Influence of Blockage Ratio on the DDT and Detonation Propagation Limits for an orifice Plate Filled Tube

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1 Introduction

The accidental release of fuel vapor into the atmosphere during an industrial accident can result in an explosion if a suitable ignition source is present. In the worst case scenario, a detonation wave can form and propagate through the fuel-air cloud causing severe structural damage to the plant. In order for a detonation wave to form, not only does an ignition source need to exist, but also obstacles must be present to produce turbulence in the unburned gas ahead of the flame. If the flame is able to accelerate to a velocity on the order of a 1000 m/s, a detonation wave can be initiated. This process is referred to as deflagration-to-detonation transition (DDT). In order to simulate the flame acceleration process, Chapman and Wheeler [1] were one of the first to perform experiments to investigate the effect of obstacles on flame acceleration. Starting in the early 1980s flame acceleration leading to DDT has been investigated primarily in round tubes equipped with repeated orifice plates [2]. Peraldi et al. [3] showed that in this configuration a quasi-steady explosion front can propagate at a velocity between the speed of sound of the combustion products and the CJ detonation wave velocity. This type of wave was referred to as a "quasi-detonation." For a given tube diameter and orifice plate blockage ratio (BR) the quasi-detonation regime is defined by the lean and rich composition limits. These DDT limits represent the initial mixture condition required to achieve flame acceleration leading to hot spot generation and transition to detonation. In a recent study performed by Cross and Ciccarelli [4] the detonation limits were measured by an experiment involving the transmission of a CJ detonation wave from a smooth tube into an orifice plate filled tube of the same diameter. These limits may be considered *propagation limits* (as opposed to DDT limits) since there is no need for flame acceleration and the establishment of the initial hot spot to start the detonation wave. Cross and Ciccarelli showed that for equally spaced 75 mm diameter orifice-plates (BR=44%) the measured propagation limits for hydrogen-air and ethylene-air are similar to the DDT limits. It was also shown that at the limits the ratio of the orifice plate diameter and the detonation cell size was roughly unity ($d/\lambda=1$), consistent with the finding of Peraldi et al. [3]. In the present study the influence of the orifice plate BR on the DDT and detonation propagation limits is investigated for hydrogen, ethylene, and acetylene air mixtures.

2 Experimental

Experiments were carried out in an apparatus consisting of a 6.1 m long, 100 mm inner-diameter tube. As shown in Fig. 1 the second half of the tube contained orifice plates equally spaced at the tube diameter. Six different orifice plate diameters were used between 38.1 mm (1.5 inches) and 76.2 mm (3 inches), in increments of 6.4 mm (1/4 inches). For the DDT experiments (see Fig. 1a) ignition was via a weak automotive capacitive discharge spark positioned centrally at the right-endplate, such that flame acceleration occurred from right-to-left in the obstacle field. For the detonation propagation limit experiments, a CJ detonation wave was initiated at the left-end of the tube using an oxygen-acetylene gas driver using the same spark ignition system, as shown in Fig. 1b. The CJ detonation wave is transmitted into the obstacle section. The average wave velocity was obtained from flame time-of-arrival measurements deduced from ionization probe (IP) signals. The IPs were distributed evenly, 305 mm apart (spanning roughly three orifice plates), down the length of the tube. The test mixture was prepared by the method of partial pressures in a separate mixing chamber equipped with an air driven stirrer. The mixture constituents were mixed in a separate chamber. Gases were supplied from standard compressed gas cylinders.

