Characteristics of gasoline–air mixture explosions with different obstacle configurations

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A B S T R A C T
The effects of obstacle distance from ignition point, the blockage ratio of obstacle (BR) and the separation distance of obstacles on the characteristics of gasoline–air mixture explosions have been examined by a series of contrast experiments in a semi-confined organic glass pipe (with a square cross section size of 100 mm*100 mm and 1000 mm long, L/D = 10, V = 0.01 m³). It was shown that before the flame fronts propagated to the obstacle, the flame fronts remained regular shape and spread in a low speed, while passed across the obstacle, the flame fronts could be sharply accelerated and became distorted. And it was obvious that the shorter the distance between obstacle and ignition point, the earlier the flame was accelerated, and eventually led to a higher maximum flame speed. Meanwhile, the maximum overpressures and maximum rates of overpressure rise were obtained at L = 400 mm, and the shorter the distance between the obstacle and ignition point, the shorter the time taken to reach the maximum overpressure. Three kinds of blockage ratios (BR = 36.4%, 49.8%, 71.7%) were tested, and it was found that the maximum flame speeds, maximum overpressures, average rates of overpressure rise and maximum rates of overpressure rise increased with the growth of blockage ratio. It was also discovered that the maximum effect of the combined obstacles on flame acceleration behavior could be obtained at an obstacle separation distance of 1 time to 4 times the length of pipe diameter. And the time taken to obtain the maximum overpressures became shorter with the growth of the obstacle separation distance, while the maximum overpressures and maximum rates of overpressure rise were obtained at an obstacle separation range from D/D = 3 to 5 (or 300 mm–500 mm).

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1. Introduction

It is well known that flammable gas explosion is a frequently occurring accident in the process industry, such as chemical plant, coal mines, oil depots etc. [7,21]. Once explosion occurs in these places, it would led to serious injuries, death, destruction of equipment and downtime, especially in some cases when gas explosion happens in a space containing solid obstacles or congested areas that can be treated as a large porous structure [9]. The interaction of the explosion induced unburnt gas flow with obstacles results in the generation of turbulence downstream of the obstacle and the acceleration of the flame when it reaches this turbulence. Extremely fast explosion flames can be generated by this mechanism giving rise to severe overpressures. Therefore, it is essential to understand and predict these phenomena in process industries, and particularly to assess the risks and design suitable protection and mitigation measures against vapor cloud explosions.

Former studies have been performed to gain an insight into the effect of obstacle on the propagation characteristics of flammable gas explosions, and great attention has been paid to the studies of the effect of the structure of obstacles, the number of obstacles, the cross-wise location of obstacles, the blockage ratio (BR) of obstacles etc. on the flame forms, flame speeds and overpressures change rules [2,6,9–13,15,18]. Moreover, with the development of advanced test technologies and computing technologies, schlieren technology, PIV...
technology and LES-based CFD simulation have been applied by some researchers in order to deeply investigate the mechanisms that correlate flame dynamics and result in overpressures in flammable gases explosions, and great progress has been made [2,3,6,8,16]. However, most of the previous investigations on flammable gases explosions in an obstructed vessel were about hydrogen, methane, propane, ethylene [1,5,9,11,16]. Few of them were about gasoline vapor, which is also a hazardous explosive gas and extensively used fossil fuel, and once mixed with air or other oxidant, a potential explosive atmosphere might be formed, which can lead to a destructive explosion and form damaging overpressures and high temperature [7,17,19,20]. In the former studies, Zhang and Li investigated the gasoline–air mixture explosions characteristics both in a closed straight pipe and a closed pipe with a T-shaped branch structure, and they found the existence of T-shaped branch structure had significant effect on overpressure and flame behaviors [7,20]. Du investigated suppressions of the gasoline–air mixture explosion by non-premixed nitrogen in a closed tunnel [4]. Qi studied the effect of vent size and concentration on vented gasoline–air explosions and the effects of concentration, temperature, humidity, and nitrogen inert dilution on the gasoline vapor explosion. However, most of the former studies on gasoline–air mixture explosions were experimentally studied using a long closed pipe, a constant volume container, or a non-obstructed vented chamber, and there were no reports on the effects of obstacles on the characteristics of gasoline–air mixture explosions.

