DDT run-up distance measured by visualization of an obstructed tube

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1 Introduction

Peraldi et al. [1] performed the first comprehensive flame acceleration and DDT study in metal round tubes filled with orifice plates. The DDT limits for different fuel-air mixtures and orifice plate blockage-ratios (BRs) were deduced from the combustion front velocity obtained from front time-of-arrival measurements. They proposed the DDT criterion of $d/\lambda \geq 1$, where d is the diameter of the orifice plate and λ is the detonation cell size. They defined the DDT limit by the transition from fast-flame to detonation based on the jump in measured average velocity across the calculated isobaric products speed of sound.

It has been shown that the critical condition $d/\lambda>1$ is valid for BRs up to about 50% for fuel-air mixtures [2]. Dorofeev et al. [3] proposed that for BR>50% $d/\lambda>1$ is conservative, e.g., they reported the limit for BR=60% as $d/\lambda>3$. This indicates that the onset of detonation is governed by factors besides the blockage minimum open area. Dorofeev et al. proposed a different DDT criterion based on a length scale $L = (S + D)/2/(1 - d/D)$ that takes into account the tube diameter D and the obstacle spacing S. If the obstacle spacing is equal to the tube diameter, the criterion reduces to $L = D/(1 - d/D)>7\lambda$. In a separate study by the same group [4], they showed that for mixtures with a regular detonation cell structure (argon or helium dilution) the critical d/λ was an order of magnitude larger than unity, for all BRs.

Schlieren photography has been used to elucidate the detonation propagation mechanism in obstructed channels with flat windows [5]. Schlieren photography cannot be used with clear round tubes due to distortion of the light by the curved walls. Self-luminous, high-speed photography was used by Rainsford et al. [6] to study quasi-steady detonation propagation in an acrylic tube filled with orifice plates (same one used in this study). In the Rainsford et al. study, a self-sustained CJ detonation wave transmitted into the orifice plate filled tube, and it was shown that quasi-detonation propagation is characterized by repeated detonation failure and re-initiation. Detonation failure results from diffraction through the orifice and re-initiation occurs following shock reflection at the tube wall, or the orifice plate upstream surface. The Rainsford et al. study did not consider flame acceleration and DDT. The objective of this study is to look at the initiation mechanism for the onset of detonation, i.e., DDT, as well as to study the transient behaviour before the quasi-steady detonation wave stabilizes to the final propagation mechanism. We also investigate the effect of cell regularity on the DDT limit.

2. Experimental

The combustion chamber consists of two mated acrylic cylindrical tubes equipped with orifice plates. The tube length for the majority of the tests was 288 cm equipped with 33 orifice plates, the last 38 cm of

the tube was free of orifice plates. The tube was lengthened to 367 cm, with 42 orifice plates, to verify that the DDT limit recorded with the shorter tube was independent of the tube length. Two sets of 1.27 cm thick orifice plates with inner-diameters of 5.33 and 3.89 cm were used yielding 50% and 75% BRs. An orifice plate spacing of 7.6 cm was maintained by 7.6 cm inner-diameter acrylic spacer-sleeves. Three high-speed CMOS cameras were used in the experiments to capture the combustion front. A standard coil over plug automotive spark system ignited a flame at one end of the tube. A high-speed camera operated at 54 kfps was used to cover a major part of the length of the tube in order to get the flame velocity history and the DDT location. For most tests, a second synchronized camera operated with a smaller field-of-view (FOV) operated at 100-400 kfps was used for analyzing the quasi-detonation propagation mechanism. Soot foils were placed between orifice plates to record reinitiation events, as well as at the end of the tube to measure the detonation cell size. The initial pressure controlled the reactivity of premixed stoichiometric ethylene-oxygen diluted with nitrogen. Table 1 provides a list of the mixtures where β is the diluent-to-oxygen mole ratio. Tests with stoichiometric ethylene-oxygen diluted with argon (β=3), and hydrogen-oxygen with 70% and 80% argon dilution were performed to study the affect of cell structure regularity on DDT.

