Detonation Hazard Classification Based on the Critical Orifice Plate Diameter for Detonation Propagation

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1 Introduction

Accidental explosions in the chemical and oil and gas industry are a serious problem. Normally the plants are located far from residential areas so the impact of such an explosion is confined to the plant boundaries, e.g., Buncefield explosion. The trend towards the use of higher-hydrogen content fuel (i.e., syngas or coke gas) in gas turbine and IC engine power generation stations could result in an increase in the explosion hazard for the industry. This is a concern because these power stations are generally located closer to, or within, populated areas. A sensitivity parameter (measured from a standardized experiment) is required to categorize the detonation hazard potential for these multi-component fuels, as well as other single-component fuels.

Lee [1] proposed that the minimum initiation energy be used as a parameter for the sensitivity of a fuel-air mixture to detonation. In a follow-up study Matsui and Lee [2] inferred the minimum initiation energy of a range of fuel-oxygen and fuel-air mixtures from critical tube experiments. The critical tube diameter represents the smallest diameter of an open-ended tube from which a detonation wave can emerge and continue to propagate in the surrounding explosive atmosphere. The scale of a critical tube diameter apparatus is very large because a "receiver vessel" is required. For less reactive fuels, tests are carried out in remote outdoor test sites using plastic bags. Due to the experiment scale requirement, critical tube diameter data is only available for a limited number of hydrocarbon fuel-air mixtures [3]. Correlations exist relating both the critical tube diameter and critical initiation energy with the detonation cell size [3, 4]. However, detonation cell size measurements are subject to a high level of subjectivity and uncertainty that greatly reduce their reliability and usefulness for safety applications. The objective of this paper is to establish a new parameter that can be used to categorize the relative detonation explosion hazard of a fuel that can be measured in a smaller, more practical apparatus. This new parameter is the minimum orifice plate diameter required for detonation propagation in a tube (of given diameter) equipped with orifice plates. For diameters below the critical orifice plate diameter a fast-flame (or choked flame) propagates [5]. In this study the critical orifice diameter is measured for stoichiometric acetylene, hydrogen, ethylene, propane and dimethyl ether (DME) air mixtures.

2 Experimental

Experiments were carried out in a 6.1 m long, 100 mm inner-diameter stainless steel tube, composed of 2 equal length sections. A detonation was initiated in the first half of the tube using an acetylene-oxygen driver ignited by a weak spark. The second half of the tube contained orifice plates equally

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spaced at the tube diameter. Six different orifice plate diameters between 38.1 mm (1.5″) and 76.2 mm (3″), in increments of 6.4 mm (1/4″) were used in the study. The average combustion front velocity was obtained from ionization probe time-of-arrival measurements. The probes were distributed evenly, 305 mm apart (spanning roughly four 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. Gases were supplied from standard compressed gas cylinders.

3 Critical orifice plate diameter experiments

The measured explosion front velocity versus distance for stoichiometric hydrogen-air and ethylene-air for different size orifice plates is provided in Fig. 1. In all the tests a CJ detonation wave (1979 m/s for hydrogen-air, 1825 m/s for ethylene-air) entered the obstacle section that starts at 3.05 m. The velocity data point at 3.05 m in Fig. 1 represents the average velocity measured between ion probes located 305 mm before and after the first obstacle. In most cases, the front stabilizes to a sub-CJ detonation velocity within the first 0.5 m of the obstacle section. The data shows that the smaller the orifice plate diameter, the lower the steady-state wave velocity. For hydrogen a transition in the propagation regime occurs for an orifice plate diameter of 44.5 mm, see Fig. 1a. For diameters smaller than 44.5 mm a significantly lower final velocity is achieved (roughly 650 m/s). For ethylene the change in propagation regime occurs for a 63.5 mm diameter.