In this paper, a series of explosion experiments on gasoline–air mixtures were carried out in a semi-confined pipe under the initial gasoline vapor concentration of 1.70% [7], taking account of 17 different kinds of obstacle configurations. The work of this paper aims at investigating the effects of obstacles on the overpressures and flame behaviors of gasoline–air mixture explosions, therefore providing reference for explosion safety protection of oil and gas industry.

2. Experimental

2.1. Experimental system and apparatus

The experimental equipment applied in this article as shown in Fig. 1 consisted of a semi-confined organic glass pipe (with a square cross section size of 100 mm*100 mm and 1000 mm long, L/D = 10, V = 0.01 m³), a dynamic data testing system, a high-speed camera, a

![Fig. 1. Schematic of experimental system.](image-url)
A hydrocarbon concentration test system, an ignition system, a gasoline vapor generation system, and a synchronous controller. One of the ends of the pipe was sealed by a metal blind plate, and the open end was sealed by a thin polyethylene film to contain the gasoline–air mixtures before ignited. The polyethylene film could be easily ruptured at a very low pressure and had little impact on the overpressure caused by the gas explosions. Three kinds of obstacles with different blockage ratio (BR = \(1 - \pi R^2/H^2\)) of 36.4%, 49.8% and 71.7%, respectively, as shown in Fig. 2 were applied in the experiments.

Overpressure histories were recorded by a dynamic data acquisition software called DAP 7.10 (Tai Site Technology Institution of Chen Du), and a piezo-resistive pressure transducer (ZXP type 660, with a range of 0–200 kPa and a total error <0.3%), located close to the ignition position. The gasoline–air mixtures were produced by a gasoline vapor generation system. The gasoline vapor concentration was tested by a GXH-1050 infrared gas analysis apparatus (Jun Fang Physicochemical Science and Technology Institution of Beijing). The initial mixture was supplied by circulating the air through liquid gasoline within confined pipes and the vessel. After a certain time (depending on the needed vapor concentration), values before and after the oil bottle were closed and the pump continued to work for 3 min to create a uniform mixture [14]. All the gas mixtures used in these experiments were at ambient pressure and temperature. Gas mixtures were ignited by an ignition system, which consisted of a spark plug, a capacitor and a transformer, and giving an ignition energy varying from 2 J to 20 J. The position of the spark plug was constantly kept at the center of blind plate, and a constant ignition energy was set at 6 J in case of the significant effects of ignition position and energy on the initial flame propagation and the resulting flame speed and overpressure [7]. A high speed camera (with a shutter of 2 ms and at a speed of 500 frames per second) was applied to record the images of flame propagation process during gas explosions [14].

2.2. Experimental methods and contents

In this paper, a series of contrast experiments were carried out in 17 kinds of obstacle configurations as shown in Fig. 3, to investigate the effects of obstacles on the gasoline–air explosion characteristics. For each test, an initial gasoline vapor concentrations of 1.7% was adopted. And a piezo-resistive pressure transducer was mounted close to the ignition position to record the overpressure histories during explosions. At the same time, a high speed camera was used to record the flame locations and flame structures during flame propagation process.

Most experiments were carried out for at least three times in order to ensure the accuracy of experimental results, depending on the reproducibility of the overpressures and flame speeds. And the arithmetic mean of the repeated tests was applied to analyze the flame speeds, maximum overpressures, average rates of overpressure rise and maximum rates of overpressure rise.