Table 1. The initial pressure at the DDT limit for each test matrix

BR	Mixture	β	Dilution	P (kPa)	λ (cm)	d/λ	L/λ	*n*
50%	C_2H_4+3O2	0	none	-	-	-		0.65
		1	43% N_2	6.7	2.6	2.0	9.6	0.59
		1.5	53% N_2	12.7	2.5	2.1	10.2	0.71
		2	60% N_2	20	2.6	2.1	9.9	1.25
		2.5	65% N_2	32.7	2.2	2.4	11.5	1.27
		3	70% N_2	60.1	2.1	2.5	11.9	3.71
		3	70% Ar	7.4	2.3	2.4	11.2	0.49
	$2H_2$ +O_2	7	70% Ar	16.3	2.2	2.4	11.6	0.65
		8	80% Ar	39.5	1.7	3.3	15.3	0.66
75%	C_2H_4+3O_2	0	none	4.4	2.5	1.5	6.2	0.70
		1	43% N_2	27.9	0.8	4.4	18.0	1.12
		3	70% Ar	25	6.1	6.2	27.1	1.22
	$2H_2$ +O_2	7	70% Ar	52.2	0.6	6.6	25.4	1.4

3. Results and Discussion

Figure 1 shows a x-t diagram obtained by plotting a series of video frames, where the time between consecutive frames is 18.5 ms. In general the detonation can be identified between orifice plates, however, for fast-flames the flame is detectable on after an interaction with the reflected shock. Detonation initiation following shock reflection generates strong local emission of light. The slope of the curve has a deviation at point A, that coincides with the appearance of bright spots associated with detonation initiation. The flame velocity before this point increases (decreasing slope), and after this point the velocity is constant corresponding to steady detonation propagation. The DDT run-up distance is defined by the axial distance from the igniter to the location where detonation initiates for the first time (point A). For initial pressures near the DDT limit, the detonation fails and reinitiates after each orifice plate following the initial DDT.

The average combustion front velocity measured in ethylene-oxygen-nitrogen (β=1) at different initial pressures for 50% and 75% BR, is shown in Fig. 2. For tests with DDT, the average velocity is calculated for the detonation wave portion only, whereas, if there is no DDT the average velocity is based on the full FOV. Using the products speed of sound to define the DDT limit, the limits are 7.3 kPa and 35 kPa for the 50% and 75% BR. For the 50% BR there is a little scatter in the data near the limit and the average detonation velocity increases with pressure approaching the CJ value; whereas, for 75% BR there is significant data scatter and the average velocity remains not much above the isobaric speed of sound.

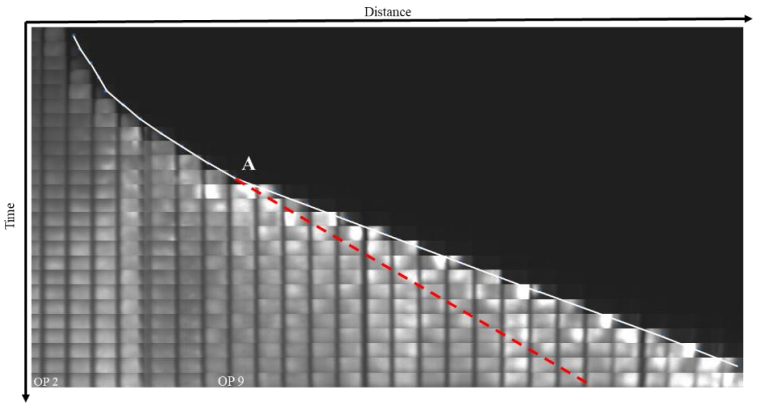

Figure 1. X-t diagram, from video frame time sequence, showing DDT at OP9 for ethylene-oxygen β=1 at initial pressure of 15.2 kPa, BR=50% (test 185)

