Experimental Study on Shock Waves, Spontaneous Ignition and Flame Propagation Produced by Hydrogen Release through Tubes with Varying Obstacle Location

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ABSTRACT

Experimental investigations were performed to evaluate the effects of obstacles inside tube on the pressure dynamics evolution, spontaneous ignition and flame propagation during pressurized hydrogen release. The obstacles region was consisted of seven metal obstacles and six metal spacers. Pressure transducers and light detectors were installed along the tube to measure pressure variation and hydrogen flame inside tube. The influence of obstacles was examined for three different locations inside tube. The results show that the strength of shock wave is weaken by flow divergence, and then gradually recovers as it travelling along the tube. The light signal analysis shows that the presence of obstacles in different locations has almost no influence on the minimum burst pressure for spontaneous ignition in our tests. However, the presence of obstacles plays an important role in the hydrogen combustion inside tube. Once the spontaneous ignition occurring inside tube, the reflected shock wave promotes combustion before obstacles. And the probability of the flame intensity enhancement increases with increasing distance between burst disk and obstacle location. In addition, the combustion inside tube is only temporarily intensified after obstacles.

KEYWORDS: High-pressure hydrogen, spontaneous ignition, obstacle locations, shock wave, flame propagation.

INTRODUCTION

As a renewable clean energy, hydrogen presents excellent characteristic such as high efficiency and no-emissions. The application of hydrogen fuel cell vehicles (HFCVs) is gaining an increasing attention worldwide. However, there are some technical problems impeding the development of HFCVs, one of which is the onboard high-pressure hydrogen storage safety. Severe fires and explosions maybe caused when hydrogen sudden leaks from high-pressure container or a pipe without the presence of ignition sources. It is necessary to understand the kinetic characteristic of spontaneous ignition and subsequent flame evolution during pressurized hydrogen release.

The diffusion ignition mechanism for spontaneous ignition was first proposed by Wolanski and Wojcicji [1], and it has been extensively studied since then. Wolanski and Wojcicji [1] demonstrated that ignition may occur inside the tube when the temperature of hydrogen-air mixture behind the leading shock wave is flammable and the temperature is high enough. Dryer et al. [2] suggested the multi-dimensional transient flow plays an important role in spontaneous ignition, which can facilitate mixing of shock-heated air and expanding hydrogen behind the shock wave. Shock-induced vortices and turbulence generated at the hydrogen-air contact surface promote molecular diffusion and provide more combustible mixtures for spontaneous ignition [3-5]. Except for high temperature hydrogen-air mixture in contact surface, another key factor for spontaneous

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ignition is that the mixture maintains for a long enough time until inflammation [6, 7]. Several flow visualization studies [8-11] were conducted to investigate the ignition process and the flame propagation inside tube by the shadowgraph and high-speed direct photography. The duration period of mixing increases as the leading shock wave travels along the tube, and the ignition takes place after a certain induction time elapsing from the start of mixing [9]. There were two possible locations where initial ignition was captured: one was in the boundary layer along the wall and another one was on the tube axis at the contact region [9-11]. The hydrogen flame produced by spontaneous ignition inside the tube may be quenched or developed into a hydrogen jet flame after it exits the tube. It was suggested that the formation of a complete flame across the tube is important for a sustained hydrogen jet flame outside the tube [12]. The hydrogen flame propagation dynamics outside tubes was also studied in [13-16]. It was found that the flame grows gradually after jetting into air, then vortex induces the flame splitting into upstream and downstream region, and the upstream flame region sustains near the tube exit finally [15, 16].

The majority of previous studies have focused on the spontaneous ignition of high-pressure hydrogen sudden release through a tube without obstacles. In practice, there is often the presence of obstacles either inside or outside tube during pressurized hydrogen release. Xu et al. [17] found that the presence of obstacle may quench the flame when a direct pressurized hydrogen release into air by numerical simulation. However, Kim et al. [18] pointed out that the existence of an obstacle outside the tube could not change the type of ignition patterns but may promote flame stabilization outside the tube. Morii et al. [19] reported that small obstacles inside a tube drastically changed the spontaneous ignition mechanisms when pressurized hydrogen sudden discharged through the tube. When the leading shock wave passed through the lateral orifice [20] or bottom orifice [21] along release tubes, it was suggested the reflected shock wave was produced and was necessary for spontaneous ignition. Nevertheless, the experimental investigation is necessary to deep understand the effects of obstacles inside tube on hydrogen spontaneous ignition. In this paper, an experimental study is carried out to investigate the effect of obstacle locations inside the tube on the shock wave, spontaneous ignition and flame propagation of high-pressure hydrogen.