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3. Results and discussion

3.1. Effects of obstacle distance from ignition point

As shown in Fig. 3, configurations 2, 3, 4, 5 had only one obstacle mounted inside the experimental pipe, and the distance between each obstacle and the ignition point was 200 mm, 400 mm, 600 mm and 800 mm, respectively. Images of the flame development process during explosions in configurations 1, 2, 3, 4 and 5 are compared in Fig. 4. It is obvious that both the flame front structure and flame propagation velocity in the five configurations had great difference with each other. For configuration 1, the flame front remained finger-like shape along the pipe until it propagated outside the pipe, because of the fact that there was no any obstacle inside the pipe. For the rest four configurations, the flame fronts remained finger-like shape before propagating to the obstacle, and once passing through the obstacle, the flame fronts became distorted and formed a tongue-like shape, which subsequently resulted in profound flame acceleration. Another significant phenomenon could be also observed that as the flame front reached the exit of the pipe, the propagation flame front moved laterally and formed a mushroom-like shape with a significant increase in flame surface area, for the reason that the axial flame velocity was greater than the radial velocity.

Fig. 5(a) shows the effects of the distance between obstacle and ignition point on the flame front locations. The flame front location was obtained by measuring the maximum axial distance of the flame front from the ignition point. It is obvious that before 20 ms, the flame fronts of the five configurations spread simultaneously in a linear growth trend due to the reason that there was no any turbulence in this stage, and the flame fronts spread in a laminar flow state. However, from 20 ms on, the propagation velocity of the flame fronts began to speed up. This phenomenon might be caused by the rupture of membranes, which could result in flame acceleration, and it could be proved by the “venting” time marked as 17.5 ms in the Fig. 5(c). Then, when the flame fronts propagated across the obstacle at about 20 ms, 30 ms, 32 ms and 34 ms for configurations 2, 3, 4 and 5, respectively, as shown by the flame images in Fig. 5(a), the flame spread velocity began to speed up sharply in an exponential growth trend until extinguished. And a significant phenomenon could be observed that the time taken by the flame fronts of each configuration to reach the maximum location became longer with the growth of the distance between the obstacle and ignition point. This is because the father the distance between obstacle and ignition point, the later the acceleration phenomenon appeared, and finally lengthened the time of flame fronts to reach the farthest location.

Fig. 5(b) presents the flame speeds along the axial direction from the ignition point in the five configurations, the value of flame speed is calculated by:

\[ S_f = \frac{(x_{n+1} - x_n)}{\Delta t_n} \]
It is observed that the maximum overpressures for configurations 2, 3, 4, 5 were about 28.60 ms, 35.00 ms, 35.80 ms and 39.20 ms, respectively, indicating the shorter the distance between obstacle and ignition point, the shorter the time taken to reach the maximum overpressure. This is because at the distance of Li = 200 mm before it reached the obstacle, and more heat could be accumulated to support the overpressure rise, hence generated higher pressure and overpressure rise rates. When the distance from ignition point increased from Li = 400 mm to Li = 600 mm and 800 mm, the flame developed more fully than Li = 400 mm, hence reduced the intensity of the overpressures and the overpressure rise rates. However, it would be noticed that the time to reach the maximum overpressures for configurations 2, 3, 4, 5 were about 28.60 ms, 35.00 ms, 35.80 ms and 39.20 ms, respectively, indicating the shorter the distance between the obstacle and ignition point, the shorter the time taken to reach the maximum overpressure.