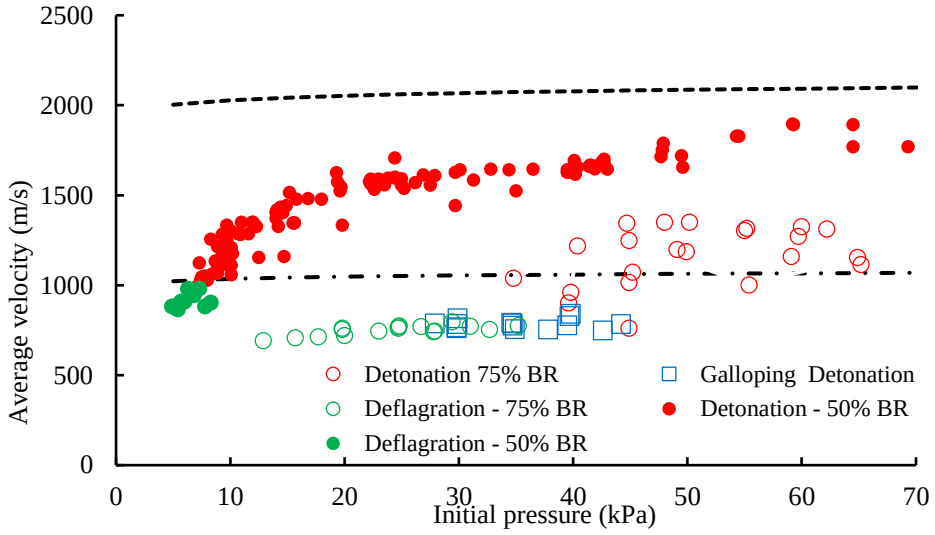

Figure 2. Average combustion front velocity versus initial pressure for ethylene-oxygen-nitrogen (β=1) for 50% BR (solid) and 75% BR (empty). The CJ velocity and product speed of sound are shown for reference.

In all the tests, video showed that DDT occurred following the interaction between the fast-flame and an orifice plate. Shock reflection off the upstream face produced multiple detonation kernels that merge to form a detonation wave, for example see Fig. 3 image 1. Following DDT for 50% BR, detonation propagation is characterized by decoupling of the detonation as it passes through an orifice, followed by detonation reinitiation at the tube wall after shock reflection. The detonation then spreads around the circumference of the tube wall and reaches the next orifice plate non-uniformly. The failure and reinitiation repeats, with initiation occurring on the opposite side of the tube wall (this was previously reported for hydrogen-oxygen [6]). This propagation mechanism results in an average velocity just above the products speed of sound. As the pressure is increased, there is a transition in propagation mechanism to a symmetric mode where wall initiation occurs at multiple points around the wall circumference. At the highest pressures, the detonation propagates continuously without failing after each orifice plate. For initial pressures near the DDT limit, detonation initiation occurs at the orifice plate face for multiple orifice plates before transitioning to the alternating wall initiation mechanism. During this orifice plate detonation-initiation phase the average velocity is close to that of a fast-flame. The longer this phase lasts the lower the average velocity, the scatter in the data near the limit is due to the variability in the length of this phase.

A "galloping mode," where the detonation temporarily decouples into a fast-flame was observed in 75% BR tests. In this mode, the front propagates at a velocity between the fast-flame velocity (when detonation initiation occurs at the orifice plate or the detonation decouples to a fast-flame) and the products speed of sound (when wall ignition occurs), see Fig. 2. Video images showing the galloping mode are provided in Fig. 3, red arrows indicate detonation initiation sites. The DDT occurs in image 1 via multiple hot spots on the OP 23 face following shock reflection. Following DDT the detonation fails and reinitiation occurs at a single hot-spot on the bottom of the tube wall in image 2. The same propagation behavior is observed between OP 24 and OP 26. The propagation mechanism then changes, where detonation is reinitiated between orifice plates 26-27 and 27-28 at multiple hot spots on the tube wall, see images 5 and 6, respectively. The detonation fails after passing through OP 28 and reinitiated via a single hot spot on the wall between OP 28 and OP 29, the next detonation initiation occurs at the OP 30 face in image 8. After OP 30, the detonation does not reinitiate, and the combustion propagates as a fast-flame through the rest of the channel. In this very unstable propagation mode, it is also possible to get detonation initiation far behind the fast-flame front, e.g., in image 10 detonation initiation occurs in an unreacted pocket before OP 31 at a time the fast-flame has already passed OP32 (this was also observed in hydrogen-oxygen [6]).

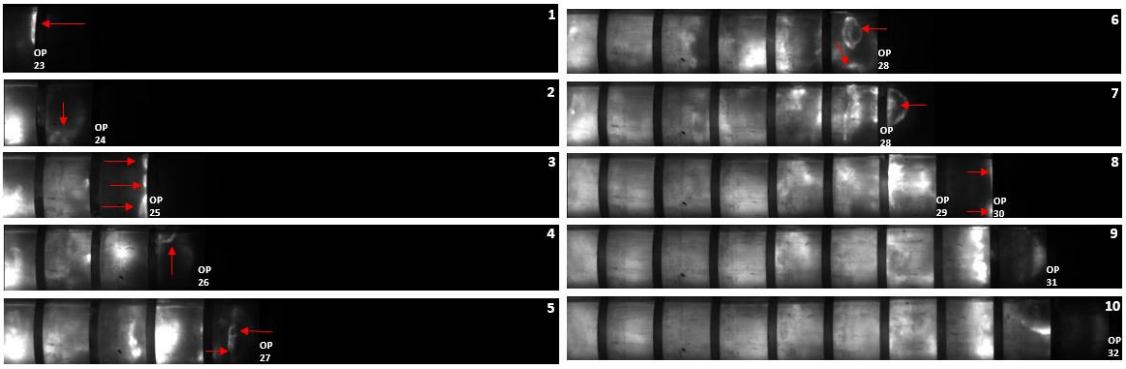

Figure 3. Images of detonation in 75% BR ethylene-oxygen-argon (β=3) at 34.6 kPa.

