EXPLOSION VENTING OF RICH HYDROGEN-AIR MIXTURES IN A CYLINDRICAL VESSEL WITH TWO SYMMETRICAL VENTS

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ABSTRACT
The safety issues related to explosion venting of hydrogen-air mixtures are significant and deserve more detailed investigation. Vented hydrogen-air explosion has been studied extensively in vessels with a single vent. However little attention has been paid to the cases with more than one vent. In this paper, experiments about explosion venting of rich hydrogen-air mixtures were conducted in a cylindrical vessel with two symmetrical vents to investigate the effect of vent area and distribution on pressure buildup and flame behaviors. Venting accelerates the flame front towards the vent but has nearly no effect on the opposite side. The maximum internal overpressure decreases and the maximum external flame length increases with the increase of vent area. Two pressure peaks can be identified outside of vessel, which correspond to the external explosion and the burnt gas jet respectively. Compared with single vent, two vents with same total vent area leads to nearly unchanged maximum internal and external overpressure but much smaller external flame length.

1.0 INTRODUCTION

Hydrogen is a promising clean energy carrier, but it is considered to be dangerous because of its extensive flammable range, low ignition energy and fast flame behavior. Explosion might occur once hydrogen-air mixture is presented in confined spaces. Therefore, explosion venting is recommended to prevent or mitigate explosion damage to enclosures.

As is well known, one key issue of explosion venting is to select the appropriate vent area so that the explosion overpressure does not exceed a maximum permissible value. The effect of vent area on explosion venting of gas mixtures has been investigated extensively [1-11]. The experimental results of Cooper et al. [1] show that, with the decrease of vent area, the first, the third and the fourth pressure peak increases, but the second pressure peak first increases and then decrease. McCan et al. [5], Kordylewski and Wach [6] and Rocourt et al [7] found that Helmholtz oscillation occurs only in vessels with large vent areas. Special attention is paid to the effect of vent area to the peak internal pressure [8,9], and it is found that smaller vent area leads to higher peak internal pressure in direct vented vessel. But it is more complex in the presence of vent duct. For example, Kordylewski and Wach [6] and Molkov et al.[10] found that an increase in the duct diameter was followed by peak pressure decrease; however, the experimental results of Ponizy and Leyer [11] revealed that an increase in the vent area does not always result in a decrease in the peak pressure, which was numerically reproduced by Ferrara et al. [12] and was explained as the outcome of the competition between the burning rate and the venting rate. In other researches [13-15], critical effect of vent area on the formation of external combustible cloud and the external pressure profile was found.

In addition to the experimental investigations, numerical works about the effect of vent area on explosion venting have been conducted to describe pressure buildup and flame propagation [12,16-20]. In the model given by Molkov et al. [21-24], the ratio of turbulence factor to discharge coefficient was introduced to account for the pressure buildup. Based on the extensive experimental and numerical works, NFPA 68 [25] and EN 14994 [26] provide the correlations for calculating the vent area.

In most of the previous investigations, explosion venting in vessel with only a single vent was concerned; however little attention has been paid to the cases with more than one vent. Solberg et al. [8] found that explosions with vent openings on one wall will result in Taylor instabilities and the vent areas were suggested to be placed on as many sides of the vessel as possible. Crowhurst et al. [27] noted that pressures of dust explosion are reduced when using several relief vent openings with the same total area and provided an empirical correlation between the external flame length and the numbers of vent, which can also be found in NFPA 68 [25]. So far, some important issues for explosion venting of hydrogen-air mixtures in vessels with more than one vent still have not been studied; for example, how does pressure build up and how does flame propagate in and outside of vessel in the case of two vents? And how much is the difference between the cases of single and two vents with same total vent area? In this paper, experiments on explosion venting of rich hydrogen-air mixtures in a cylindrical with two symmetrical vents were conducted to address the questions.

2. 0 EXPERIMENTAL

Fig.1 is a schematic of vented vessel in present study. Experiments were conducted in a stainless cylindrical vessel with two symmetrical ducts at its waist. Both inner diameter and length of the cylindrical vessel are 25 cm, and two quartz windows with same 50 mm thickness were mounted at both ends of the vessel for allowing optical access necessary to the schlieren system. The length and the cross section of the ducts are 10 cm and 7 cm×7 cm, respectively. The actual vent area (A_v) was determined by the orifice plates with central square hole fitted at the exits of ducts. Each experiment was conducted twice, and the reproducibility of the pressure profiles, peak pressures and flame behaviors was found to be good. The experimental conditions are summarized in Table 1. In test 1-2, vent area being zero means constant volume explosion; in test 3-10, one vent was used and the vent area in test 11-18 is the total of the two square holes.