Fig. 5(c) shows the overpressure time histories of the five configurations. It is easily observed that there existed a slight pressure peak at about 17.5 ms for all the tests. This pressure peak might be resulted from the instantaneous rupture of the thin polyethylene film at the exit of the pipe, therefore the pressure peak could be referred to “venting” pressure, and denoted as “Pv.” It could be also seen from Fig. 5(c) and Table 1 that the distance between obstacle and ignition point had a significant effect on the parameters of overpressures. To be concrete, the magnitude of maximum overpressures, average rates of overpressure rise and maximum rates of overpressure rise for the gasoline–air mixture explosions varied in different configurations. And it is observed from Fig. 5(c) and Table 1 that the greatest magnitude of maximum overpressures was obtained in configuration 3 (Li = 400 mm), and the same with the average rates of overpressure rise and maximum rates of overpressure rise. This is because at the distance of Li = 400 mm, the flame could develop more fully than that of Li = 200 mm before it reached the obstacle, and more heat could be accumulated to support the overpressure rise, hence generated higher pressure and overpressure rise rates. When the distance from ignition point increased from Li = 400 mm to Li = 600 mm and 800 mm, the flame developed more fully than Li = 400 mm before reached the obstacle, while the distance between obstacle and pipe exit decreased. Therefore, after the flame passed through the obstacle, the flame could jet outside the pipe in a shorter time than that of Li = 400 mm, hence reduced the intensity of the overpressures and the overpressure rise rates. However, it would be noticed that the time to reach the maximum overpressures for configurations 2, 3, 4, 5 were about 28.60 ms, 35.00 ms, 35.80 ms and 39.20 ms, respectively, indicating the shorter the distance between the obstacle and ignition point, the shorter the time taken to reach the maximum overpressure.

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speed up sharply. It could be found that the maximum velocity of \( v = 271.775 \text{ m/s} \), respectively, which were enhanced by 107.7%, 142.7% and 175.7% compared with the value of configuration 1.

The blockage ratio had a significant effect on flame propagation. It could be seen in Fig. 6(a) that before the flame fronts propagated across the obstacles, the flame locations in the four configurations were similar. And when the flame fronts touched the obstacles, at about 30 ms for configuration 6 and 7, and 32 ms for configuration 8, respectively, the velocity of flame fronts began to accelerate sharply until reached the maximum flame speed, and the magnitude of maximum flame speed increased with the growth of the blockage ratio of obstacle.

### Table 1

Effects of obstacle distance from ignition point on maximum flame speeds \( (S_v) \), maximum overpressures \( (P_{\text{max}}) \), average rates of overpressure rise and max. rates of overpressure rise for the gasoline–air mixture explosions.

<table>
<thead>
<tr>
<th>Obstacle configuration</th>
<th>Max. ( S_v ) (m/s)</th>
<th>( P_{\text{max}} ) (kPa)</th>
<th>( (dp/dt)_{\text{ave}} ) (kPa/ms)</th>
<th>( (dp/dt)_{\text{max}} ) (kPa/ms)</th>
<th>( \frac{(dp/dt)<em>{\text{ave}}}{(dp/dt)</em>{\text{max}}} \times 100% )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Configuration 1</td>
<td>98.56</td>
<td>9.52</td>
<td>0.31</td>
<td>6.81</td>
<td>-</td>
</tr>
<tr>
<td>Configuration 2</td>
<td>272.68</td>
<td>34.39</td>
<td>1.20</td>
<td>25.71</td>
<td>277.56%</td>
</tr>
<tr>
<td>Configuration 3</td>
<td>207.68</td>
<td>56.40</td>
<td>1.61</td>
<td>36.40</td>
<td>434.43%</td>
</tr>
<tr>
<td>Configuration 4</td>
<td>187.5</td>
<td>51.78</td>
<td>1.45</td>
<td>32.76</td>
<td>380.98%</td>
</tr>
<tr>
<td>Configuration 5</td>
<td>168.74</td>
<td>18.56</td>
<td>0.47</td>
<td>12.86</td>
<td>88.77%</td>
</tr>
</tbody>
</table>

