Combined effects of obstacle position and equivalence ratio on overpressure of premixed hydrogen–air explosion

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Abstract

To investigate the combined effects of obstacle position and equivalence ratio on overpressure of premixed hydrogen–air explosion, an experimental study was performed in a 5 L duct with premixed hydrogen–air mixtures over a wide range of equivalence ratios, and along with the variation of a single obstacle position. In this paper, the equivalence ratios of the hydrogen–air mixtures were varied from 0.6 to 1.4, the obstacle was centrally located and was respectively 100, 200, 300 mm from the bottom end of the duct, the experiment without an obstacle was designed as a control experiment. For brevity, four configurations were defined according to the variation of the single obstacle position. The results indicated that the overpressure of premixed hydrogen–air explosion was closely related to the flame structure. The rise of \( \frac{dp}{dt} \) for hydrogen–air mixtures occurred when the flame started to feel the presence of the obstacle. The maximum overpressure could be observed at the moment that the two flames, generated from the gap between the obstacle and the inwall of the duct, just started to merge in the downstream region of the obstacle. It was also found that the venting overpressure might be barely observed under the combined effects of obstacle position and equivalence ratio. The rise time of \( \frac{dp}{dt} \) in a given configuration was gradually shortened with increasing equivalence ratio. Additionally, it was not simply a synergistic effect of obstacle position and equivalence ratio on peak overpressure. The peak overpressure increased with increasing obstacle position for lean hydrogen–air mixtures, and the maximum peak overpressure occurred in the downstream region of the farthest obstacle position. Interestingly, for the stoichiometric and rich mixtures, the peak overpressure reached the maximal when the obstacle was at the middle position. The occurrence of the maximum peak overpressure mainly depended on the maximum flame surface area within the duct.

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Introduction

As one of the most potential energy in the 21st century, hydrogen has received more and more concern because of its cleanliness, high calorific value and renewable capability. But some unique properties of hydrogen, such as its wider flammability ranges, higher diffusivity, lower ignition energy and larger burning velocity, make itself being a great hazard during the process of production, storage, distribution and consumption. So the concomitant hydrogen safety issues, mainly the hydrogen explosion hazards, have to be fully estimated along with its wide adoption. A lot of studies indeed have been conducted associated with the severity of hydrogen–air explosion. The previous studies indicated that the flame front speed and the overpressure increased significantly with the hydrogen addition [1]. And the occurrence time corresponding to maximum overpressure $t_{\text{max}}$ decreased with hydrogen addition [2]. The premixed hydrogen–air flame underwent more complex shape changes and exhibited more distinct characteristics than that of other gaseous fuels [3]. The intensity of hydrogen–air explosion was greater than that of methane–air and hydrogen–air explosion had greater explosion hazard effects [4]. Also, a lot of studies had been conducted to gain insights into the effect factors of hydrogen–air explosion, such as vent area, vent burst pressure, vent number, ignition position, initial turbulence etc. [5–9]. These study results provided us with a basic understanding of hydrogen–air explosion. In general, obstacles usually exist during the utilization of hydrogen, including other combustible gas. The explosion flame front surely will undergo complex shape change and results in unpredictable pressure wave once explosion occurs when it develops from an ignition source and travels through the obstacles. So far, large amounts of outstanding researches have been carried out on the effect of the obstacle on the characteristics of gas explosion widely including the obstacle shape, blockage ratio, number, location, and separation distance, which were mainly concerned with methane, propane, LPG, and other combustible gas [10–15]. However, targeted researches on the effect of obstacle are still not enough for high reactive hydrogen. From the previous literatures, the peak pressure of hydrogen flames were about an order of magnitude higher than for LPG or CNG flames. The degree of wrinkling and contortion in the flame front increased significantly with increasing blockages. The flame front was laminar as the separation between successive obstacles increase, resulting in the decreasing pressure with increasing separation. For a given configuration, the structure of hydrogen flames showed less distortion and wrinkling than that for the other two hydrocarbon fuels at the same equivalence ratio [16,17]. Abdel-Raheem et al. presented the same flame shape as the experimental images showed in Refs. [16,17] with the help of the Large Eddy Simulations, and found that both the peak overpressure and flame position were affected by the number of baffles positioned in the path of the flame [18]. The numerical study conducted by Xu et al. indicated that the flame was strengthened by the sharp increase in internal energy at stagnation as the thin flame reaches the lower surface of the obstacle plate [19]. Emami et al. conducted LES of flame acceleration and DDT in hydrogen–air mixture using artificially thickened flame approach and detailed chemical kinetics, and discussed the different acceleration principle between the slow flame propagation regime and the high propagation regime during the process of DDT [20]. To sum up, all the previous studies acknowledged the basic principle of flame–obstacle interaction for hydrogen–air explosion. The interaction caused a laminar flame to become turbulent, then resulted in flame acceleration and pressure rise. Several researchers also showed great effects of the obstacle blockage ratio, separation distance between successive obstacles and obstacle number on hydrogen–air explosion, as described in Refs. [16–18]. However, few studies pay attention to the effect of obstacle position relative to the ignition source. On the other hand, most of the literature indicated higher overpressure would generate along with the change of flame structure under the effect of obstacle, but detailed conjoint analysis on flame structure and overpressure is still scarce. Thus, to complement this gap, the experimental study should be conducted on the effect of obstacle position on hydrogen–air explosion and on the relationship between the overpressure and flame structure. Additionally, the hydrogen–air explosion accident may happen for a large variation range of hydrogen concentration due to its unique property of wider flammability ranges. The previous study results showed a significant effect of hydrogen concentration on the overpressure and flame velocity [21,22]. In combination with the possible effect of obstacle position on hydrogen–air explosion in actual accident scenarios, the investigation on hydrogen–air explosion with the variation of equivalence ratio and a single obstacle position is necessary. And then the further study on the combined effects of obstacle position and equivalence ratio may be of some practical significance for taking reasonable measures to deal with some complicated hydrogen–air explosion accident. In consideration of the representativeness of overpressure in evaluating explosive damage, the present work mainly focused on the combined effects of obstacle position and equivalence ratio on overpressure of premixed hydrogen–air explosion.