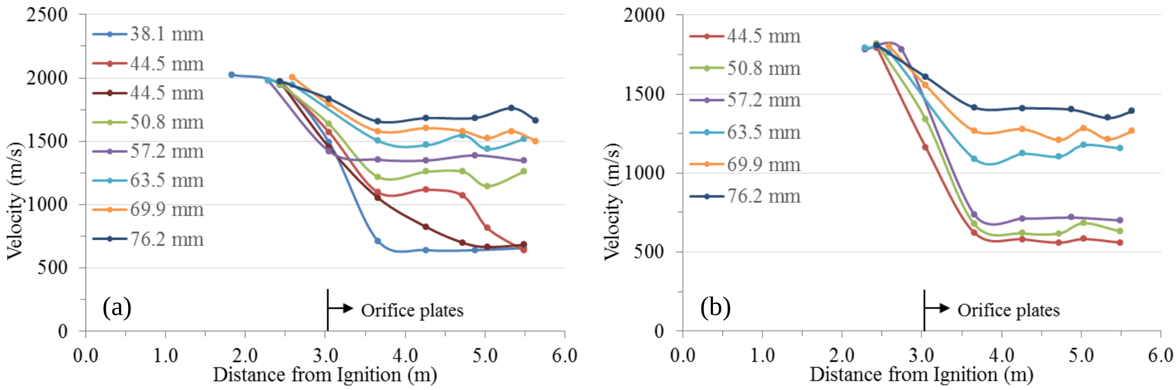

Figure 1. Explosion front velocity versus distance for stoichiometric a) hydrogen-air and b) ethylene-air

The steady-state average wave velocity (normalized with the CJ detonation velocity) measured at the end of the obstacle section for stoichiometric hydrogen (30% by volume) is plotted in Fig. 2a. The average velocity measurement was made over the last 1 m of the tube and the “error bars” correspond to the maximum and minimum velocity measured over this distance. Note the deviation in velocity is typically no greater than ±3% of the average value. Also shown in Fig. 2a is the data for 35% hydrogen that corresponds to the hydrogen-air mixture with the smallest detonation cell size. The speed of sound of the combustion products for these two mixtures is roughly half the CJ detonation velocity (i.e., 984 m/s). The step change in average velocity for the 44.5 mm and 50.8 mm orifice plate diameters for 30% hydrogen (and between 38.1 mm and 44.5 mm for 35% hydrogen) represents a change in propagation mode from fast-flame to quasi-detonation. The smaller critical orifice plate diameter, and slightly smaller detonation velocity deficit, for 35% hydrogen suggests that the change in propagation mode is influenced by the detonation cell size. There is a linear drop in the CJ detonation velocity deficit with increasing orifice plate diameter. The average velocity measured for the two mixtures in the 38.1 mm diameter orifice plate, where fast flames were observed, are identical.

The average wave velocity measured at the end of the obstacle section for the different orifice plate diameters for stoichiometric ethylene (6.5% by volume) and 7% ethylene are plotted in Fig. 2b. Again there is a linear drop in the detonation velocity deficit with increasing orifice plate diameter. The critical orifice plate diameter for both mixtures is 63.5 mm, which is larger than that observed in both the hydrogen-air mixtures, see Fig 2a. The average fast-flame velocity data (obtained for three orifice plate sizes) are identical for both mixtures (6.5% and 7% ethylene-air) and show a linear dependence with the orifice plate diameter, similar to the quasi-detonation velocity but with a different slope.

