직사각형 폭발 챔버에서 화염전파와 직사각형 장애물의 상관관계

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Interactions Between a Propagating Flame and Rectangular Wall Obstacles in a Rectangular Confinement

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Abstract : Experimental studies have been performed to examine the influences of wall obstructions in a rectangular confinement. Three wall obstacles with blockage ratios ranging from 10 to 30% were used. Temporally resolved flame front images were recorded by a high-speed video camera to investigate the interaction between a propagating flame and the obstacle. The local flame displacement speed and its probability density functions(PDFs) were obtained for the wall obstructions. During the interaction with the sharp-edges of the wall obstacles, the local propagation speed increased. The increase of local speed became larger as the obstruction ratio increased. However, the averaged flame displacement speeds with different blockage ratios were not significantly different within the chamber as shown in the paper of Park et al6). The flame front interaction investigated in this work was less dependent of the obstacle obstructions compared to that published in the literature for large L/D.

초 록 : 직사각형 폭발 챔버에서 전파하는 화염과 직사각형 장애물의 상관관계를 조사하기 위한 실험적 연구가 수행되었다. 챔버내에 10%, 20% 및 30%의 blockage ratio를 가지는 3가지 직사각형 장애물들이 사용되었다. 전파하는 화염과 장애물의 상관관계를 조사하기 위해 고속카메라가 사용되었다. 고속카메라로 얻어진 화염 이미지로부터 장애물 주위의 국부 화염속도 및 그 화염속도의 확률밀도함수가 계산되었다. 실험결과, 전파하는 화염이 직사각형 장애물의 모서리와 상호작용할 때 국부 화염속도는 증가하였다. 그 증가속도는 장애물의 Blockage Ratio가 증가할 때 더욱 커지는 것으로 나타났다. 그러나, 평균화염속도는 Blockage Ratio에 큰 의존성을 가지지 않는 것으로 나타났다. 이 연구에서 사용된 작은 L(Lenlgth)/D(Diameter)비를 가지는 폭발 챔버내에서 전파하는 화염전면과 직사각형 장애물과의 상관관계는 L/D비가 큰 문헌에서 보고된 결과와 비교하면, Blockage Ratio에 따른 의존성은 작은 것으로 나타났다.

Key Words : obstruction ratio, flame displacement speed, flame propagation

1. Introduction

It is well known that the existence of turbulence during accidental gas explosions can accelerate the propagating flame, increasing the flame surface area and enhancing the burning rate. The turbulence occurs from the interaction between a freely propagating flame and equipment such as pipe-work and vessels in congested regions of plant. The flame/obstacle interaction causes local flame acceleration of the moving flame front.

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The local acceleration of the flame front is a result of a complex interaction between the propagating flame and the local blockage caused by the existence of obstacle. The influences of such local blockage on the explosion process have been performed in large length to diameter(L/D) ratio vessels and pipes by many investigators[1-5]. In previous measurements of Park et al.[6], the experimental data were reported for flame interactions with different single obstacles in a rectangular enclosure of small L/D ratio and a large rectangular venting area. The mean flame speeds did not increase much with blockage ratio for the same obstacle examined and they were also not significantly different for different shapes at the same blockage ratio compared to results reported in the literature for large L/D ratios. A detailed discussion of the main reasons was given by the authors in that paper. However, the influences of rectangular obstructions causing the fastest increase in flame speeds were not investigated in their explosion chamber. The purpose of the present paper is to examine interactions between propagating flame and wall obstacles with different blockage ratios up to 30% within the chamber described in the study of Park et al.[6]

2. Experimental

The apparatus, techniques, and reactive mixture used in this work are the same with reported in previous work[6].

Three rectangular obstacles with blockage ratios from 10, 20 to 30% were mounted inside the chamber and centred at 117.5mm from the bottom of the chamber. The dimensions and configurations are given in Table 1.

3. Image processing & flame front tracking

Table 1. Configurations of rectangular wall obstacles used in the explosion chamber

Type	Symbol	Dimension (mm)	*H* (mm)	B.R. (%)
Rectangular obstacles	RW1	950×100	10	10
	RW2	950×200	10	20
	RW3	950×300	10	30

Note. *H* : Distance from the bottom of chamber to the front end of the obstacle facing the ignition point.

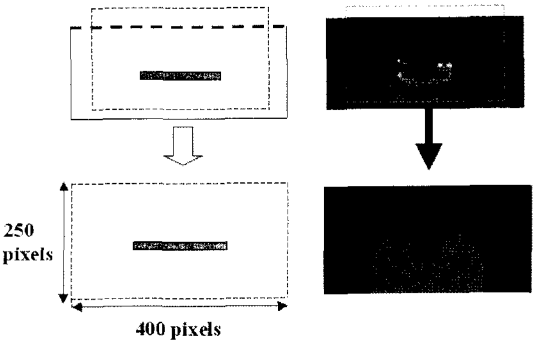


Fig. 1. (a) Selection of a local area of interest; (b) Example of image processing applied to the original flame image in the area of interest.