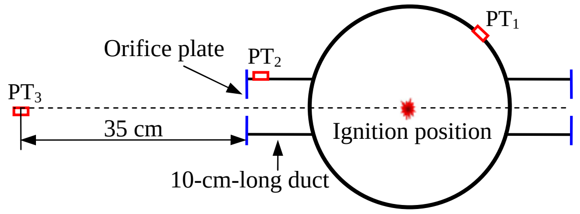

Figure 1. Schematic of vented vessel. (PT_1-PT_3: pressure transducer)

The hydrogen-air mixtures were ignited at the center of the vented vessel by the electrodes which were

2 mm in diameter and 1.5 mm in gap width, and the ignition energy is kept about 500 mJ. Three piezoelectric pressure transducers were employed to record pressure history inside and outside of vessel during venting process, which were fitted respectively on vessel wall (PT_1) , 2 cm away from exit (PT_2) and 35 cm away from vent exit outside of vessel (PT_3), as shown in Fig.1.

The experimental layout can be found in our previous study [28]. Schlieren system combined with a high speed camera (NAC HX-3) was adopted to visualize the explosion flame in vessel. Another high speed camera was used to record the explosion flame inside and outside of the vessel. Frame rate of the high-speed cameras was 10,000 fps. The vessel was first filled with hydrogen-air mixture with equivalence ratio 2.0. After that, a piece of paper was lightly glued to seal the vents. And then the high speed cameras and the oscillograph were triggered simultaneously by transistor-transistor logic (TTL) signal from a signal synchronizer to ignite hydrogen-air mixtures, record flame images and pressure-time histories, respectively. The initial pressure and temperature of hydrogen-air mixture in all tests were 1 atm. and 280 K, respectively.

Table 1. Summary of the experimental conditions.

Test number	Number of vent	Vent area (cm^2)	Vessel volume(cm^3)	Duct length (cm)
1,2	0	0	12266	10
3,4	1	6.12		
5,6	1	12.25		
7,8	1	24.5		
9,10	1	49		
11,12	2	6.12×2=12.24		
13,14	2	12.25×2=24.5		
15,16	2	24.5×2=49		
17,18	2	49×2=98		

3.0 RESULTS AND DISCUSSION

3.1 Flame propagation in vessel

Fig.2 shows typical schlieren images of the internal flame for different vent areas. In the early stage after ignition, the flame bubble was kept spherical in all tests as shown in Fig.2. But with further expansion of the flame bubble, the flame surface was stretched to the vent, and the flame distortion was fount to occur earlier for larger vent area. For example, the flame entered the duct at 5 ms after ignition in test 9, but no obvious flame distortion was observed till at 6 ms after ignition in test 3.

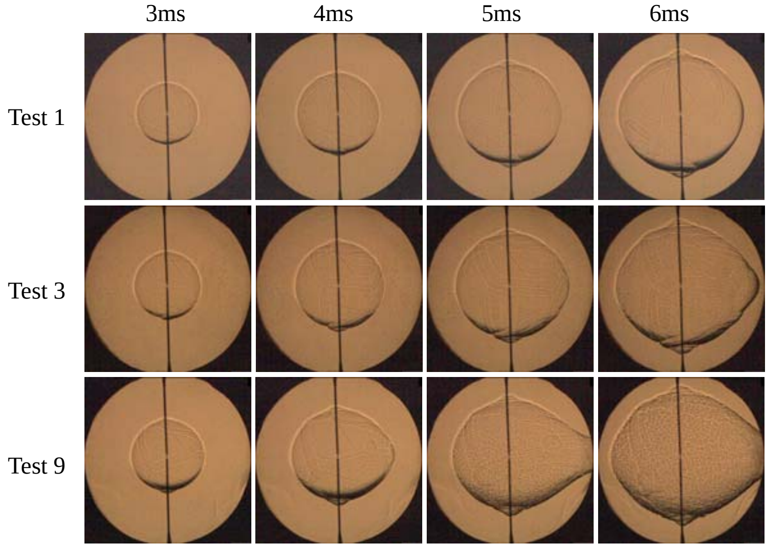

Figure 2. Schlieren images of internal flame for different areas.