Experimental setup

A schematic diagram of the experimental set-up is shown in Fig. 1. The experimental set-up is very similar to the one that used in the previous study [23]. The experiments were performed in a 5 L duct with a cross-section of $100 \times 100 \text{ mm}^2$ and a height of 500 mm. The bottom end of the duct is fully closed by a steel plate, and the open end is sealed with a thin polyvinyl chloride (PVC) membrane to contain the premixed flammable mixture. When explosion occurs, the thin PVC membrane is ruptured at low pressure, allowing the high-pressure gases, including unburned and burned mixtures, to escape. The duct walls are constructed using 20 mm thick Perspex to facilitate the application of optical diagnostic. The obstacle ($100 \times 50 \times 10 \text{ mm}$) is respectively centrally located at 100 mm, 200 mm, and 300 mm from the bottom end thus giving an overall blockage ratio of 50%. Four corresponding experimental configurations are recorded according to the obstacle position, and they are successively Configuration 1,
Configuration 2, Configuration 3, Configuration 4, as shown in Fig. 2. Specially, Configuration 1 represents the experimental configuration without an obstacle, which is designed as the control experiment in this study.

The hydrogen–air mixtures enter the duct through an inlet at the bottom steel plate, and it may be vented through a valve positioned near the top of the Perspex wall. The flow rate of the premixed hydrogen–air is about 5 L/min, and the process is continued for 10 min supplying a total of 50 L hydrogen–air mixtures, which is more than 4 times the volume of the duct. This step is necessary to purge the duct and ensure that the mixture in the test unit is homogenous [24]. The flow is then stopped, and the mixtures within the duct are allowed to settle for 15 s before ignition. An electronic ignition, activated by 6 V DC voltage, is used as the ignition source positioned at the center of the bottom steel plate [25].