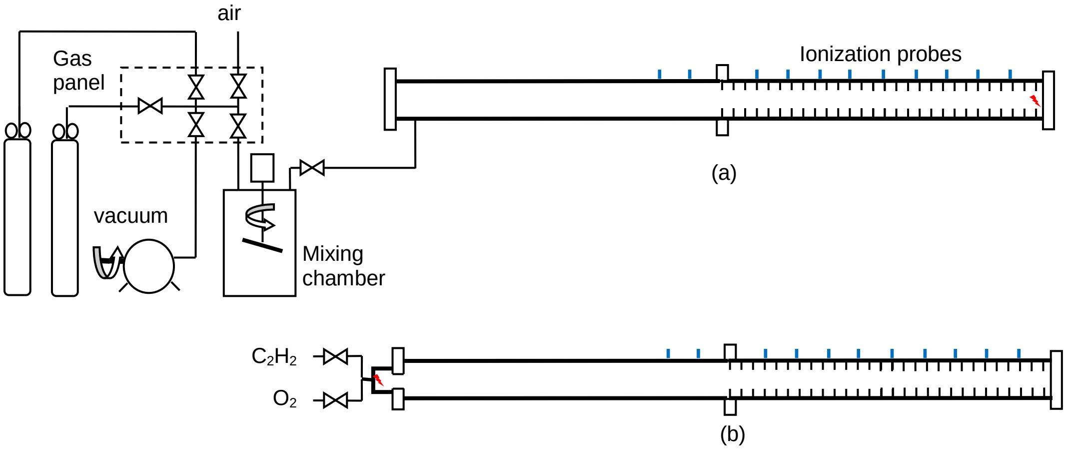

Figure 1: Experimental apparatus showing the gas handling system and obstacle filled tube. a) The DDT limits setup - flame propagation right to left, b) The detonation propagation limits setup - detonation propagation from left to right.

3 Results and Discussion

A series of tests were performed where the lean and rich DDT and detonation propagation limits were obtained for different BR plates by measuring the explosion front velocity for different mixture compositions. The DDT experiments were performed using the setup shown in Fig. 1a. The flame velocity measured down the obstacle filled first-half of the tube equipped with 69.9 mm orifice plates is shown in Fig. 2a. For most of the tests the flame accelerates reaching a quasi-steady velocity before the end of the obstacles at 3.05 m. For example, for the 30% hydrogen test the flame accelerates quickly with a sudden jump in velocity establishing a steady-state velocity before the end of the obstacle section. Whereas for 22% and 52% hydrogen the flame acceleration is slower and there is no sharp rise in velocity associated with a DDT event, resulting in a shorter velocity plateau. For the other two tests the terminal velocity is lower and thus a longer velocity plateau is established.

The detonation propagation experiments were performed using the setup in Fig. 1b. The explosion front velocity measured in the obstacle section filled with 69.9 mm orifice plates is shown in Fig. 2b. The detonation velocity measured in the smooth tube just before the obstacles corresponds to the data point at 2.6 m. In all the tests the velocity measured at the end of the smooth part of the tube was within 2% of the theoretical CJ detonation wave velocity. The velocity data point at 3.05 m in Fig. 2b represents the average velocity measured between ion probes located 305 mm before and after the first orifice plate (located at the mid span of the tube). For all the mixtures tested, the detonation velocity drops rapidly upon entering the obstacle section and stabilizes within the first 0.5 m of the start of the obstacle section.

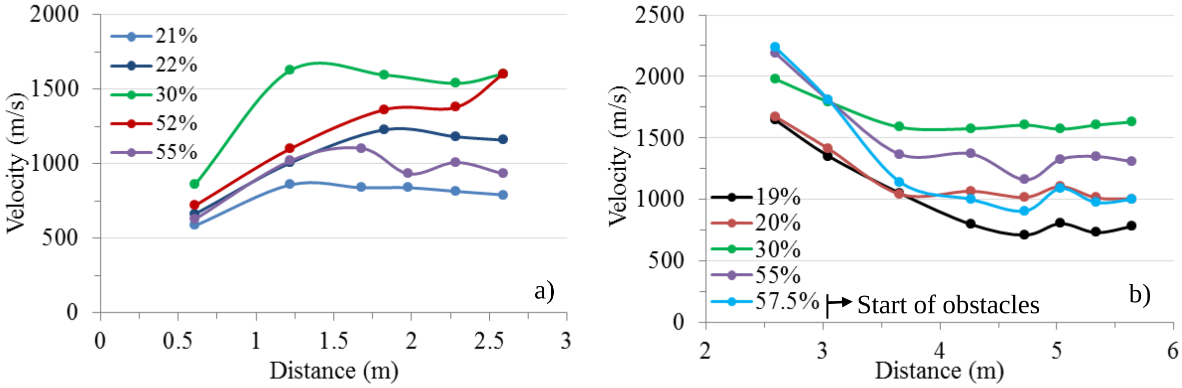

Figure 2. Explosion front velocity versus distance for hydrogen-air mixtures with 69.9 mm orifice plate