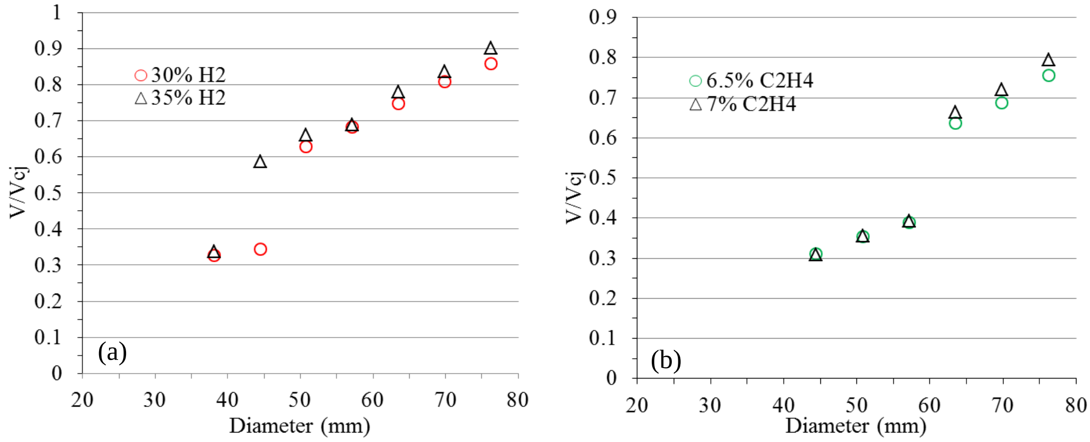

Figure 2. Normalized detonation velocity versus orifice plate diameter for hydrogen-air (a), and ethylene-air (b).

Additional experiments were performed with stoichiometric acetylene, propane and DME air mixtures, the results are summarized in Fig. 3. Tests were carried out with stoichiometric methane-air but a stable detonation before the obstacle section could not be generated. In. Fig. 3 the critical orifice plate diameter (corresponding to an abrupt change in average velocity) for each fuel is highlighted by a dotted vertical line. The smallest to largest critical orifice plate diameter corresponds to: acetylene, hydrogen, ethylene, DME, propane. This ranking is slightly different from that of Matsui and Lee [2], as they categorized hydrogen as being less sensitive to detonation than propane.

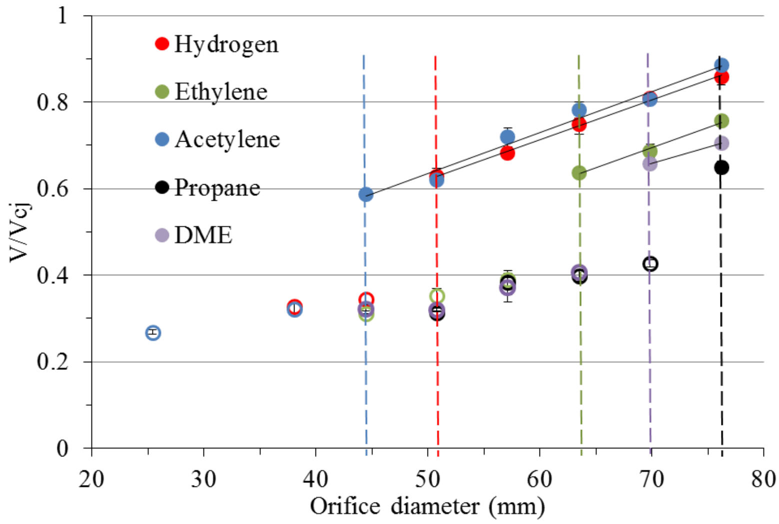

Figure 3. Front velocity as a function of orifice plate diameter for different stoichiometric fuel-air mixtures

The linear relationship between the wave front velocity (both for the fast-flame and quasi-detonation) and the orifice plate diameter appears to be universal for all the fuels tested. Figure 3 indicates that the velocity deficit itself could also be used as a detonation sensitivity parameter, e.g., the larger the deficit the less sensitive the fuel. In fact for each orifice plate the ranking of the fuels based on velocity deficit is the same as that for the critical orifice plate diameter. However, it is prudent to only use the velocity deficit to fine-tune data where two fuels have similar critical orifice plate diameters.

A similar linear relationship between CJ detonation velocity deficit and diameter is observed in smooth tubes [6]. In smooth tubes the linear drop in velocity deficit is due to the curvature of the detonation wave caused by the interaction of the detonation wave with the boundary layer. In a very-rough wall tube the boundary layer is severely disrupted by the orifice plates and thus cannot explain the linear velocity dependency with orifice diameter. Assuming detonation initiation occurs at the outer- edge of the upstream orifice plate face following shock reflection, as observed in [7], a decrease in the orifice diameter translates into a proportional increase in distance for the detonation to travel across the obstacle-face resulting in a slower axial velocity. A better understanding of the detonation propagation mechanism in a *round* tube with orifice pates is required to advance this postulation.