### 3.2. Effects of obstacle blockage ratio (BR)

Examples of flame locations, flame speeds and overpressure time histories in four pipe configurations (BR = 0, BR = 36.4%, BR = 49.8% and BR = 71.7%) are shown in Fig. 6. To avoid repetition, the flame images of these four configurations are not displayed in this section. It should be noted that in Fig. 6(a), and Fig. 6(c), only one example of each experimental configuration is displayed in order to illustrate the effect of BR. It could be seen in Fig. 6(a) that before the flame fronts propagated across the obstacles, the flame locations in the four configurations were similar. And when the flame fronts touched the obstacles, at about 30 ms for configuration 6 and 7, and 32 ms for configuration 8, respectively, the velocity of flame fronts began to accelerate sharply until reached the maximum flame location position away from the ignition point. However, it is obvious in Fig. 6(a) that after the flame fronts passed through the obstacles, the propagation velocity of flame location for configuration 8 yielded the highest, followed by configuration 7 and 6 successively. Meanwhile, it is easily observed that the flame fronts in configurations 6, 7 and 8 could propagate to a maximum distance of about 1.6 m, while it could only be about 1.3 m for configuration 1, indicating that obstacle mounted in the flame propagation channel could have significant effect on the maximum propagation distance of flame fronts.

Fig. 6(b) represents the flame speeds of the four configurations, it could be easily observed that before 20 ms, the flame speeds of the four configurations were nearly the same, remaining at a speed of about 9 m/s. And between 20 ms and 30 ms, slight oscillations of flame speeds were found, but no large difference for the four configurations were seen, indicating the obstacle had little effect on the upstream flow. However, significant difference took place after 30 ms when the flame fronts propagated across the obstacles, and the flame speeds began to speed up sharply. It could be found that the maximum flame speeds of configurations 6, 7 and 8 were 204.72 m/s, 239.165 m/s and 271.775 m/s, respectively, which were enhanced by 107.7%, 142.7% and 175.7% compared with the value of configuration 1, indicating that the blockage ratio had a significant effect on flame speed, and the magnitude of maximum flame speed increased with the growth of the blockage ratio of obstacle.

![Flame location versus time](image1)

![Flame speed versus time](image2)

![Overpressure time histories](image3)

**Fig. 6.** Variation of flame locations, flame speeds and overpressures versus time with different BR of obstacles.
Representative overpressure versus time profiles for the four configurations are shown in Fig. 6(c), it could be found that the parameters of overpressures differed greatly among the four configurations. Generally, it is obvious in Fig. 6(c) and Table 2 that the maximum overpressures, average rates of overpressure rise and maximum rates of overpressure rise increased profoundly with the growth of BR of obstacles. Meanwhile, the significant effect of BR on the maximum rates of overpressure rise would be noticed, for the reason that the severity factor (or deflagration index) $K_C$ applied to examine the violence of explosions is associated with the maximum rate of pressure rise $\frac{\Delta P}{\Delta t}$. Therefore, in the industry process, the BR of obstacles should be taken into account as part of safety analysis when placing explosion suppression devices, flame arresters and venting devices.

3.3. Effects of obstacle separation distance

In order to investigate the effects of obstacle separation distance (defined as $D_i$ in this paper) on the characteristics of gasoline--air mixture explosions, two flat obstacles with the same blockage of 49.8% were applied in the experimental study. In each test, the first obstacle was fixed 100 mm to the ignition point, and the position of the second obstacle was methodically changed from 100 mm to 900 mm away from the first obstacle.

Fig. 7(a) shows the flame locations of the 10 configurations, it could be easily found that the propagation speeds of flame locations for configurations 9–17 were much higher than configuration 1, and the maximum flame locations were also farther than configuration 1, indicating that the obstacles had significant effects on the flame location propagation process. For configurations 9–17, the velocity of flame locations began to speed up at about 10 ms, when flame fronts propagated across the first obstacle, shown as the emblematical flame image in the Fig. 7(a), and finally reached to a maximum distance about 1.61 m. Based on the flame acceleration trend, the flame propagation process in Fig. 7(a) might be divided into two sections as Ⅰ and Ⅱ from the point of 10 ms. It is easily observed that in section Ⅱ the change rules of the flame locations for the 9 configurations just had no large differences, and the effects of the second obstacle on flame location propagation were not so profound as the effects of obstacle blockage ratio and obstacle distance from ignition point, indicating that the effects of separation distance of obstacles on the flame location propagation process were limited. This is because with the existence of the first obstacle, flame had been accelerated to some extent in each configuration before they reached the second one, and as a result, the acceleration effect of the second obstacle on flame behavior was not motivated as significantly as the first one.