EXPERIMENTAL APPARATUS

Figure 1 shows the schematic of experimental apparatus which is based on a shock tube system. The drive section is a 0.44 l high-pressure hydrogen tank and the driven section is a downstream release tube with ambient pressure air. A circular nickel burst disk with cross scores (Dalian Ligong Safety Equipment Co., Ltd) is used as diaphragm to separate the high-pressure tank and release tube. The burst pressure (P_b) is measured by a strain gauge pressure sensor (Kulite, ETM-375M-20MPa) mounted in the high-pressure tank. Cylindrical release tubes with three obstacle locations are considered and the schematic of obstacle locations inside tube is shown in Fig 2 (a). The experimental results of the tube with obstacles in location 3 have been reported in our recent publication [22]. Figure 2 (b) presents the detailed composition of obstacle region, which is composed of 7 metal obstacles (2 mm width) and 6 metal spacers (4 mm width) alternately. The burst disk, downstream release tube, metal obstacle and metal intervals have the same internal diameters of 15 mm. Four pressure transducers P_n (PCB Piezotronics, 113B22) and four light detectors L_n (Thorlabs, Si photodiode, FDS010) are symmetrically installed along the release tube for measuring the pressure dynamics and flame signals. The burst pressure (P_b) is varied from 2 MPa to 7 MPa in this study.

The experimental procedure is as follows. First, air is evacuated from high-pressure tank and supply gas pipeline. High-pressure hydrogen is then gradually supplied to the tank until the diaphragm ruptures, resulting in the sudden release of hydrogen into the semi-confined exhaust chamber through the downstream release tube with obstacle. The exhaust chamber is a rectangular cavity of

1200 mm × 470 mm × 500 mm, which is connected with release tube on the left and open to atmosphere on the right. There is a pressure transducer (PCB Piezotronics, 113B22) installed on the top wall of the chamber to measure the overpressure (P_{out}) variation in the exhaust chamber. A high-speed video camera (Phantom, v700) is used to record the flame propagation phenomena outside tube from two viewports (230 mm × 230 mm) on the two exhaust chamber sides. The images are obtained at the recording speed of 79069 fps and resolution of 256×256 pixels. The time when P_1 detects a sudden pressure increase is set to trigger the high-speed video camera and the data recording system (HIOKI, 8860-50).

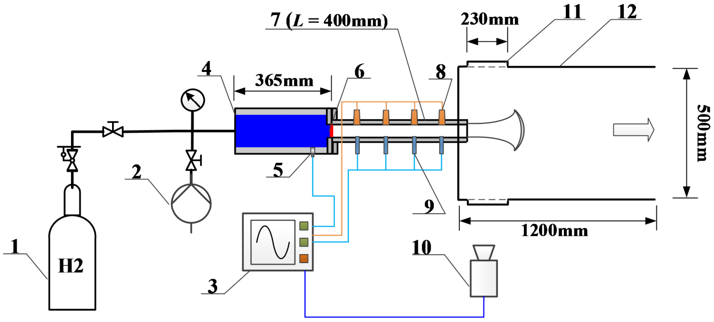

Fig. 1. Schematic of experimental apparatus:(1) compressed gas cylinder, (2) vacuum pump, (3) data recorder, (4) high-pressure tank, (5) strain gauge pressure sensor, (6) burst disk, (7) release tube, (8) light detector, (9) piezoelectric pressure transducer, (10) high-speed video camera, (11) viewport, (12) exhaust chamber.

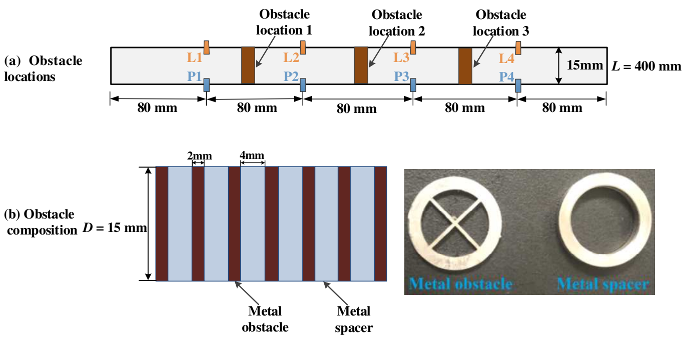

Fig. 2. (a) Schematic of obstacle locations inside tube, L – tube length, P_n – pressure transducer, L_n – light detector; (b) Schematic of obstacles arrangement and photos, D – diameter.

RESULTS AND DISCUSSION

The sudden release of high-pressure hydrogen into the tube can generate a shock wave which impacts on the piezoelectric pressure transducers (P_n). When spontaneous ignition occurs inside the tube, light signal can be detected by the light detectors (L_n). In total, 71 tests are conducted with different release tubes, in which 18 tests are carried out in a tube without obstacles for comparison. Here, the effects of obstacles inside tube on shock wave propagation are first discussed. Then, the spontaneous ignition inside the tube with and without obstacles is analyzed. Finally, the influence of obstacles on hydrogen flame propagation inside tube is studied.