The critical orifice plate diameter data obtained from Fig. 3 is summarized in Table 1, along with the detonation cell size data. Note, two cell sizes were reported for DME in [11]. The critical orifice plate diameter represents the detonation *propagation* limit for a given fuel-air mixture. Unlike the classical DDT limit, it is independent of the flame acceleration process and the condition required for the onset of the detonation wave. Cross and Ciccarelli [7] recently showed that for an orifice plate diameter of 76 mm (BR=0.44) (in the same tube as the present study) that the detonation propagation composition limits for hydrogen, ethylene and acetylene air mixtures are similar to the classical DDT limits. They showed that at the limit the ratio of the orifice diameter and the mixture detonation cell size was roughly equal to unity ($d/\lambda=1$), in agreement with DDT criterion obtained by Peraldi et al. [5]. They also showed that for BR>0.44 the propagation and DDT limits did not agree and d/λ at the limits were significantly larger than unity, even taking into account the large uncertainty in the detonation cell size. The last column of Table 1 provides the value of d/λ for the detonation propagation limit measured in the present experiment and it is clear that the detonation propagation limit does not universally correlate with $d/\lambda=1$. The trend in the data indicates that as the BR decreases, the critical orifice plate diameter approaches the cell size (i.e., as BR decreases, $d/\lambda \rightarrow 1$). This is consistent with the limiting condition for a smooth tube (BR=0) where the DDT limit is characterized by $d/\lambda=1$, as was shown by Knystautas et al. [9]. Based on the correlation between d/λ and the critical orifice plate size, one can conclude that for DME the smaller cells appear to govern detonation propagation.

Table 1: Detonation propagation limits for stoichiometric fuel-air mixtures speed diagnostics

Fuel	Fuel % By volume	Critical orifice plate diameter (mm)	Blockage ratio	Cell size, λ (mm)	d/λ
Acetylene	7.8	45.5	0.83	5.7 [10]	7.9
Hydrogen	29.6	50.8	0.78	7.6 [7]	6.7
Ethylene	6.5	63.5	0.61	31.5 [7]	2.0
DME	6.54	69.9	0.53	34 [11]	2.1
				119 [11]	0.6
Propane	4.0	76.2	0.44	53 [10]	1.4

4 Quasi detonation-wave structure

In order to get a sense of the quasi-detonation wave structure, soot foils were placed at the end of the tube between adjacent orifice plates. The two types of soot foils used are shown in Fig. 4. A curved foil was placed on the tube-wall between orifice plates (#1 and #2 in Fig. 4), with a 10 mm gap left on the top of the tube for easy foil installation and retraction. A flat foil, sooted on both sides, was placed horizontally across the tube diameter (between #2 and #3 in Fig. 4). Three 6.4 mm diameter threaded rods fit through the holes in the orifice plate that maintain the angular alignment. Tube spacers (89 mm long, 12.7 mm outer-diameter), that are not shown in Fig. 4, are slid over each threaded rod between the orifice plates, to maintain axial spacing. The flat foil was held in place by tabs (at the four corners) that permitted the foil to fit into the orifice plate, as seen in Fig. 4, resting on one of the spacer tubes.

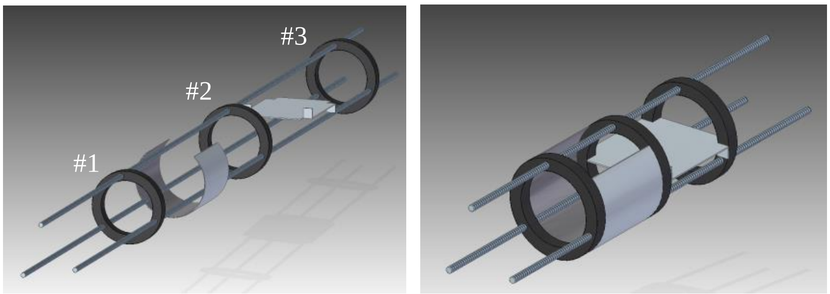

Figure 4. Soot foil installation between orifice plates.