Table 2
Effects of blockage ratio (BR) on maximum flame speeds ($S_f$), maximum overpressures ($P_{\text{max}}$), average rates of overpressure rise and max. rates of overpressure rise for the gasoline–air mixture explosions.

<table>
<thead>
<tr>
<th>Obstacle configuration</th>
<th>Max. $S_f$ (m/s)</th>
<th>$P_{\text{max}}$ (kPa)</th>
<th>$\frac{\Delta P}{\Delta t}_{\text{ave}}$ (kPa/ms)</th>
<th>$\frac{\Delta P}{\Delta t}_{\text{max}}$ (kPa/ms)</th>
<th>$\frac{\Delta P}{\Delta t}_{\text{max}} \times 100%$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Configuration 1</td>
<td>98.56</td>
<td>9.52</td>
<td>0.31</td>
<td>6.81</td>
<td></td>
</tr>
<tr>
<td>Configuration 6</td>
<td>204.72</td>
<td>44.95</td>
<td>1.22</td>
<td>25.71</td>
<td>277.46</td>
</tr>
<tr>
<td>Configuration 7</td>
<td>239.17</td>
<td>51.98</td>
<td>1.41</td>
<td>28.88</td>
<td>324.14</td>
</tr>
<tr>
<td>Configuration 8</td>
<td>271.78</td>
<td>80.40</td>
<td>2.24</td>
<td>47.55</td>
<td>598.16</td>
</tr>
</tbody>
</table>

![Flame location versus time](image1)

![Flame speed versus time](image2)

![Overpressure time histories](image3)

![The effect of dimensionless separation distance on the Max. overpressures and Max. rates of overpressure rise](image4)

Fig. 7. Variation of flame locations, flame speeds and overpressures versus time with different obstacle separation distance.
In the present work of this paper, the effects of obstacle distance from ignition point, the blockage ratio of obstacle (BR) and the separation distance of obstacles on the characteristics of gasoline–air mixture explosions have been examined by a series of contrast experiments in a semi-confined organic glass pipe (with a square cross section size of 100 mm*100 mm and 1000 mm long, L/D = 10, V = 0.01 m²/s). The main conclusions could be summarized as follows:

It was shown that before the flame fronts propagated to the obstacle, the flame fronts remained regular shape and spread in a low speed, while passed across the obstacle, the flame fronts could be sharply accelerated and became distorted. And it was obvious that the shorter the distance between obstacle and ignition point, the earlier the flame was accelerated, and eventually led to a higher maximum flame speed. Meanwhile, the maximum overpressures and maximum rates of overpressure rise were obtained at L = 400 mm, and the shorter the distance between the obstacle and ignition point, the shorter the time taken to reach the maximum overpressure. Three kinds of blockage ratios (BR = 36.4%, 49.8%, 71.7%) were tested, and conclusions showed that the maximum flame speeds, maximum overpressures, average rates of overpressure rise and maximum rates of overpressure rise increased with the growth of blockage ratio. It was also discovered that the maximum effect of the combined obstacles on flame acceleration behavior could be obtained at a separation distance of 1 time 4 times the length of the pipe diameter, and similar conclusions had also been discovered in the study by Na’inha [9]. This phenomenon arose probably due to the following reasons: 1. the turbulence flow induced by the two combined obstacles might be more intensive when the separation distance was between 100 mm and 400 mm, which would enhance the exchange rate of burned and unburned gases, and as a result improved the burning rate. 2. the time taken by the flame to evolve from laminar flow to turbulent flow became shorter when the separation distance was nearer than 400 mm, therefore the flame could be accelerated earlier and eventually led to a higher maximum flame speed.