The overpressure generated from the premixed hydrogen–air explosion is measured at 15 kHz using a Keller type PR-23 piezoresistive pressure sensor, with a range of −1.0–1.5 bar and a total error <0.25%. It is located 20 mm from the ignition position, at which location the maximum overpressure can be generated. A photodiode sensor (type RL-1) is positioned outside the explosion duct, pointing towards the ignition source. The photodiode signal is used to determine the onset of ignition. The images of the explosion flame are captured by a “Lavision 4G” high-speed camera, which can achieve acquisition rate at a speed of 2000 frames/s with an array of 1024 × 1024 pixels. And the images are simultaneously processed by a software “Davis 7.2”. When the ignition contact switch is closed, a data acquisition card (USB-1208FS) is triggered to record the signals from the pressure sensor and the photodiode, with 12-bit resolution at a rate of 15 kHz per channel. Once the output of the photodiode signal switches to low electric levels, the premixed hydrogen–air is considered ignited, and the high-speed digital camera begins to record. All experiments were performed in darkness to avoid interferences from other light sources.

Fig. 1 – Schematic diagram of experimental set-up.

Fig. 2 – Four configurations varying in terms of the obstacle position.
Results and discussion

Conjoint analysis on flame structure and overpressure

The flame–obstacle interaction resulted in higher flame speed and overpressure for methane-air explosion. There was a coupled relationship between flame structure and overpressure wave [11,23]. For high reactive hydrogen, the premixed hydrogen–air flame underwent more complex shape changes and exhibited more distinct characteristics than that of other gaseous fuels [3]. The development of explosion flame and overpressure in the duct with an obstacle for hydrogen–air mixtures may need more detailed description. In this study, detailed analysis is carried out on the development of overpressure from the hydrogen–air mixtures with the variation of the equivalence ratio and the single obstacle position. It is found that equivalence ratio has little effect on the relationship between flame structure and overpressure for the considered variation range. Nevertheless, the effect is apparent in terms of the presence of obstacle. Typical hydrogen–air mixtures at the equivalence ratio $\Phi = 1.0$ is taken for example to conduct conjoint analysis on flame structure and overpressure, as shown in Figs. 3–5.

Fig. 3 presents the flame structures and flame propagation images in the four configurations for the equivalence ratio $\Phi = 1.0$. Initially, the flame structures in all configurations are similar and hemispherical, as can be seen from the images at about 2 ms after ignition. The flame structures in the four configurations show difference due to the presence of the obstacle during the subsequent propagation process. The flame in Configuration 1 undergoes the development process of hemisphere and finger shape. The flames in the other three configurations undergo more complicated development process under the effect of the obstacle. Namely, the flame front flattens off slightly while moving closer to the obstacle. Then two symmetrical flames are generated on the both sides of the inwall of the duct, and the two flames draw close to one another towards the centerline of the duct in the downstream area of the obstacle due to the existence of vortex. Fig. 4a and b respectively shows the curve of flame front position versus time and the curve of flame propagation speed versus flame front position for the equivalence ratio $\Phi = 1.0$. It is easily found that the obstacle results in flame acceleration. The flame in Configuration 2, Configuration 3 and Configuration 4 successively gains acceleration, as shown in Fig. 4a. The flame propagation speed decreases sharply when the flame starts to feel the presence of the obstacle, as shown in Fig. 4b. Fig. 5 exhibits the overpressure and its growth rate $dp/dt$ in different configurations for the equivalence ratio $\Phi = 1.0$. In this figure, the overpressure oscillates with low amplitude, even negative overpressure is generated after the flame arrived to the vent. This phenomenon was closely related to the alternating leading role between the volume production rate and the venting rate, as described by Gubba et al. [11]. The peak overpressure occurred when the volume production rate was equal to the venting rate [24]. But the venting
overpressure described in the literature [26] is not observed here. This may be attributed to the enhancement of combustion reaction caused by the increase of hydrogen concentration, which in turn increased the net rate of volume production of combustion that offset the volumetric flow rate through the vent. And this is well in line with the previous study in Ref. [1]. Further analysis on the venting overpressure in different experimental conditions will be carried on in the following.