Soot foils obtained from a test with stoichiometric hydrogen-air propagating through 69.9 mm orifice plates (BR=0.53) are provided in Fig. 5. The location of the two lower spacer tubes is shown with dotted lines in Fig. 5a. From the wall foil in Fig. 5a it is clear that the explosion front propagating between orifice plates is not uniform. A detonation wave is initiated on the top half of the tube but not the bottom half. It appears that a detonation wave survives the diffraction process around the left-side of the orifice plate. Based on the cascade of cells from a point (on the right hand side) most likely a detonation wave was initiated when the diffracted shock wave reflected off the tube wall. Based on the wall foil it appears that a detonation front forms across the entire tube entering the next orifice plate before the horizontal plate. However, a non-symmetric pattern appears on the bottom and top of the horizontal foil in Fig 5b and 5c, respectively. On the bottom side of the foil (Fig. 5b) transverse waves collide at the centerline forming a hot spot (see arrow) from which a detonation wave forms and then fails (evidenced by the increasing size of the cells). On the top side of the foil (Fig. 5c) a detonation wave sweeps around the right side of the orifice plate (arrow points to a band of small cells) but fails by the time the front reaches the next orifice plate.

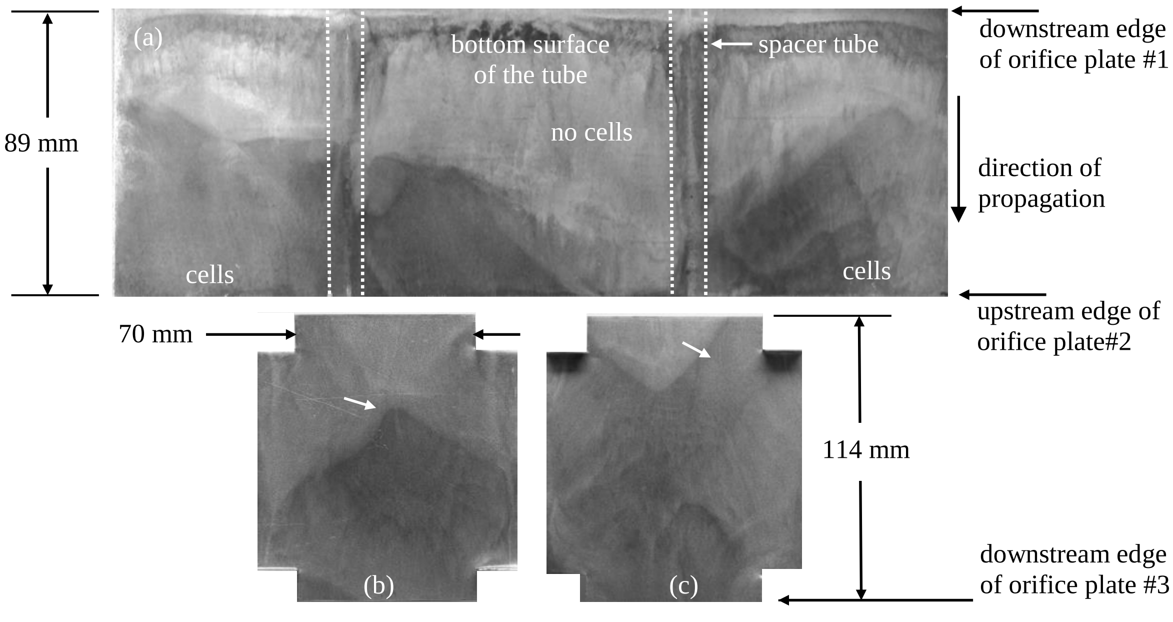

Figure 5. Soot foils for stoichiometric hydrogen-air with 70 mm orifice plates (test 296); a) wall foil b) bottom of horizontal foil, c) top of horizontal foil. Orifice plate numbers correspond to designation in Fig. 4.