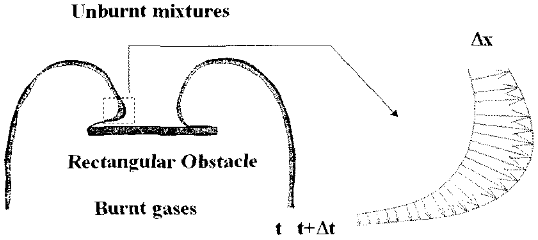


Fig. 2. Flame-front position and calculation of the local flame-front displacement.

The procedures to investigate the interactions between the flame and the rectangular wall obstacles were the same as previous work of Park et al.[6] As shown in Fig. 1(a), the local region of interest selected here was around the central obstacle. The subregion area was 400 × 250 pixels[2]. Fig. 1(b) shows one example of image processing applied in the area of interest to the original flame image obtained at 66 ms after ignition. The extraction of the flame front position is obtained from the processed images similar to Fig. 1(b). Fig. 2 shows an example of flame movement around rectangular obstacle obtained at 66ms after ignition.

4. Results and Discussions

4.1. Statistics of local flame propagation speed

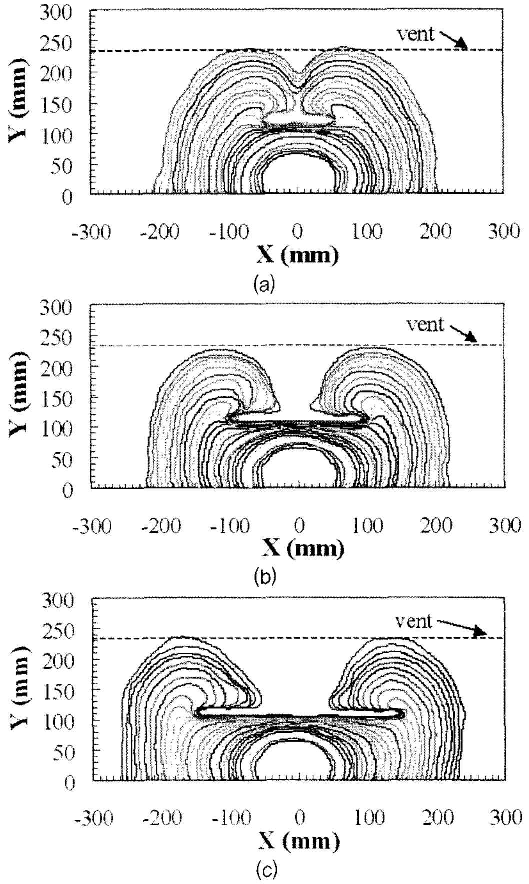
Fig. 3(a), (b) and (c) show the temporal evolution of propagating flame front contours around the cross-sections of rectangular obstacles with blockage ratios of 10, 20 and 30% respectively. Subsequent flame fronts are traced with an interval of 2 ms. The local flame displacement speed and its probability density functions(pdfs) outside the vent are excluded from the analysis.

A statistical approach to producing pdfs of local flame displacement for each identified stage of development has been described in Park et al.[6]. Although five stages were described previously, in this analysis stage III, flame propagation up the side of the obstacle, is too short to be observed and stage IV, reconnection in the wake of the obstacle, sometimes occurs outside of the vessel. In this latter case, stage IV is combined with stage V. The flame displacement speed pdfs for the rectangular wall obstacles which have blockage ratios from 10 to 30% are shown in Fig. 4(a) to (c).

Stage I occurs before the propagating flame impinges on the front face of obstacle and the flame front propagates at the laminar flame speed since the flow field ahead of the flame remains undisturbed. This early flame propagation has no turbulent structure. Consequently, the pdf during stage I has a relatively narrow distribution around the laminar flame speed, $(\rho_u/\rho_b) \cdot S_L = 2.85$m/s. As the degree of blockage increases the pdfs become slightly skewed to lower displacement speeds($S_{fd} < 2.85$m/s) because of the increased stagnation pressure and expansion of hot gases under the obstacle.

Stage II occurs from the time of flame front impingement on the obstacle to the time where the flame reaches the sharp edge of the front face of the obstacle. As the flame fronts interact with the front face of the obstacle facing the ignition point, the eddies that occur along the front face of the obstacle decelerate the flame near the front face of the obstacle while accelerating the flame in leading flame fronts emerging between the sharp edge of the obstacle and sidewalls of chamber. On average this leads to a moderate flame acceleration, the pdfs during this stage appear more bimodal with a larger spread that is larger as the obstruction ratio increases.