Fig. 5a shows that the overpressure waveforms in four configurations are similar in the initial stage. But the waveforms turn to be prominently different when the flames start to feel the presence of the obstacle. This is because the presence of obstacle results in flame acceleration, and induce earlier rise of $\frac{dp}{dt}$ at the same time. Contrasting Figs. 3–5, it can be seen that, for Configuration 2, overpressure gains the earliest rapid growth due to the first presence of obstacle at 2.35 ms, at which moment the flame propagates about 61 mm from the bottom end of the duct. Then its propagation starts to be limited under the effect of the reflected pressure wave from the obstacle. Subsequently, the overpressure continues rising rapidly until it reaches the maximum overpressure at 4.5 ms, at which moment the flame front is 231 mm from the bottom end, and two flames just start to merge, as shown in Figs. 3 and 4. In general, the maximum overpressure will be generated when the flame surface area is the maximal. As described in Ref. [20], flame–vortex interaction together with the consequent flame folding and wrinkling are the main mechanism for the increase in the flame surface area. Comparing the flame structures in each configuration in Fig. 3, it can be easily found that the flame surface area just reaches to the maximum when two flames start to merge in the downstream region of the obstacle. For Configuration 3 and Configuration 4, similar relationship can be found between overpressure and flame structure. In short, the rise of $\frac{dp}{dt}$ occurs when the flame starts to feel the presence of the obstacle. The maximum overpressure occurs at the moment that two flames, generated from the gap between the obstacle and the inwall of the duct, just start to merge in the downstream region of the obstacle.

**Combined effects of obstacle position and equivalence ratio on overpressure waveform of premixed hydrogen–air explosion**

Fig. 6 depicts the overpressure varying in four configurations for hydrogen–air mixtures at different equivalence ratios. Configuration 1 without an obstacle represents the control experiment. It shows that the overpressure waveforms almost undergo the development processes of slow growth, rapid growth and rapid decrease when the flames propagate in the duct. Then the overpressure waveforms oscillate with low amplitude after the flame propagated outside the duct, as discussed earlier.
The venting overpressure is observed only for the equivalence ratio \( \Phi = 0.6 \), as described in Fig. 6a. This phenomenon can be explained by the lower chemical reaction rate due to the decrease of the equivalence ratio. Whereas, in Fig. 6a, the venting overpressure isn’t existed in Configuration 2 by contrasting with that in other configurations, which demonstrates the obstacle position has an effect on the generation of venting overpressure. For Configuration 1 in Fig. 6a, the venting overpressure appears at about 10 ms, and the flame front at this moment is 146 mm from the bottom end. When the overpressure in Configuration 1 is taken as reference, only the obstacle in Configuration 2 is located within the development stage (100 mm < 146 mm) where the venting overpressure is generated. Thus the inexistence of venting overpressure in Configuration 2 should be attributed to the rapid growth of overpressure under the effect of the obstacle. In other words, the presence of the obstacle is so early that there is no a development opportunity for the occurrence of venting overpressure.

The rapid growth of overpressure in Configuration 2 distinctly occurs earlier than that in other configurations due to the smaller distance between the obstacle and the ignition source, as shown in Fig. 6. Even more remarkable, the overpressure waveforms in Configuration 2 are very different from that in other configurations. The variation trends of overpressure waveforms in Configuration 3 and Configuration 4 are similar and approximately in agreement with that in Configuration 1. In consideration of the difference of experimental conditions, the obstacle in Configuration 2 is located closer to the ignition source, and its location is just within the development stage of spherical flame when the explosion flame in Configuration 1 is taken as reference. The obstacles in Configuration 3 and Configuration 4 are both located within the acceleration stage of finger-type flame. Then the following results can be got that, the closer the obstacle is to the ignition source, the more apparent the overpressure change will be, especially when the obstacle is located within the development stage of spherical flame. Subsequently, the overpressure
waveforms don’t show obvious difference when the obstacle is located within the acceleration stage of finger-type flame because the overpressure changes finish in a very short time due to the higher reaction rate for hydrogen in this stage.