Effect of obstacles on shock wave propagation inside the tube

Figure 3 shows the typical time history of pressure and light signals at different positions inside tube with varying obstacle locations. A shock wave is formed and propagates inside tube with the fact that a sharp pressure rise is sequentially detected by pressure transducers P_1, P_2, P_3 and P_4. When the shock wave impacts on the obstacles, a reflected shock wave is formed and propagates to upstream in the tube. As the reflected shock wave passing the pressure transducers in upstream, a second pressure rise is detected by transducer P_1 in Fig. 3(a), P_2, P_1 in Fig. 3(b) and P_3, P_2, P_1 in Fig. 3(c). However, there is no reflected shock wave in the tube without obstacles.

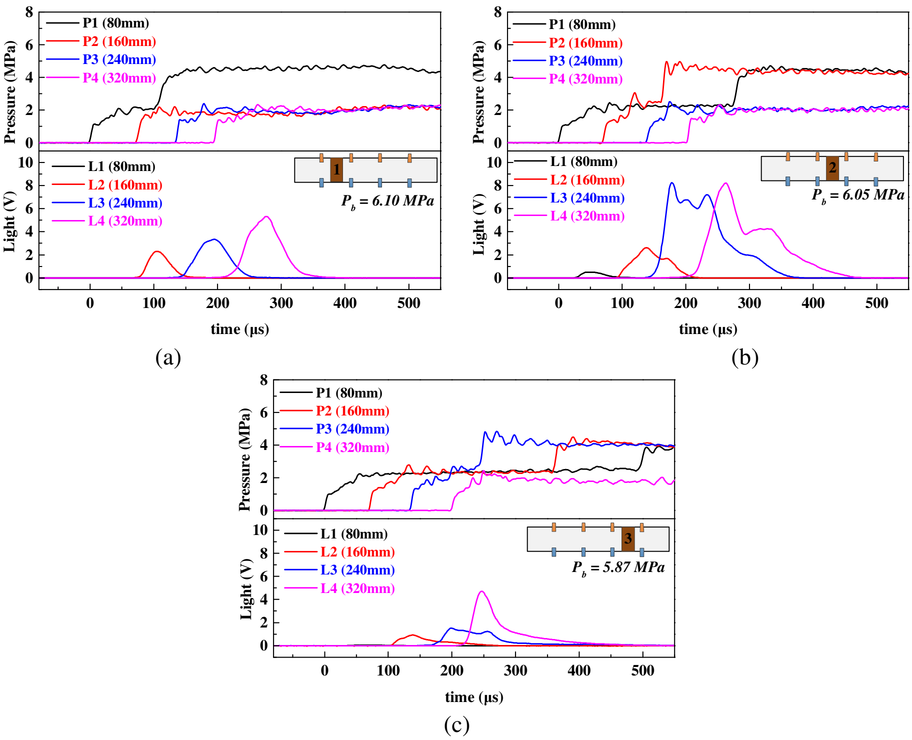

Fig. 3. Time history of pressure and light signals at different positions inside tube with varying obstacle location. (a) Obstacles in location 1, (b) obstacles in location 2, (c) obstacles in location 3.

Figure 4 shows relationships of the shock Mach number in tube with and without obstacles versus burst pressure for varying obstacle locations. The shock Mach number inside tube is obtained from the mean shock speed calculated between two adjacent pressure transducers. It is found that the shock Mach number increases with increasing the burst pressure in tube either with obstacles or without obstacles. In addition, the shock Mach number in tube with obstacles is always less than that without obstacles under the same burst pressure as shown in Fig. 4. This indicates that the shock strength undergoes a reduction when the shock wave passes through obstacles, which may be caused by the flow divergence.

In order to further understand the effect of obstacles on the shock wave propagation inside tube, Fig. 5 plots the shock Mach number versus propagation distance for some typical tests with different release tubes. It is shown in Fig. 5(a) that the shock Mach number almost keeps at a constant value as the shock wave propagates in the tube without obstacles. However, the appearance of obstacles in tube would weaken the strength of the shock wave. Experimental results show that the shock Mach number in the obstacles region, such as at 120 mm in Fig. 5(b), 200 mm in Fig. 5(c) and 280 mm in Fig. 5(d), is less than that at the same location in the tube without obstacles in Fig. 5(a). After the shock wave passes through obstacles, the strength of the shock wave increases gradually due to shock focusing, shock-shock and shock-wall interactions [23, 24]. The stronger initial shock wave increases more quickly than weaker ones after passing through obstacles. As shown in Fig. 5(b), when placing the obstacle at the location 1, the shock Mach number decreases at the position 120 mm compared with that in the tube without obstacles. And it increases at the position 200 mm for burst pressure P_b = 4.32/5.72/7.13 MPa (in red colors), while the shock Mach number begins to increase until the shock wave propagating to the position 280 mm for relatively low burst pressure P_b = 2.04/2.95 MPa (in blue colors). When the obstacles are arranged at the location 2 in Fig. 5(c), the shock Mach number decreases at the position 200 mm due to obstacles, and it increases immediately at the position 280 mm for burst pressure P_b = 5.27/6.39/7.60 MPa (in red colors). It can be inferred that for the relative low burst pressure P_b = 2.00/2.86 MPa (in blue colors), the shock Mach number would increase as the shock wave propagating to the downstream of the tube.