Fig.3 presents the flame front location and speed evaluated from the schilieren images by dividing the distance the flame front travels with the time difference between two frames (0.1 ms). Note that the negative sign means the direction opposite to the vent. As can be seen clearly in Fig.3, the flame is accelerated towards the vent and reaches about 9 m/s when it enters the duct in test 9. However, venting has little effect on flame propagation in the direction opposite to the vent. Compared with test 1 (constant volume explosion), no much difference in the tracks of flame front propagating opposite to the vent can be observed in test 9, and the flame expands with a speed oscillating from about 1.0 m/s to 2.5 m/s.

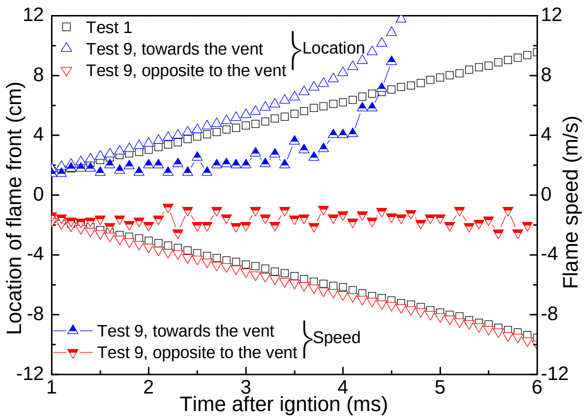

Figure 3. Location of flame front vs. time.

In addition, vent area also affects the formation of cellular structures on flame surface. As shown in Fig.2, the flame surface is still kept quite smooth except for some wrinkles at 6 ms after ignition in test 1. However much more wrinkles appear in test 3 and the flame surface is not relatively smooth. When the vent area increases to 49 cm^2 (test 9), a lot of cells appear on the bottom of the flame bubble at 5 ms after ignition. Then flame cellularity evolves quickly and ends in a millisecond. The effect of vent area on the appearance of flame cellularity lies in the fact that flame elongation due to venting contributes to the appearance of the cellular structures on flame surface [5]. Larger vent area leads to higher outflow rate of gas mixtures and larger flame elongation. As a result, flame cellularity occurs earlier. When two vents with same total vent area are used, Fig.4 shows that the flame bubble is stretched symmetrically, and flame cellularity occurs earlier than the case with one vent. As shown in Fig.4, only a few cells appear at 5 ms after ignition in test 7. However the flame surface has become completely cellular at that time in test 13. But the difference in flame distortion and cellularity between the case of single vent and two vents makes no obvious difference in the internal pressure profile, as will be shown in the next section.

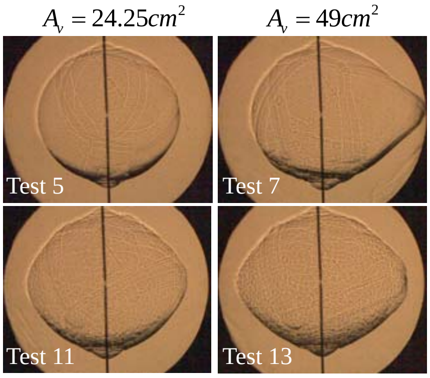

Figure 4. Flame images at 5 ms after ignition in the cases of single vent and two vents.

3.2 Pressure profile in vessel

Fig.5 presents typical unfiltered pressure histories for different vent area. Different from the pressure profile with multi-peak for hydrocarbon-air mixtures obtained by the former researchers [3,9,20], only one dominant pressure peak can be observed due to the faster burning rate of hydrogen in current study. The internal pressure first increases steeply to its maximum value and then decreases gradually. Except the pressure oscillation in test 17 which will be discussed in the next section, the pressure histories vary in quite a similar way. Fig.5 also shows that the time needed for the internal pressure to decrease to ambient pressure increases with the decrease of vent area. For example, it increases from about 50 ms in test 5 to about 80 ms in test 3, and a much longer time is needed in test 1 due to the heat losses to vessel wall.

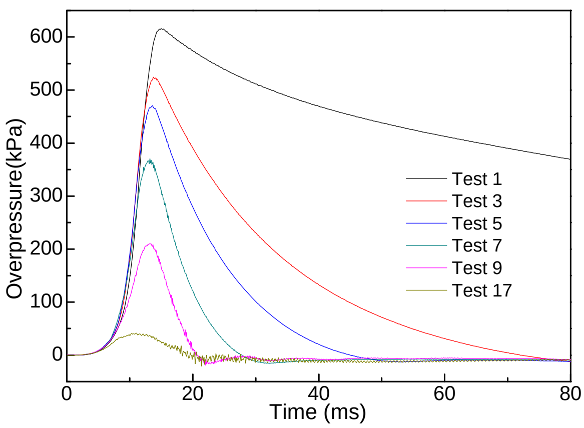

Figure 5.Internal pressure histories for different vent areas.