Fig. 7 shows overpressure versus time with different equivalence ratios in four configurations. It is found that the overpressure waveforms are almost the same for the equivalence ratio $\Phi = 1.2$ and $\Phi = 1.4$ in all configurations, and their rises of $\frac{dp}{dt}$ are ahead of that of other equivalence ratios. So for a given configuration, the faster the flame propagation is, surely the earlier the flame–obstacle interaction will occur, then results in earlier rise of $\frac{dp}{dt}$. Thus the results presented in Fig. 7 can be attributed to the faster flame propagation speed with $\Phi = 1.2$ and $\Phi = 1.4$ compared with that of other equivalence ratios, as can be seen from Fig. 8, which shows the flame front position versus time over different equivalence ratios in four configurations.

In Fig. 8, all slopes of curves increase over time. Furthermore, the slopes of curves of the equivalence ratio $\Phi = 1.2$ and 1.4 are indeed the highest and almost overlapped, then are that of the equivalence ratio $\Phi = 1.0, \Phi = 0.8, \Phi = 0.6$ successively. The result pointed out by Bychkov et al. [27] indicated that the flame acceleration in the early stage of explosion was due to the thermal expansion of combustion products in the unburned mixture. Additionally, a geometrical model had been built to predict the trajectory of the flame tip during the anisotropic finger phase by Clanet and Searby as early as 1996 [28]. In Ref. [28] a formula $1/T = 2EU_l/R$ was proposed, where $R$ was the radius of the tube, $U_l$ was the laminar burning velocity, $E$ was the gas expansion ratio, and $T$ was the characteristic time during this phase. So in the present experimental study, the flame propagation speed of hydrogen–air mixtures at different equivalence ratios directly depends on the corresponding mixture gas expansion ratio and laminar burning velocity, which are both closely related to temperature. Nevertheless, the temperatures during the process of combustion reaction were not been accurately measured in the present experiment, thus quantitative research can’t be carried out on the flame propagation speed that shown in Fig. 8.

**Combined effects of obstacle position and equivalence ratio on peak overpressure**

Fig. 9 shows the peak overpressure in different experimental conditions. For a given configuration, the peak overpressure increases firstly and then slightly decreases with increasing equivalence ratio. The peak overpressure is the maximum for the equivalence ratio $\Phi = 1.0$. This is attributed to the more and more stronger combustion reaction rate with the equivalence ratios for lean hydrogen–air mixtures, then the reaction rate reaches the fullest when equivalence ratio $\Phi = 1.0$. Subsequently, the extent of the reaction has no significant reduction with increasing equivalence ratio once the equivalent ratio is beyond 1.0. Fig. 9 also indicates that the peak overpressures in Configuration 1 and Configuration 2 are always less than that in Configuration 3 and Configuration 4 no matter what the equivalence ratio is. The peak overpressures in Configuration 1 are all less than that in Configuration 2 due to the inexistence of obstacle. This is ascribed to the existence of the obstacle.
of obstacle inducing higher overpressure peak. More importantly, the obstacle position has a large effect on the peak overpressure for the conditions studied. Meanwhile, it can be easily found that the peak overpressures increase with increasing obstacle position when the equivalence ratio is less than 1.0. While the peak overpressure in Configuration 2 is the maximum when the equivalence ratio is equal or greater than 1.0. As proposed in the first part, the maximum overpressure will occur when the flame surface area is maximized. Therefore, this result can be easily explained in terms of the flame surface area. From the measured results shown in Fig. 6a and d, the occurrence time of the maximum overpressure is respectively 11.47 ms, 12.53 ms, 13.47 ms for the equivalence ratio $\Phi = 0.6$, and 3.8 ms, 5.27 ms, 5.47 ms for the equivalence ratio $\Phi = 1.2$, with the configuration ranging from Configuration 2 to Configuration 4. The corresponding flame structures, appeared closest to the occurrence time of the maximum overpressure, are exhibited in Fig. 10. It can be qualitatively estimated that the flame surface area reaches the maximum when the obstacle is positioned the farthest for the equivalence ratio $\Phi = 0.6$. Nevertheless, the maximum flame surface area is generated at the middle obstacle position for the equivalence ratio $\Phi = 1.2$. The results are also true for the other lean or rich mixtures. Thus in the case of the stoichiometric and rich hydrogen--air mixtures, the flame reaches a maximum flame surface area after much of the flame has exited the duct if the obstacle is located near the exit, as can be seen from the flame structure of Configuration 4 in Fig. 10b. For the lean mixtures, the lower flame velocities allows the flame to reach a maximum flame surface area within the duct and the longer run-up distance results in a higher velocity when the obstacle is farther from the ignition source. For brevity, it is not simply a synergistic effect of obstacle position and equivalence ratio on peak overpressure. The peak overpressure increases with increasing obstacle position for lean hydrogen--air mixtures, and the maximum peak overpressure occurs in the downstream region of the farthest obstacle position. Interestingly, the peak overpressure reaches the maximal for the stoichiometric and rich mixtures when the obstacle is located at the middle position rather than at the farthest position. It is believed that the occurrence of the maximum peak overpressure mainly depends on the
maximum flame surface area within the duct, which is strongly influenced by the combined effects of the obstacle position and equivalence ratio.