The video-based DDT limits are provided in Table 1. For BR=50%, the lowest initial pressure that the β=0 mixture could be ignited was 4.4 kPa, and DDT was observed. Note, the galloping mode could not be identified using the traditional DDT criterion, i.e., the minimum initial pressure that yields an average velocity above the products speed of sound. Cell size data measured at the end of the tube is reported in Table 1. For 75% BR the cell size was measured with the tube partially filled with 50% BR plates. Since the detonation failed after the last orifice plate, the cell size for the 50% BR limit pressure was estimated by extrapolating the measured cell size for a pressure just above the limit using the ZND reaction zone length. The ratio of the orifice diameter to cell size (d/λ) at the limit for all the ethylene-oxygen mixtures lies in the range 2-2.5. Considering the ±50% uncertainty on the measured cell size, this finding is consistent with the d/λ =1 and L/λ =7 limit criteria [1, 3]. This also holds for 70% argon dilution for both the ethylene and hydrogen-oxygen mixtures, despite the increase in cell regularity. This is in contrast to the findings in [4]; however, increasing the argon dilution to 80% does produce a larger d/λ of 3.3. The d/λ at the limit for the 75% BR tests are significantly larger than unity, similar to that reported in [2] and [6]. In the case of [6] flow visualization was not used so the galloping detonations could not be identified, possibly resulting in a larger limit d/λ. Again, the affect of the argon dilution is not as pronounced as reported in [4].

The measured DDT run-up distance is provided in Fig. 4. Silvistrini et al. proposed a smooth tube DDT run-up distance correlation based on the flame reaching ½V_{CJ}, and for an orifice-filled tube the correlation is multiplied by 1/(1+15BR). The correlation and the measured DDT run-up distance from the videos are compared in Fig. 5. Cosilab code and the San Diego mechanism were used to calculate the flame properties. The calculated X_{DDT} shows no effect of initial pressure, whereas the experimental data does.

The data point with the largest experimental X_{DDT} for each mixture corresponds to the DDT limit. The data points corresponding to increasing pressure approaches the "perfect correlation" line. The larger X_{DDT} measured for the less reactive mixtures indicates that there is an added distance after the flame reaches $\frac{1}{2}V_{CJ}$ that is not captured by the correlation, effectively a DDT induction distance.