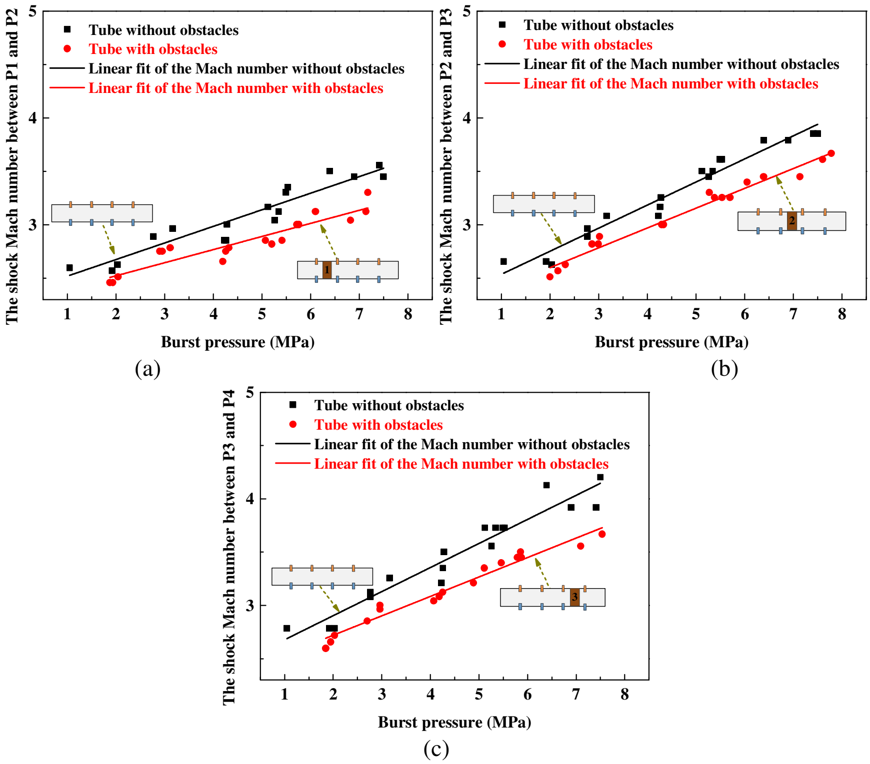

Fig. 4. Relationships of the shock Mach number in tube with and without obstacles versus burst pressure for varying obstacle locations: (a) Obstacles in location 1, (b) obstacles in location 2, (c) obstacles in location 3.

In order to further understand the effect of obstacles on the shock wave propagation inside tube, Fig. 5 plots the shock Mach number versus propagation distance for some typical tests with different release tubes. It is shown in Fig. 5(a) that the shock Mach number almost keeps at a constant value as the shock wave propagates in the tube without obstacles. However, the appearance of obstacles in tube would weaken the strength of the shock wave. Experimental results show that the shock Mach number in the obstacles region, such as at 120 mm in Fig. 5(b), 200 mm in Fig. 5(c) and 280 mm in Fig. 5(d), is less than that at the same location in the tube without obstacles in Fig. 5(a). After the shock wave passes through obstacles, the strength of the shock wave increases gradually due to shock focusing, shock-shock and shock-wall interactions [23, 24]. The stronger initial shock wave increases more quickly than weaker ones after passing through obstacles. As shown in Fig. 5(b), when placing the obstacle at the location 1, the shock Mach number decreases at the position 120 mm compared with that in the tube without obstacles. And it increases at the position 200 mm for burst pressure P_b = 4.32/5.72/7.13 MPa (in red colors), while the shock Mach number begins to increase until the shock wave propagating to the position 280 mm for relatively low burst pressure P_b = 2.04/2.95 MPa (in blue colors). When the obstacles are arranged at the location 2 in Fig. 5(c), the shock Mach number decreases at the position 200 mm due to obstacles, and it increases immediately at the position 280 mm for burst pressure P_b = 5.27/6.39/7.60 MPa (in red colors). It can be inferred that for the relative low burst pressure P_b = 2.00/2.86 MPa (in blue colors), the shock Mach number would increase as the shock wave propagating to the downstream of the tube.