Conclusions

In the present study, the combined effects of obstacle position and equivalence ratio on overpressure of premixed hydrogen–air explosion have been investigated. Tests were carried out in a 5 L simple obstructed duct under ambient conditions, with the equivalence ratio $\Phi$ ranging from 0.6 to 1.4, and the obstacle position varying from 100 mm to 300 mm from the bottom end of the duct. From the results obtained, the main conclusions can be described as the following points:

1. The overpressure waveform of premixed hydrogen–air explosion is closely related to the transient flame structure. The rise rate $\frac{dp}{dt}$ occurs when the flame starts to feel the presence of the obstacle. The maximum overpressure is observed at the moment that the two flames, generated from the gap between the obstacle and the inwall of the duct, just start to merge in the downstream region of the obstacle.
2. Obstacle position and equivalence ratio have strong combined effects on the overpressure waveform of premixed hydrogen–air explosion. The presence of obstacle induces more rapid growth and higher values of over-pressure. When the explosion flame without an obstacle is taken as reference, the overpressure waveform in the configuration that the obstacle is located within the development stage of spherical flame, shows significant difference from that in other obstructed configurations. The venting overpressure can’t be observed for the hydrogen–air mixtures with the equivalence ratio $\Phi > 0.6$ due to their high reactivity. And it also can’t be observed for mixtures with the equivalence ratio $\Phi = 0.6$ when the obstacle position is 100 mm from the bottom end. This is because the presence of the obstacle is so early that there isn’t a development opportunity for the generation of the venting overpressure. Additionally, the rise time of $\frac{dp}{dt}$ for a given configuration is gradually shortened with increasing equivalence ratio.
3. It is not simply a synergistic effect of obstacle position and equivalence ratio on peak overpressure. The peak overpressure increases with increasing obstacle position for lean hydrogen–air mixtures, and the maximum peak overpressure occurs in the downstream region of the farthest obstacle position. Interestingly, the peak overpressure reaches the maximum for the stoichiometric and rich mixtures when the obstacle is at the middle position rather than at the farthest position. It is believed that the occurrence of the maximum peak overpressure mainly depends on the maximum flame surface area within the duct, which is strongly influenced by the combined effects of the obstacle position and equivalence ratio.
4. The small-scale duct in this experimental study is simpler obstructed compared with the previous experimental or simulation model. The study results may be helpful to the development and validation of CFD models for hydrogen–air explosion. On the other hand, the presentation of the nonsynergistic effect of obstacle position and equivalence ratio on the peak overpressure may be of a certain practical significance to the safety utilization of hydrogen in actual engineering field. For an obstructed venting pipeline, it is a worse case when the obstacle is located farther from the ignition source for lean hydrogen–air mixtures. But for rich hydrogen–air mixtures, the worst case may exist when the obstacle is located at a certain distance from the vent.

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