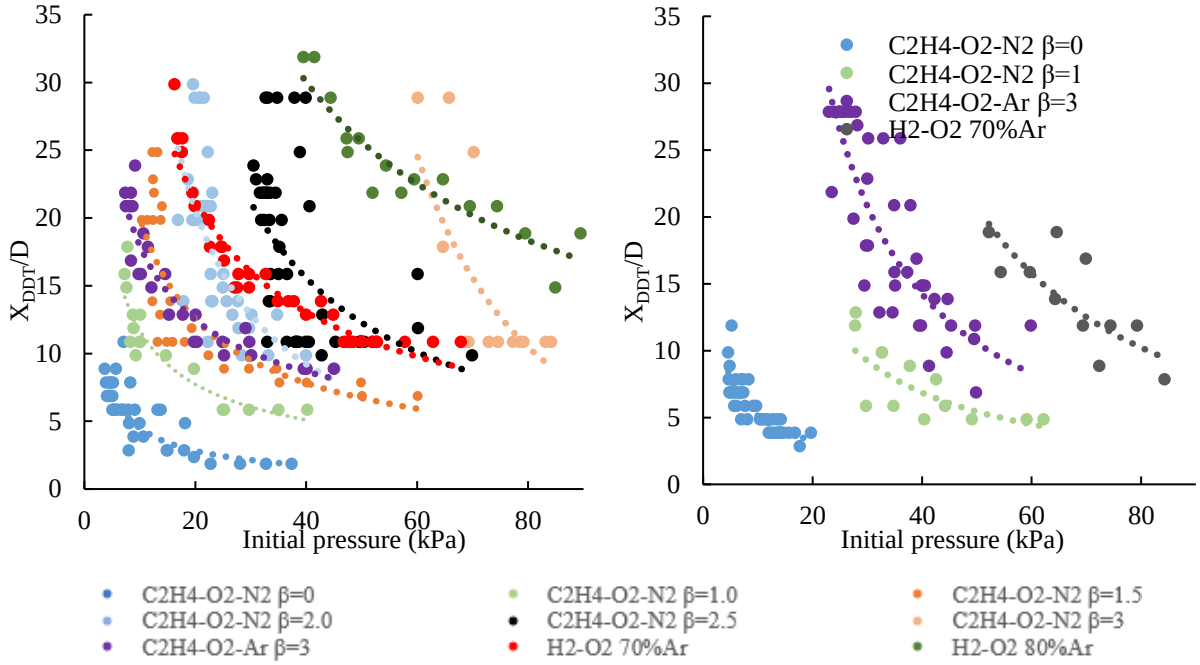

Figure 4. DDT run-up distance versus initial pressure: left) 50% BR, right) 75% BR

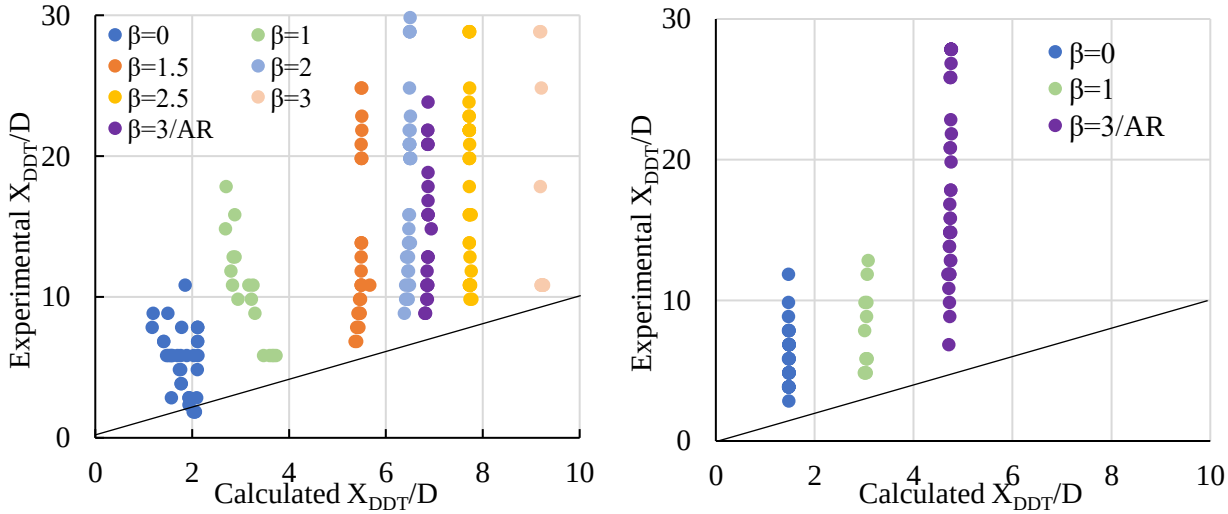

Figure 5. Comparison of the measured X_{DDT}/D to the flame acceleration based correlation in [7]

The DDT induction distance should scale with the detonation length scale. The DDT run-up distance data is plotted versus the inverse of detonation cell size, normalized with orifice diameter, in Fig. 6. There is clear dependence of X_{DDT} on $1/\lambda$ that is not included in the Silvistrini correlation. For the highest pressure, corresponding to the largest d/λ, the X_{DDT}/D is predicted by the correlation. The X_{DDT}/D increases as the d/λ decreases, terminating at the limit where $d/\lambda=2$. The data is fit with a power law $X_{DDT}/D=c(d/\lambda)^{-n}$, the value of n is provided in Table 1. For the ethylene-oxygen mixtures, the sensitivity of the run-up

distance to cell size (given by *n*) increases with nitrogen dilution. For example, for β=3 the curve is very steep compared to β=1, and the value of *n* is 3.71 versus 0.59. The argon diluted mixtures show a lower sensitivity, for β=3 with argon dilution *n*=0.49. This sensitivity to cell size is consistent with the activation energy increasing with nitrogen and decreasing with argon dilution. A compound DDT run-up distance correlation $X_{DDT}=X_{½Vcj}+10.3(2.4/(d/\lambda))^{(7.6x10^{-4}\ (Ea/RT)^{3.7}+1243)}$ is proposed to fit the data, see Fig. 7.