Stage IV is from sharp edges of the lower face of the obstacle to the flame reconnection in the wake of the obstacle. For the blockage ratios of 20 and 30%, the stage IV only considered up to the flame reaches the chamber exit because the flame fronts are reconnected outside the chamber exit. The pdfs of displacement speed have lost their bimodal appearance and moved to higher values, although they still remain wider than those found in earlier stages.



(a)

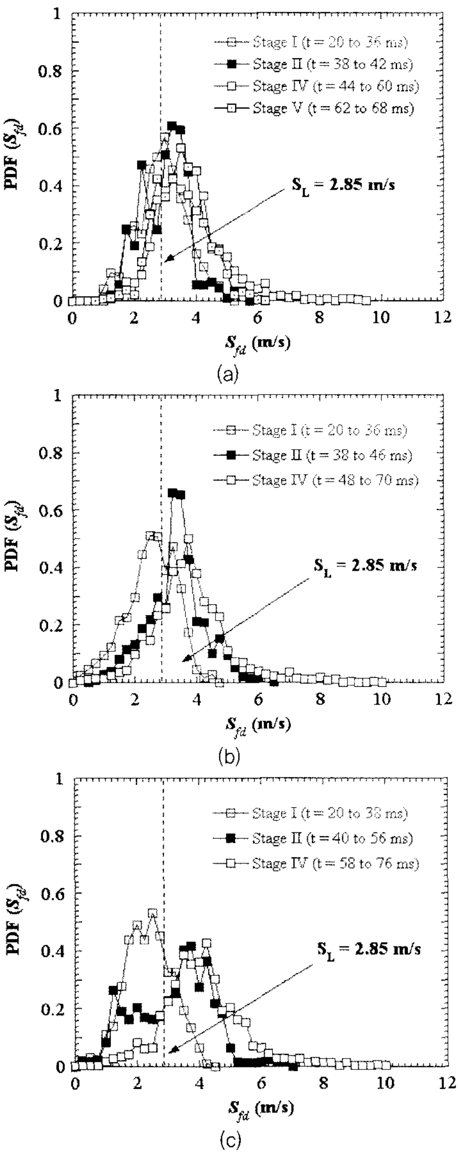
(b)

(c)

Fig. 3. Temporal evolution of flame contours (time interval = 2ms) for rectangular cross-section obstacles: RW1 (B.R. = 10%, 20 to 70ms), RW2 (B.R. = 20%, 20 to 70ms) and RW3 (B.R. = 30%, 20 to 78ms).

Stage V, when the flame front propagates towards the chamber exit after flame reconnection, is only observed with the obstacle of 10% obstruction.

The flame fronts that have merged behind the obstacle continue to propagate towards the chamber centerline as well as the exit due to interaction of the flame flow with the vortex behind the obstacle. The pdf during stage V is shifted to lower values. This stage is related to moderate flame acceleration. The flame fronts in the rectangular obstacles with the blockage ratios of 20 and 30% were reconnected outside the vent over 80ms, so the stage V is not considered in this paper.



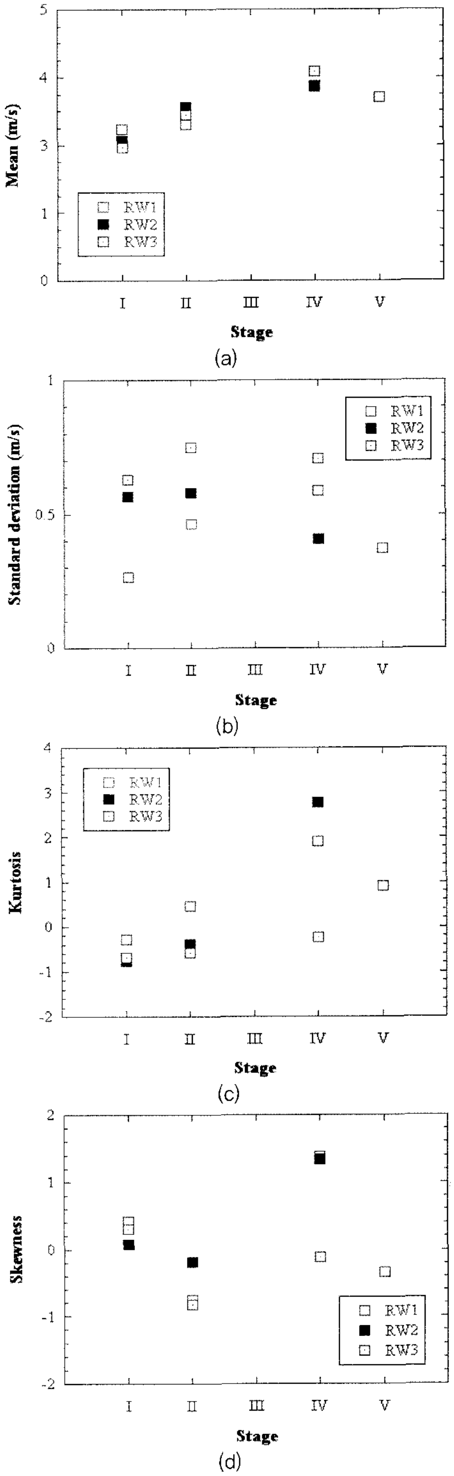
(a)