For both the DDT and detonation propagation experiments the average velocity measured at the end of the obstacle section (69.9 mm orifice plate diameter) for hydrogen-air mixtures is plotted in Fig. 3. The error bars represent the maximum and minimum velocity measured over the steady part of the velocity profile. For points with no error bars a velocity plateau was not achieved and the velocity based on the last two ionization probes was used. Also shown in Fig. 3 for reference are the theoretical CJ detonation velocity and the speed of sound of the products (isobaric process). The velocity data shows that two propagation regimes exist. In the quasi-detonation mode, as defined by the lean and rich limits (shown as vertical dotted lines), the velocity is between the isobaric speed of sound of the products and the CJ detonation velocity. In general, the magnitude of final average velocity for each mixture is similar for both the DDT and the detonation propagation experiments. This is an indication that the propagation mode is independent of the initiation process. However, the initiation process does influence the quasi-detonation regime limits. Specifically, the propagation limits are wider than the DDT limits. Similar experiments were carried out with ethylene-air mixtures, the average velocity data is provided in Fig. 4. The DDT limits are narrower than the detonation propagation limits, similar to that observed for hydrogen-air, with a significant difference on the rich side, also reported in [4].

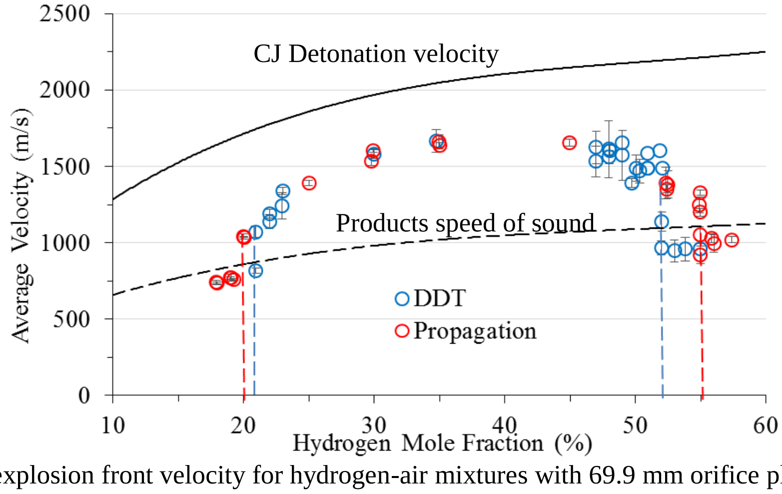

Figure 3. Average explosion front velocity for hydrogen-air mixtures with 69.9 mm orifice plate

Similar experiments were carried out for different orifice plate diameters for hydrogen, ethylene, and acetylene (only lean) air mixtures. The quasi-detonation regime limits obtained for all the orifice plate diameters for the DDT experiments are summarized in Table 1. The limits represent the leanest and richest mixture that resulted in DDT before the end of the obstacle section. The data for the 76.2 mm orifice plate is taken from Cross and Ciccarelli [4]. The data shows that the DDT limits widen with increase in orifice diameter for both hydrogen and ethylene. The value of d/λ corresponding to the DDT limits varies significantly with the orifice plate BR. For both fuels the value of d/λ (lean and rich) decreases with decreasing orifice plate BR to a value of roughly 1 for BR=0.44, in agreement with the Peraldi et al. [5] DDT criterion. The exception to this trend is rich ethylene-air for which d/λ=1.9. The breakdown of the d/λ=1 criterion for BR greater than 0.6 was also reported by Kuzntesov et al. [6].

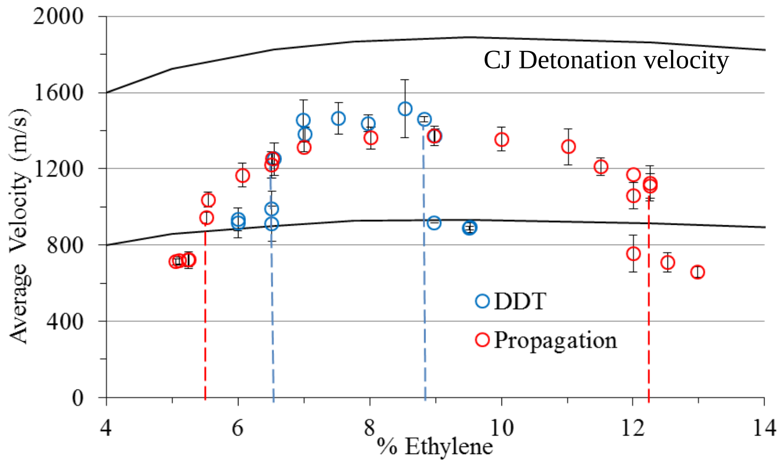

Figure 4. Average explosion front velocity for ethylene-air mixtures with 69.9 mm orifice plate