Fig.6 compares the pressure histories in the case of single vent and two vents with same total vent area.

The pressure histories are quite similar and no significant change of the maximum overpressure occurs when the vent area is equally divided, which is different from the result of Crowhurst et al. [27] that pressures of dust explosion were reduced when several relief vent openings with the same total area were used.

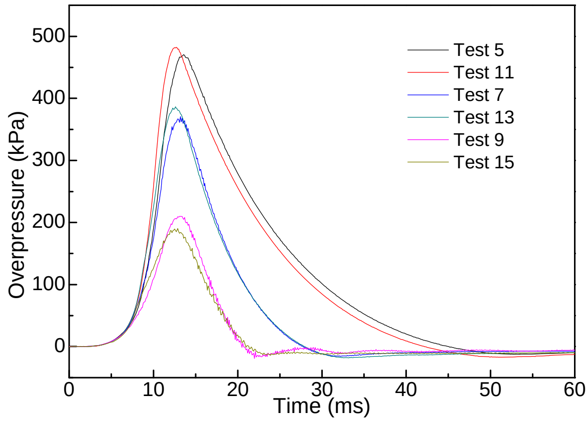

Figure 6. Comparison of internal pressure histories in the cases of single vent and two vents.

As reported in the previous investigations about explosion venting of hydrogen [2,6], the maximum overpressure decrease with the increase of vent area. As shown in Fig.7, the maximum overpressure decrease exponentially with the increase of vent area both in the cases of single vent and two vents with same vent same area. It is worth noting that the maximum overpressure of hydrogen-air mixtures is much higher than that of hydrocarbon-air mixtures [1,3], which can be attributed to the higher burning rate of hydrogen. For example, the measured maximum overpressure is around 200 kPa when vent area is 49 cm^2, which yields a vent parameter $V^{2/3}/A_v$ being 10.9, where, V is vessel volume and A_v is vent area. So, compared to hydrocarbons, larger vent area is needed for hydrogen to keep the explosion overpressure below a maximum permissible value.

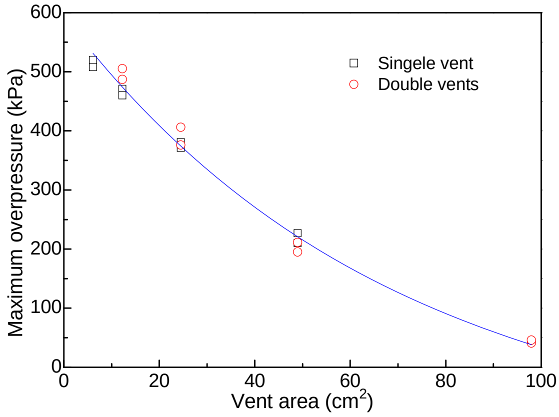

Figure 7. Maximum internal overpressure vs. vent area.

3.3 Flame behavior and pressure profile outside of vessel

Typical images of the external flame are presented in Fig.8. When the vent area is large, for example in test 7, a fireball with a diameter much larger than the length of vent size first appears in front of the vent and then it is distorted to become a jet flame. The latter extends quickly to its maximum length, then decreases in length and disappears at last. However, the fireball can hardly be observed when then vent area is small, for example in test 3 as shown in Fig.8. Daubech et al. [15] found that vent area has a significant influence on the formation of external cloud and a jet like structure appears when the vent area is reduced. So it can be deduced that, for large vent areas, the fireball is resulted from the quick combustion of the unburnt external cloud and the following jet flame forms due to the continuous combustion of the vented burnt gas mixtures which is initially hydrogen- rich. For small vent areas, for example in test 3, the jet flame may be the result of the combustion of the "jet like structure" as observed by Daubech et al. [15].