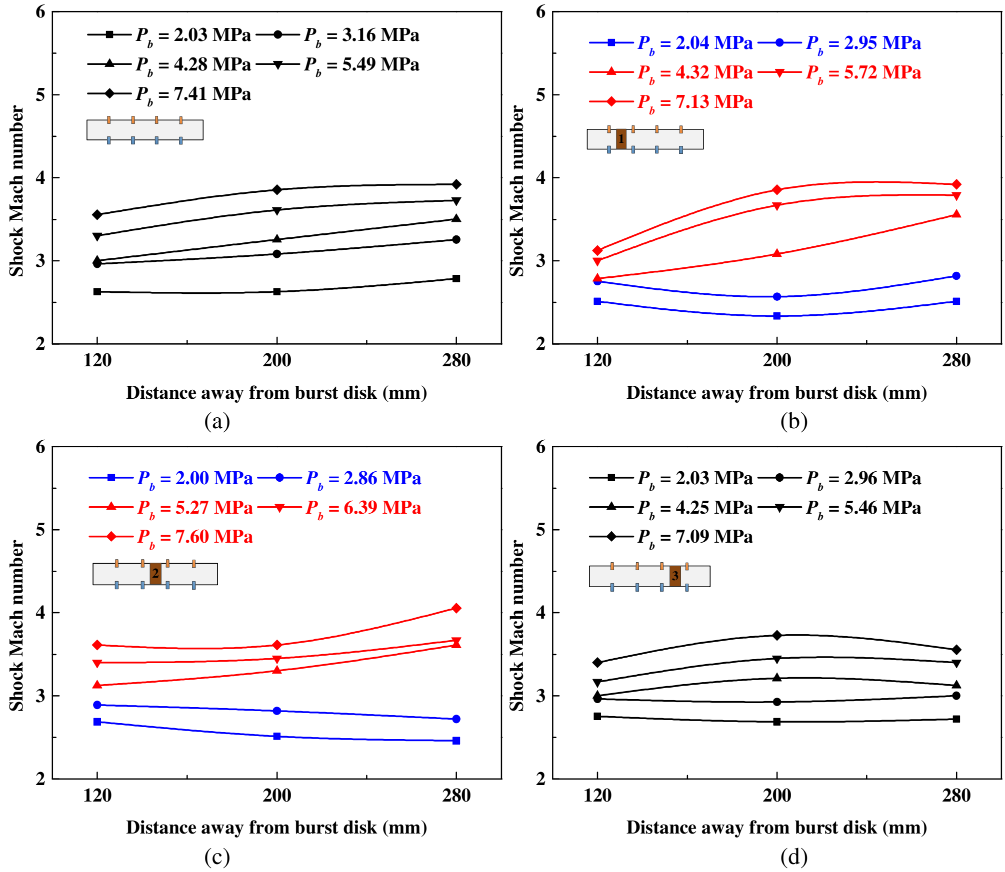

Fig. 5. Shock Mach number versus propagation distance in different tubes. (a) Tube without obstacles, (b) tube with obstacles in location 1, (c) tube with obstacles in location 2, (d) tube with obstacles in location 3.

When the shock wave propagates into the exhaust chamber and strikes the pressure transducer P_{out}, a rapid increase in pressure can be detected in either the self-ignition case or the non-ignition case. Figure 6 shows the typical overpressure variation in exhaust chamber as a function of time in the tube with obstacles in location 2. The initial increase in pressure is caused by the shock wave originating from the tube, and the shock wave overpressure are 0.044 MPa and 0.018 MPa for the self-ignition case and non-ignition case in Fig. 6, respectively. The shock wave overpressure refers to the peak pressure of the shock wave striking the pressure transducer. Furthermore, Fig. 7 plots the relationships of shock wave overpressure with burst pressure from tubes without obstacles and with varying obstacle locations. It is found that the shock wave overpressure increases with the burst pressure in all tubes, and the presence of obstacles in tube has no significant effects on the shock wave overpressure in the exhaust chamber, as shown in Fig. 7. For example, under the same burst pressure, the shock wave overpressure in the exhaust chamber shows almost the same in the four tubes. That is, the strength of the shock wave decreases when passing through the obstacles inside tube first, and then gradually increases and finally recovers to a similar value to the shock intensity in the tube without obstacles as propagating to downstream the tube.

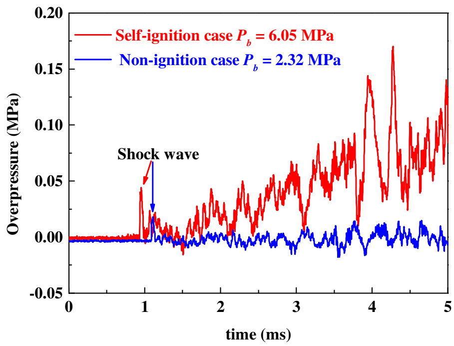

Fig. 6. Typical overpressure variation in exhaust chamber as a function of time (with obstacles in location 2).

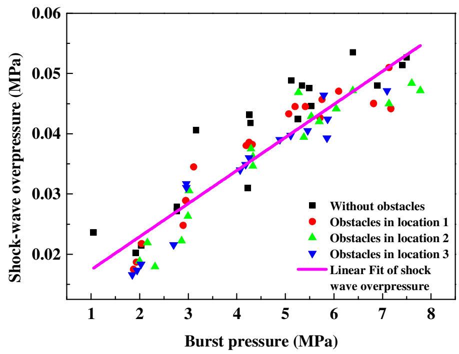

Fig. 7. Relationships of shock wave overpressure with burst pressure from different tubes.

