., 1991. Turbulent jet initiation of detonation. *Combustion and Flame*, **84**:170-180.

Catlin, C.A., 1991. Scale effects on the external combustion caused by venting of a confined explosion. *Combustion and Flame*, **83**:399-411.

Du, Z.M., 2003. Study of External Explosion Phenomenon During the Venting Process. Nanjing University of Science and Technology, Master's Thesis (in Chinese).

Harrison, A.J., Eyre, J.A., 1987. "External explosions" as a result of explosion venting. *Combust. Sci. Technol.*, **52**:91-106.

Holbrow, P., Andrews, S., Lunn, G.A., 1996. Dust explosions in interconnected vented vessels. *J. Loss Prev. Process Ind.*, **9**:91-103.

Hu, J., Pu, Y.K., 2001. Experimental investigations of pressure development during explosion vent from cylindrical vessels. *Explosion and Shock Waves*, **21**(1):47-52.

Razus, D.M., Krause, U., 2001. Comparison of empirical and semi-empirical calculation methods for venting of gas explosions. *Fire Safety Journal*, **36**:1-23.

Thomas, G.O., Jones, A., 2000. Some observations of the jet initiation of detonation. *Combustion and Flame*, **120**:392-398.

Wu, Y., Swithenbank, J., 1992. Experimental studies on gas-dynamics of venting explosions. *Trans. IChemE*, **70** (Part A):200-203.