(b)

(c)

Fig. 4. PDFs of flame displacement speed for rectangular obstacles: (a) RW1, (b) RW2 and (c) RW3.

The mean, standard deviation, skewness and kurtosis of the flame displacement speed PDFs were calculated and are shown in Fig. 5 plotted for the different stages explained above. The mean displacement speed for the different blockages was similar, becoming higher through the stages and a maximum at stage IV. The RW1 generally caused the relatively lower standard deviation at all stages, excepting for stage IV while the higher one through the stages was at the RW3.



(a)

(b)

(c)

(d)

Fig. 5. Moments of the flame displacement speed PDFs for rectangular wall obstructions at different stages in Fig. 4; (a) mean (b) standard deviation (c) skewness and (d) kurtosis.

Among the stages, stage II had a lower skewness while stage IV had a higher skewness. The RW3 had the much lower skew and kurtosis for stage IV due to a lower number of contours that can be analyzed before flame exits and hence is only a small portion of the reconnection time. The kurtosis for the obstructions ratios was becoming through higher through the stages, excepting for the drop in the stage V of RW1. The maximum was at stage IV while the minimum was at stage I.

4.2. Mean local flame displacement speed

Fig. 6 shows variations of the averaged local flame displacement speed, $\overline{S_{fd}}$ as a function of time for rectangular obstacles with blockage ratios of 10, 20 and 30%.

Despite some fluctuations, the general trend of the displacement speeds calculated at the different obstructions up to about 40 ms remains similar to the laminar flame speed.

When the moving flame front impinges onto the face of the obstacle, the flame starts to interact with a modified flow-field generated around the obstacle. The displacement speed increases due to the increase in the flame surface area following interaction with the obstacle.

Faster flame speed times were observed with the RW1, indicating the blockage ratio of 10% where the flame starts to increase at about 44ms compared with 48 and 52ms for the obstacles of the blockage ratios of 20 and 30%, respectively. The smaller obstructions yielded the higher flame speeds in the initial stages of flame propagation while the larger obstructions resulted in the higher speeds during the later stages of flame propagation. The maximum average flame speed increased and occurred later as the blockage ration was increased: with 4.9m/s at 30%; 4.3m/s at 20% and 3.9m/s at 10%. As the obstruction ratio increased, the flame speeds were slightly affected by the obstruction ratios.

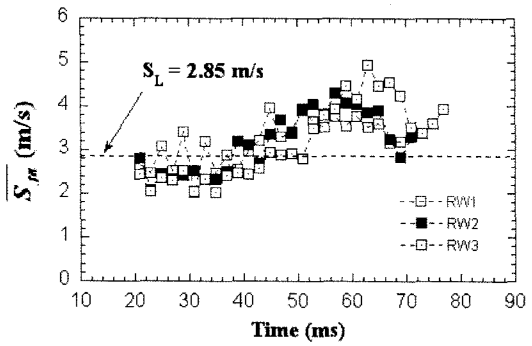


Fig. 6. Temporal evolution of the averaged flame displacement speed after ignition for rectangular wall obstacles(RW1, RW2 and RW3).

5. Conclusion

Experimental investigations were performed to examine the influence of rectangular wall obstacles within the chamber with a small L/D ratio and large rectangular vent. Three wall obstacles with blockage ratios ranging from 10 to 30 % are used. The main results obtained from the present work are presented as follows:

1) As the blockage ratio increased, the pdfs of local flame displacement speeds during stage I become slightly skewed to lower displacement speeds than the laminar flame speed. During stage II, the pdfs had a larger spread than stage I as the obstruction ratio increased. The pdfs during stage IV were distributed towards higher values than those found in other stages. This stage is linked to the highest flame acceleration. The local flame speeds were found to be largely dependent on the obstruction ratios

2) The largest increase in the averaged local flame displacement speed with time was obtained with the obstruction ratio of 30% although this occurred later than smaller blockages. However, the mean flame speeds did not increase much with the blockage ratios compared to those published in the literature for large L/D. This less increase is associated with the different calculation methods of flame speeds and the different measurement systems as mentioned in the previous work[6].

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