EFFECT OF OBSTACLES ON SPONTANEOUS IGNITION INSIDE TUBE

To investigate the effect of obstacles on the spontaneous ignition, the relationship between ignition and burst pressure for different tubes are plotted in Fig. 8. There are two experimental phenomena observed according to the measurement of light signal inside tube, which are non-ignition and self-ignition. Regardless of whether obstacles are placed in the tube, the likelihood of spontaneous ignition increases with increasing the burst pressure. A higher burst pressure leads to a stronger shock wave, which produces higher temperature of air and promotes the occurrence of ignition. The minimum burst pressure which induces spontaneous ignition in tubes with varying obstacle locations are listed in Table 1. It is found that the minimum burst pressure for the four tubes are about 3 MPa and the appearance of obstacles inside tube has no significant influence on minimum burst pressure in our tests. This is not consistent with the result of Baev et al. [21, 25], which suggested that the reflected shock wave from obstacle is necessary for spontaneous ignition and a larger distance between burst disk and obstacle leads to a smaller minimum burst pressure for spontaneous ignition.

Figure 9 shows the pressure profiles (left axis) and light signals (right axis) at different positions under minimum burst pressure of self-ignition inside tubes with varying obstacle locations. When obstacles are placed in the location 2 (Fig. 9(c)) and location 3 (Fig. 9(d)), the light signal are first detected by L_1 as the case in the tube without obstacles (Fig. 9(a)), which means that the initial ignition occurs before obstacles. Thus it is reasonable that the occurrence of obstacles has no significant effect on the minimum burst pressure in our tests. The reflected shock wave is formed inside tube when the shock wave passes through obstacles as discussed in section 1. When the reflected shock wave propagates upstream and strikes the nearest pressure transducer, such as P_1 in Fig. 9(b), P_2 in Fig. 9(c), and P_3 in Fig. 9(d), the H_2-air mixture is heated and the mixing of H_2-air is promoted. However, the temperature and the amount of the hydrogen-air mixture maybe not enough to induce ignition [2, 21], so there is no light signal detected by the light sensors.

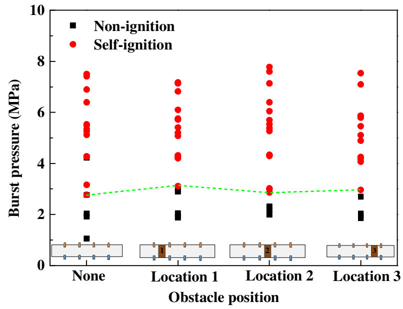

Fig. 8. Ignition occurrence associated with burst pressure for tubes with varying obstacle location.

Table 1. Minimum pressures of hydrogen spontaneous ignition in tubes with varying obstacle locations

Obstacle location	Minimum burst pressure of spontaneous ignition (MPa)
Without obstacles [22]	2.77
Location 1	3.11
Location 2	2.86
Location 3 [22]	2.96