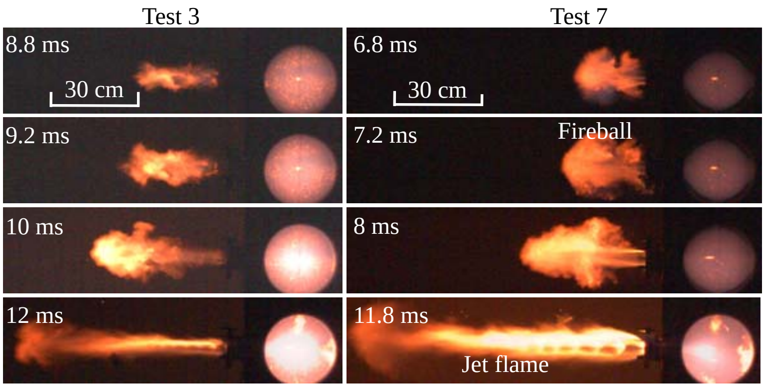

Figure 8. Flame images outside of vessel.

In this paper, attention is paid to the maximum length of the external flame, which is found to be closely related with distribution of vent. In the case of single vent, Fig.8 shows that the maximum length of the external flame is much longer in test 7 than that in test 3. Fig.9 presents the maximum flame length in the case of single vent (test 9) and two vents (test 15) with same total vent area. It can be clearly seen that the flame length through one of the symmetrical vents decreases much, but the total length through the two vents in test 15 has no much difference with that in test 9.

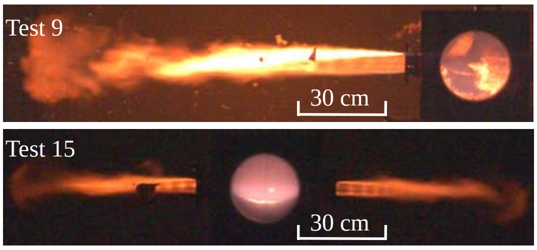

Figure 9. Maximum flame length in the cases of single vent and two vents.

The maximum flame lengths in tests 3-18 are summarized in Fig.10. Note that the values in the case of two vents are the flame lengths through one of the symmetrical vents. It is found that the maximum flame length increases with an increase of the vent area in case of a single vent. As discussed above, the jet structure is resulted from the continuous combustion of vent fuel-rich mixtures outside of vessel, and its maximum length should depend on the volume flow rate of vented gas mixtures. Under current experimental conditions, the vented flow is choked in most cases, so its volume flow rate increases with vent areas and as a result the maximum flame length also increases. When the vent area is equally divided, the flame length is much decreased, which follows qualitatively with the empirical equation of dust flame length ($L_f = k\sqrt[3]{V/n}$, where, L_f is flame length, k is flame length factor, V is vessel volume and n is the number of evenly distributed vents) provided by Crowhurst et al.[27] and NFPA 68 [25].

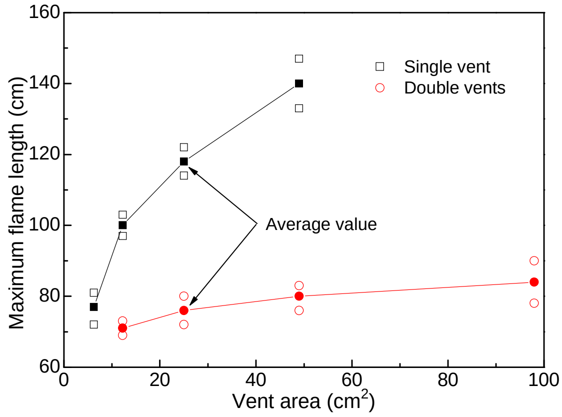

Figure 10. Maximum flame length vs. vent area.

In addition, it is found that the external pressure profile is closely related with the behavior of external flame and depends on experimental conditions. As shown in Fig.11, two pressure peaks p_1 and p_2 can be clearly identified in test 7, which are the due to the formation of fireball and the following jet structure, respectively. When the vent area is large, a large amount of unburnt gas mixtures was discharged to form a combustible cloud in front of vent, which was ignited by the vented flame to result in an external explosion [1,14,15], and consequently the first pressure peak p_1 appears. Burnt gas mixtures were vented at high speed following the external explosion, which leads to the appearance of the second pressure peak p_2 . But when the vent area is small, the fireball can hardly be observed in Fig.8; that is to say, no turbulent external explosion occurs, so p_1 can hardly be distinguished in test 3.

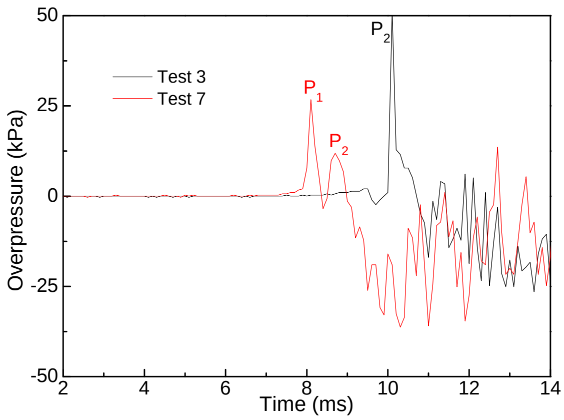

Figure 11. External pressure histories outside of vessel.