Table 1: DDT limits for hydrogen-air, ethylene-air, and acetylene-air

Orifice diameter (mm)	BR	Limit resolution (% fuel)	Lean limit (%fuel)	Equiv. ratio	Lean limit d/λ	Rich limit (%fuel)	Equiv. ratio	Rich limit d/λ
Hydrogen-air								
44.5	0.81	DDT not observed						
50.8	0.75	1	30	1	6.9	33	1.2	6.4
57.2	0.68	1	29	0.95	6.8	37	1.4	6.6
63.5	0.61	1	24	0.74	4.2	44	1.8	4.8
69.9	0.53	1	22	0.66	2.2	52	2.5	1.8
76.2	0.44	1	19	0.55	1.3	57	3.1	1.1
Ethylene-air								
63.5	0.61	DDT not observed						
69.9	0.53	0.25	6.5	0.99	2.1	9	1.41	2.7
76.2	0.44	0.25	4.75	0.71	0.9	11.4	1.84	1.9
Acetylene-air								
44.5	0.81	0.25	9	1.18	4			
50.8	0.75	0.25	8.75	1.14	3.7			
57.2	0.68	0.25	6.75	0.86	2.5			
63.5	0.61	0.25	6	0.76	1.9			
69.9	0.53	0.25	4.75	0.59	0.7			
76.2	0.44	0.25	4.25	0.53	0.4			

The quasi-detonation limits from the detonation propagation experiments using the setup in Fig 1b are provided in Table 2. Again, the data for the 76.2 mm orifice plate is taken from Cross and Ciccarelli [4]. Similar to that observed for the DDT limits, the propagation limits widen with decreasing BR, and the d/λ corresponding to the limits (lean and rich) decrease to a value of roughly unity for BR=0.44. The detonation propagation and DDT composition limits from Tables 1 and 2 are plotted as a function of the orifice plate BR in Fig. 5. The propagation and DDT limits for the largest orifice plate diameter

(BR=0.44) are in general very similar. The exception is rich ethylene that also has the DDT limit anomaly of d/λ=1.9. For all the fuels the DDT limits are narrower than the detonation propagation limits, and the DDT limits are more strongly affected by the orifice plate BR.

Table 2: Detonation propagation limits for hydrogen-air, ethylene-air, and acetylene-air

Orifice diameter (mm)	BR	Limit resolution (% fuel)	Lean limit (% fuel)	Equiv. ratio	Lean limit d/λ	Rich limit (% fuel)	Equiv. ratio	Rich limit d/λ
Hydrogen-air								
44.5	0.81	Detonation propagation not observed						
50.8	0.75	1	26	0.82	4.3	41	1.62	5.7
57.2	0.68	1	24	0.74	3.8	46	1.98	3.2
63.5	0.61	1	22	0.66	2	50	2.33	2.4
69.9	0.53	1	20	0.58	1.9	54	2.74	1.4
76.2	0.44	1	18	0.51	1	58	3.22	1.1
Ethylene-air								
54.5	0.81	Detonation propagation not observed						
50.8	0.75							
57.2	0.68							
63.5	0.61	0.25	6.5	0.99	1.7	10.5	1.68	1.9
69.9	0.53	0.25	5.5	0.83	1.2	12.25	1.99	1.3
76.2	0.44	0.25	4.75	0.71	0.9	13.5	2.23	1.1
Acetylene-air								
44.5	0.81	0.25	7.75	1	3.5			
50.8	0.75	0.25	6.75	0.86	2.8			
57.2	0.68	0.25	5.5	0.69	1.6			
63.5	0.61	0.25	4.75	0.59	0.8			
69.9	0.53	0.25	4.5	0.56	0.6			
76.2	0.44	0.25	4	0.5	0.4			