Soot foils from a test with stoichiometric hydrogen-air and a 51 mm the orifice plate (BR=0.75), the minimum size for a quasi-detonation, are provided in Fig. 6. A single hot spot that develops into a detonation wave is observed on the wall foil, see arrow in Fig 6a. The top of the horizontal foil shows no detonation cells and the bottom of the foil shows a patch of fine detonation cells (see arrow) but the detonation fails before the next obstacle. It is very difficult to interpret these flat horizontal foils because the structure and orientation of the front incident on the foil leading-edge is not known. What is clear is that the front is not uniform, e.g., in no test did cells cover the leading edge of the flat foil.

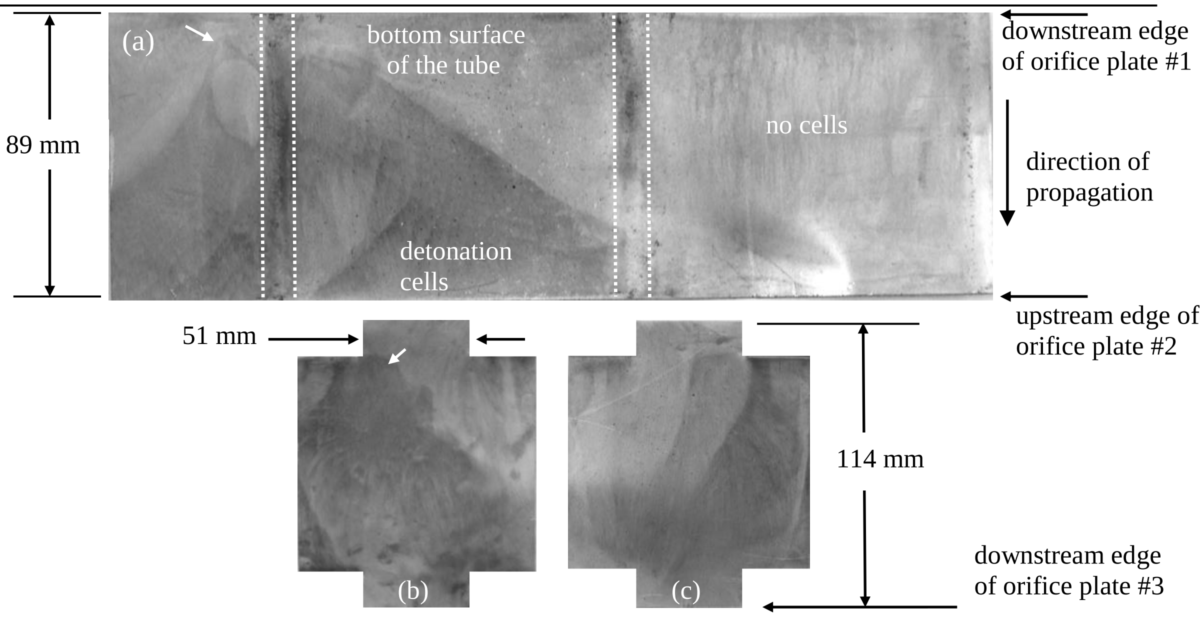

Figure 6. Soot foils for stoichiometric hydrogen-air with 51 mm orifice plates (test 309); a) wall foil b) bottom of horizontal foil, c) top of horizontal foil. Orifice plate numbers correspond to designation in Fig. 4.

5 Conclusions

The critical (minimum) orifice plate diameter required for successful transmission of a detonation from a smooth tube was measured for different stoichiometric fuel-air mixtures. The ratio of the critical orifice diameter and the detonation cell size varies strongly with the orifice plate blockage ratio, with a value approaching unity ($d/\lambda \rightarrow 1$) with decreasing blockage ratio. It is proposed that the critical orifice plate diameter (and velocity deficit) be used to categorize a fuel's detonation hazard potential. Novel use of soot foils showed that the structure of the detonation wave is very non-uniform.

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