In the external pressure profile, which pressure peak dominates depends on the vent area and the distribution of the vents, and unfortunately there is no universal rule. When vent area is 6.12 cm^2 and 12.25 cm^2, the second pressure peak always dominates the external pressure profile. But when the vent area is 24.5 cm^2 and 49cm^2, the situation may change. For example, the second pressure peak is dominant in test 9 and 10 and the first pressure peak becomes the dominant one in test 15 and 16. It should be noted that vent area has no critical effect on the maximum external overpressure with the range from about 15 kPa to 50 kPa.

Critical effect of external explosion on the internal overpressure has been found in previous studies [7,9,14,29,30], which can also be found in current experiments but only in test 17. As mentioned above, turbulent oscillation of the internal pressure occurs in this case. Fig.12 presents the pressure histories in and outside of vessel in test 9 and 17. The internal pressure is effectively released due to the large vent area (98 cm^2) in test 17. So, the pressure near vent exit (PT_2) can exceed temporarily the internal one (PT_1), which is caused by a backward propagating wave due to external explosion. The turbulent oscillation of internal pressure may be resulted from the interaction between the internal flame and turbulence generated by the backward propagating wave [31]. It can be also attributed to the Richtmyer–Meshkov instability caused by the interaction of the internal flame with the backward propagating wave and its multiple reflected waves on vessel wall. However, turbulent oscillation is absent in test 9 due to the fact that PT_1 is larger than PT_2 when external explosion occurs.

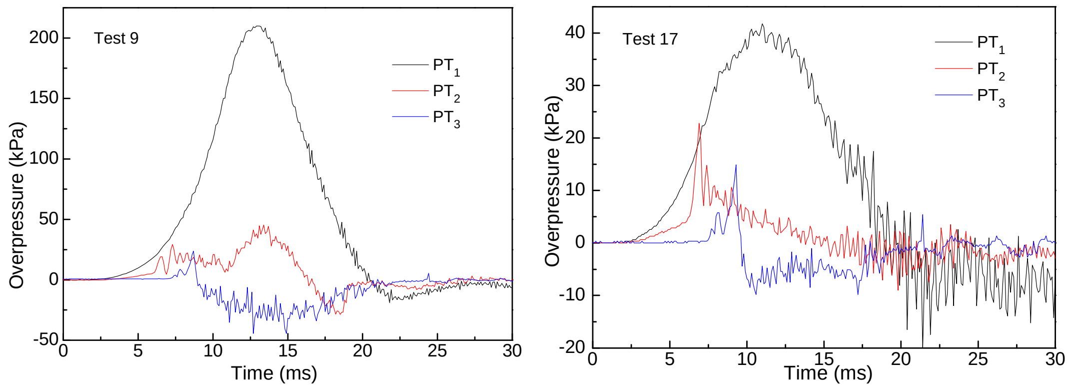

Figure 12. Pressure histories in and outside of vessel.

4. 0 CONCLUSIONS

The effect of vent area on flame propagation and pressure buildup during explosion venting of hydrogen-air mixture with equivalence ratio of 2 is experimentally investigated in a small cylindrical vessel with two symmetrical vents. The vent area was determined by the orifice plates with central square hole fitted at the exits of ducts. Experiments with a single vent and two vents with same total vent areas were conducts respectively. The conclusions can be summarized as follows.

Larger vent area leads to larger flame elongation to the vent and earlier appearance of flame cellularity, but the flame speed opposite to venting is independent of vent area and remains nearly constant. Only one internal pressure peak was observed in all tests, which decreases exponentially with the increase of vent area. Oscillation of the internal pressure occurs when the backward propagating wave caused by external explosion enters the vessel.

Two dominant pressure peaks can be found outside of vessel. The first one is resulted from the quick combustion of the vented unburnt gas mixtures while the second one is from the vented gas jet. The increase of vent area leads to the increase of the maximum length of the external flame, and however has no significant effect on the maximum external overpressure.

Compared with single vent, two vents with same total vent area leads to nearly unchanged internal and external maximum overpressures but much smaller maximum external flame length.

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