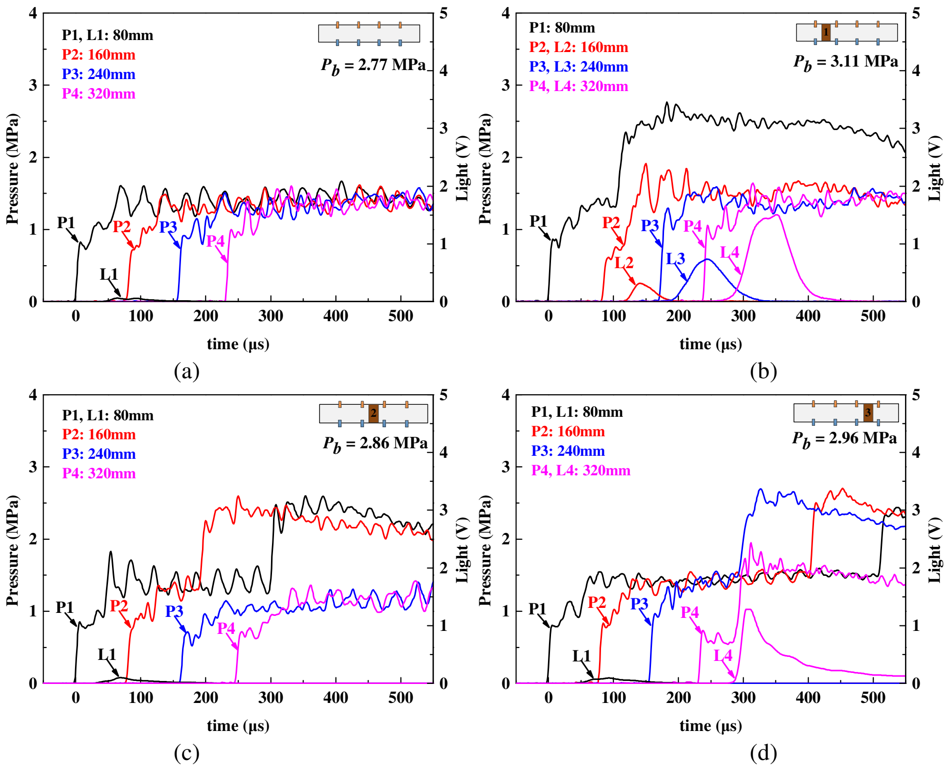

Fig. 9. Time history of pressure (left axis) and light signals (right axis) at different positions under minimum burst pressure of self-ignition inside tubes with varying obstacle locations. (a) Tube without obstacles [22], (b) tube with obstacles in location 1, (c) tube with obstacles in location 2, (d) tube with obstacles in location 3 [22].

EFFECT OF OBSTACLES ON FLAME PROPAGATION

Detected light signal is relative to flame intensity, which is one of indicators to describe hydrogen combustion intensity inside tube. It is worth mentioning that two light peak values are detected by light detector L_2 in Fig. 3(b) and L_3 in Fig. 3(c). And the second peak value is observed after the reflected shock wave passing through the position. When spontaneous ignition has induced inside tube, the reflected shock wave may further increase the temperature of hydrogen-air and promote the mixing of combustible mixture, which enhances combustion inside tube. Table 2 lists the probability of the flame intensity enhancement by the reflected shock wave when obstacles places in varying locations. It is found that the probability of the combustion enhancement by the reflected shock wave increases as the increasing distance between burst disk and obstacle location.

Table 2. Probability of the flame intensity enhancement by the reflected shock wave

Obstacle location	The light signal been enhanced by reflected wave
Location 1	0
Location 2	77%
Location 3	85%

Figure 10 shows the schematic of affected distance (L) by reflected shock wave. According to the shock tube theory, the speed of the hydrogen jet front can be obtained as [26]

$$\frac{V_2}{a_1} = \frac{2}{\gamma_1 + 1}\left(M_s - \frac{1}{M_s}\right), \tag{1}$$

where V_2 is the speed of hydrogen jet front and a_1 is the speed of sound, M_s is the shock Mach number, γ_1 is the heat capacity ratio of air. Reflected shock wave is formed when shock wave impacting on the obstacles, so the affected distance by reflected shock wave can be estimated by Eq. (2)

$$L = x_{SW} - x_{Hydrogen\ jet\ front} = M_s a_1 t - \frac{2a_1}{\gamma_1 + 1}\left(M_s - \frac{1}{M_s}\right)t\ , \tag{2}$$

where L is the affected distance by reflected shock wave, x_{sw} is the distance between burst disk and shock wave, $x_{hydrogen\ jet\ front}$ is the distance between burst disk and hydrogen jet front, t is time required for shock wave travelling to obstacles. Shock Mach number (M_s) is related to burst pressure (P_b). When the obstacles region is placed more far away from burst disk, such as location 3, a longer time (t) is required for shock wave travelling to the obstacles under a same burst pressure, which leads to the increase of the reflected shock wave affected distance (L). Meanwhile, the amount of hydrogen-air mixture increases as the shock wave travelling along tube [9]. As a result, the probability of combustion enhancement by reflected shock wave increases as the increasing distance between burst disk and obstacle location.

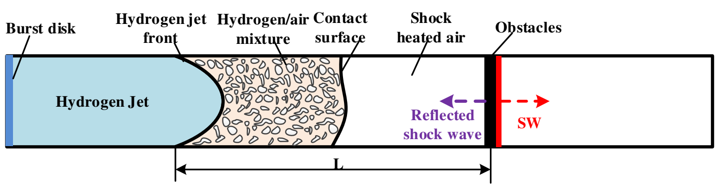

Fig. 10. Schematic of affected distance by reflected shock wave in the tube.

In order to further understand the effect of obstacles on flame propagation inside tube, the mean flame velocity relative to tube wall is chosen to represent the flame intensity, which is determined from the peak light arrival time between two light detectors. Figure 11 plots the mean flame velocity as a function of distance between the release tube and the burst disk in different tubes. The flame in the tube without obstacles is relative stable with the fact that the mean flame velocity almost keeps at a constant value, as shown in Fig. 11(a). An obvious flame acceleration is observed when flame travels across obstacles. For example, the flame velocity increases at 120 mm in Fig. 11(b), at 200 mm in Fig. 11(c), and at 280 mm in Fig. 11(d). The reasons may be as follows: (1) the presence of circular obstacle leads to the faster flow velocity in contraction structure; (2) the turbulent flow produced by obstacles, as shown in previous numerical study [23, 24], results in an increase of the amount of hydrogen-air mixture between hydrogen and shock-heated air, which enhances the combustion inside the tube. The flame velocity drops back at 200 mm in Fig. 11(b) and 280 mm in Fig. 11(c), which means that the flame intensity return to normal level once flow velocity drop back after obstacles and the extra amount of hydrogen-air is consumed.