Example overpressure versus time profiles for different obstacle separation distances are shown in Fig. 7(c). The strong effect of the obstacle separation distance on both the maximum overpressures and the development of overpressures was clearly demonstrated by the data. It is observed in Fig. 7(c) that with the growth of the obstacle separation distance, the time taken to obtain the maximum overpressures became shorter, while the maximum values of overpressures varied in a parabolic trend. The effect of the separation distance on the maximum overpressures and maximum rates of overpressure rise are more clearly illustrated in Fig. 7(d) and Table 3. In Fig. 7(d) the separation distance is presented in terms of a dimensionless distance by dividing the actual distance (D_i) with the diameter of the pipe (D). It is shown that the maximum effect of the separation distance occurred when the separation was approximately between 3 and 5 dimensionless obstacle separation distance (or between 300 mm and 500 mm). This work has important implications on the effect of repeated obstacles on flammable gases explosions and the design of appropriate experiments that are indeed worst case scenarios.

### 4. Conclusions

In the present work of this paper, the effects of obstacle distance from ignition point, the blockage ratio of obstacle (BR) and the separation distance of obstacles on the characteristics of gasoline–air mixture explosions have been examined by a series of contrast experiments in a semi-confined organic glass pipe (with a square cross section size of 100 mm*100 mm and 1000 mm long, L/D = 10, V = 0.01 m²/s). The main conclusions could be summarized as follows:

- It was shown that before the flame fronts propagated to the obstacle, the flame fronts remained regular shape and spread in a low speed, while passed across the obstacle, the flame fronts could be sharply accelerated and became distorted. And it was obvious that the shorter the distance between obstacle and ignition point, the earlier the flame was accelerated, and eventually led to a higher maximum flame speed.
- Meanwhile, the maximum overpressures and maximum rates of overpressure rise were obtained at L = 400 mm, and the shorter the distance between the obstacle and ignition point, the shorter the time taken to reach the maximum overpressure. Three kinds of blockage ratios (BR = 36.4%, 49.8%, 71.7%) were tested, and conclusions showed that the maximum flame speeds, maximum overpressures, average rates of overpressure rise and maximum rates of overpressure rise increased with the growth of blockage ratio. It was also discovered that the maximum effect of the combined obstacles on flame acceleration behavior could be obtained at an obstacle separation distance of 1 time 4 times the length of pipe diameter. And the time taken to obtain the maximum overpressures became shorter with the growth of the obstacle separation distance, while the maximum overpressures and maximum rates of overpressure rise were obtained at an obstacle separation range from D_i/D = 3 to 5 (or 300 mm–500 mm).

This work has contributed further to the argument that obstacles in a pipe or underground facilities have significant effects on the combustion and explosion process of flammable gases, and when placing explosion suppression devices, flame arresters and venting devices during an industry process, the parameters of obstacle distance from ignition point, the blockage ratio of obstacle (BR) and the separation distance of obstacles should be taken into account as part of safety analysis. Although some meaningful results were found in this study, there are still many problems unsolved in this paper like the effects of number of obstacles, the shape of obstacle cross-section and so on.

### Acknowledgment

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**Table 3**

<table>
<thead>
<tr>
<th>Obstacle configuration</th>
<th>Max. S_f (m/s)</th>
<th>P_{max} (kPa)</th>
<th>(dp/dt)_{max} (kPa/ms)</th>
<th>(dp/dt)_{max} (kPa/ms)</th>
<th>(dp/dt)_{ave} (kPa/ms)</th>
<th>(dp/dt)_{ave} (kPa/ms)</th>
<th>\times 100%</th>
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</thead>
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<tr>
<td>Configuration 1</td>
<td>98.56</td>
<td>9.52</td>
<td>0.31</td>
<td>6.81</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td>Configuration 9</td>
<td>246.72</td>
<td>46.48</td>
<td>2.07</td>
<td>26.25</td>
<td>-</td>
<td>-</td>
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<td>2.27</td>
<td>37.56</td>
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<td>Configuration 11</td>
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<td>72.93</td>
<td>2.69</td>
<td>40.96</td>
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<td>40.66</td>
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<td>16.73</td>
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References


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