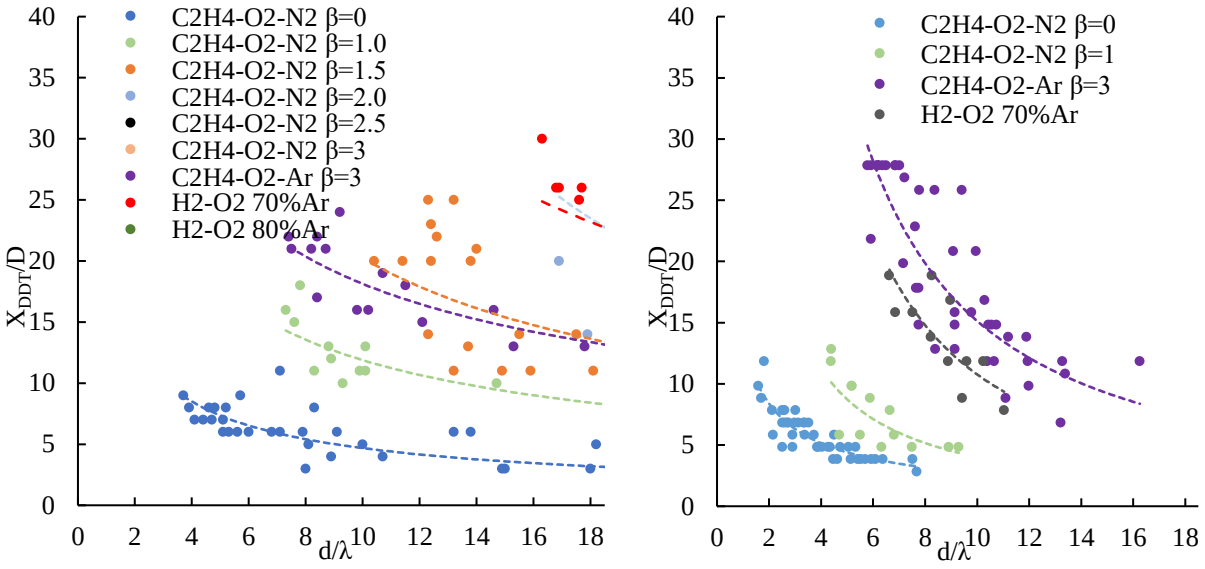

Figure 6. DDT run-up distance for 50% (a) and 75% BR (b), obtained from the video. Dotted lines are power law fits $X_{DDT}/D=c(d/\lambda)^{-n}$, where *n* is given in Table 1.

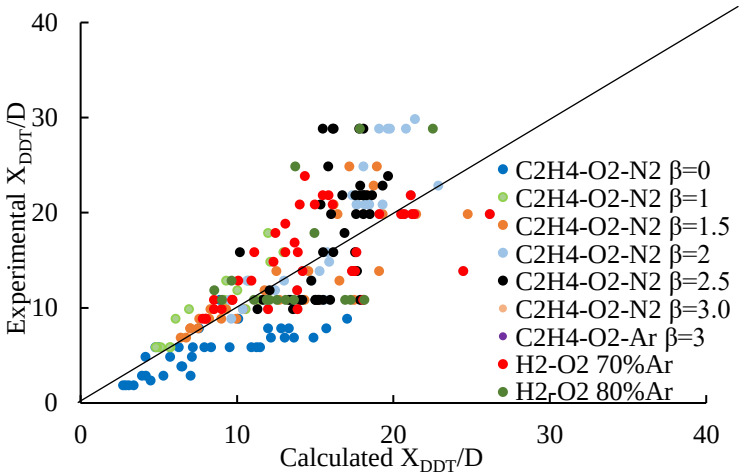

Figure 7. Comparison of the measured X_{DDT}/D to the correlation $X_{DDT}=X_{½Vcj}+10.3(2.4/(d/\lambda))^{(7.6x10^{-4}\ (Ea/RT)^{3.7}+1243)}$

Conclusions

The DDT run-up distance was measured using self luminous high-speed video. For high pressure, the Silvistrini $½V_{CJ}$ correlation predicted the measured X_{DDT}. For mixtures near the DDT limit, the flame property based correlation was not sufficient. A DDT run-up distance correlation is proposed that is the sum of the distance required for the flame to reach $½V_{CJ}$ and the DDT induction distance that scales with the cell size.

References

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