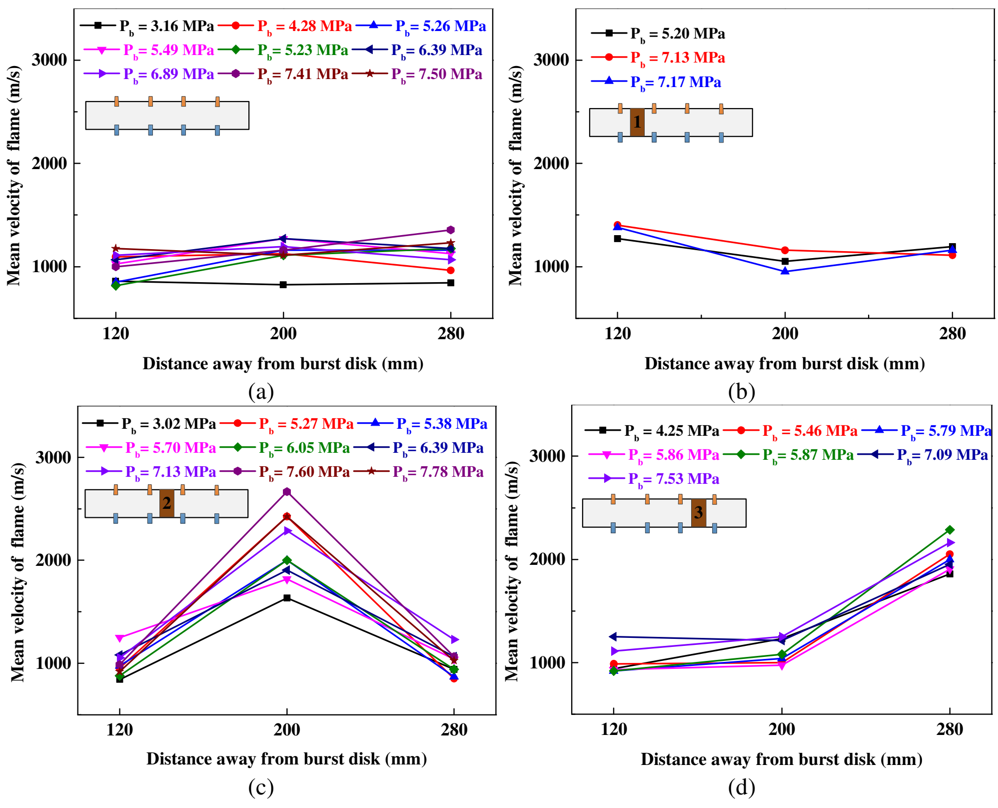

Fig. 11. The mean flame velocity relatives to the tube wall as a function of distance between the release tube and the burst disk in different tubes. (a) Tube without obstacles [22], (b) tube with obstacles in location 1, (c) tube with obstacles in location 2, (d) tube with obstacles in location 3 [22].

After the flame produced by spontaneous ignition jets out of the tube with obstacles, it propagates forward along with hydrogen flow and eventually develops into a jet flame in the atmosphere. The flame propagation characteristics outside the tube between release tubes with and without obstacles have no significant difference. A detailed discussion about the hydrogen flame propagation outside the tube has been reported in our previous work [7, 16], so no more discussion here.

CONCLUSIONS

Experimental investigation of pressurized hydrogen release in tubes with obstacles have been conducted to measure pressure variation and hydrogen spontaneous ignition inside tubes. Three kind of tubes with varying obstacle location were considered here to show the effect of obstacle location on the pressure dynamics evolution, spontaneous ignition and flame propagation.

When the obstacle is placed inside tube, the shock Mach number always decrease when the shock wave travels through obstacles. This might be due to flow divergence when the shock wave passes through obstacles. Subsequently, the strength of the shock wave gradually recovers under the effect of multi-dimensional shock wave interactions.

In tubes with varying obstacle locations, the reflected shock wave is generated when the shock wave encounters obstacles. The appearance of reflected shock wave leads to more intensive flame ahead of obstacles in the evidence of initial spontaneous ignition has been occurred inside tube. And more far away from burst disk that obstacles are placed, more likely that the reflected shock wave enhances flame before obstacles. However, the presence of obstacles has no significant influence on the minimum burst pressure which induces spontaneous ignition in the tests.

For tubes with obstacles, a faster flow velocity and a turbulent flow may be generated after obstacles, which induces an extra amount of hydrogen-air mixture formed in the obstacles region. Thus, the mean flame velocity inside the tube is always increases when the flame propagates through obstacles. After that, the velocity drops. In brief, it is suggested that the presence of obstacle inside the tube would only temporarily promote combustion inside the tube.

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