In a cylindrical tube at the limit a single head spin exists (an effective cell size of πd) and therefore the corresponding limit criterion is $d/\lambda \geq 1/\pi$. Knystautas et al [7] found when a quasi-detonation was transmitted from a rough-tube into a smooth-tube of the same diameter and found that at the limit where the detonation could not be re-established in the smooth tube, d/λ=1. The trend in the data in the present tests indicates that as the BR decreases, the critical orifice plate diameter, for both the DDT and propagation experiments, approaches the cell size (i.e., at the limit $d/\lambda \rightarrow 1$). This is consistent with the smooth-tube limit condition ($BR \rightarrow 1$) reported by Knystautas et al. [7]. For both the DDT and the propagation limits, the orifice plate diameter was at least five times greater than the detonation cell size for hydrogen-air, four times larger for acetylene, and two times larger for ethylene-air. The orifice plate plays a key role in the DDT process by providing a surface for the leading shock wave of the fast-flame to reflect and generate a hot spot. Concurrently the lead shock wave must diffract around the orifice plate, thereby weakening it before the interaction with the next orifice plate. Weakening of the shock wave makes it more difficult to generate the critical condition for a hot spot to form and transition to detonation. The beneficial effects of the orifice plate in providing a reflection surface diminishes with increased BR due to the increased effect of shock wave weakening by the diffraction. In the present study the DDT and propagation limits for a given orifice plate diameter are distinguished by the two experiments. For the larger BR orifice plates, the DDT composition limits were found to be significantly narrower than the detonation propagation limits. Kellenberger and Ciccarelli [8] showed that the global propagation of a quasi-detonation wave near the limit is governed by local detonation initiation at the obstacle face following shock reflection. The present study shows that if this mechanism can artificially be engaged (in this case by transmitting a CJ detonation wave into the obstacle field) then a detonation wave can propagate beyond the restrictions of the DDT limits that require flame acceleration to a fast-flame that subsequently transitions to a detonation wave.

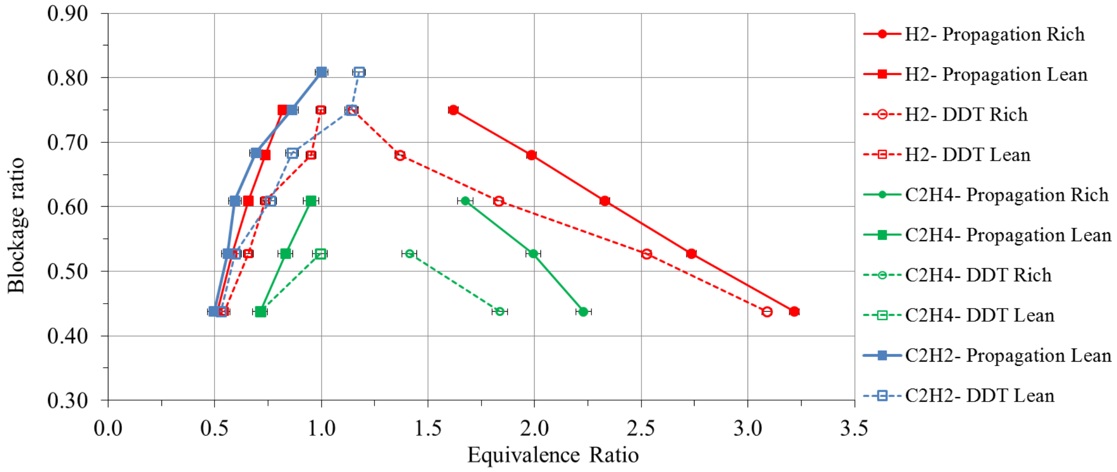

Figure 5. Detonation propagation (solid lines) and DDT limits (dotted lines) as a function of orifice plate BR

4 Conclusions

The experimental results demonstrated that the detonation propagation and the DDT limits are strongly affected by the orifice plate BR. For the 100 mm diameter tube used in the experiment, the propagation and DDT limits are similar for 0.44 BR orifice plates. Both the propagation and the DDT limits narrow with increasing BR, more significantly for the DDT limits. The narrowing of the limits with increasing BR is accompanied by a large deviation from the $d/\lambda=1$ detonation limit criterion. The beneficial effects of the orifice plate providing a reflection surface for detonation initiation diminishes with increased BR due to the increased effect of shock wave weakening by the diffraction process.

References

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