Ethylene-air detonation in water spray

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1 Introduction

In this paper, we present an experimental work on the influence of liquid water spray in an ethylene/air gaseous mixture on detonation, for equivalence ratio from 0.9 to 1.1.
Spray detonation investigations has nowadays a strong interest in propulsion by establishing mixture detonation parameters for PDEs and RDEs to design detonation chambers, and also in hazard prevention, by knowing quenching specifications for hazardous mixtures.
Early studies on spray detonations have been performed by Dabora and Raglands ([1], [2]), showing the influence of large droplet size (from 290 to $2600\mu\mathrm{m}$) desintegration, vaporization and combustion mechanisms on the detonation propagation. Mar [3] exposed that the detonability range is all the wider the droplets are small (with droplets from 9.5 to 45 $\mu\mathrm{m}$). Besides, investigations on detonation quenching with water spray injection (200-750 $\mu\mathrm{m}$ droplets, spray densities of 0.72-1.6 $\mathrm{kg/m^3}$), in a H_2/O_2 stoechiometric mixture diluted with Ar, revealed that it is more efficient with a fine spray (200 $\mu\mathrm{m}$) [4]. A 10% velocity deficit in comparison with the CJ speed has been observed for an initial pressure of 20 kPa.
Numerical works on detonation with solid particles also reveal interesting features about the two-phase influence. Williams [5], showed the stability of liquid spray based detonation. Cheatham and Kailasanath [6] developed a numerical model for liquid-fuelled detonation in tubes. They show that preheating and prevaporization of small liquid droplets generate a faster transition to a self-sustained detonation. Fedorov et al. [7] studied a 2-D detonation in a C_2H_4/air mixture with solid inert particles. Significant velocity deficit, greater than 10 %, was shown for a fairly significant solid mass fraction $Y_{\text{inert}} \approx 0.1$, and even failure for $Y_{\text{inert}} \approx 0.34$, with 10 $\mu\mathrm{m}$ particles.

But nevertheless, despite the amount of current works on spray detonations, few experiments on detonation quenching remain available.

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2 Experimental Set-Up

2.1 The Detonation Test Tube

The experimental set-up depicted in Fig. 1 is composed of a stainless steel vertical detonation tube, and consists of a square section of 53 mm per side, by 4 m long, with two pneumatic valves at each side. Oxydizer, spray and fuel are injected at the bottom and evacuated at the top. An inline mixing ensures the mixture generation. Regulation of the flow rates is achieved with two 585x series BROOKS mass flow controllers.

The detonation is initiated via a curved booster tube, placed at the bottom of the main test tube, above the lower valve. Booster and test section mixtures are separated with a Mylar film.

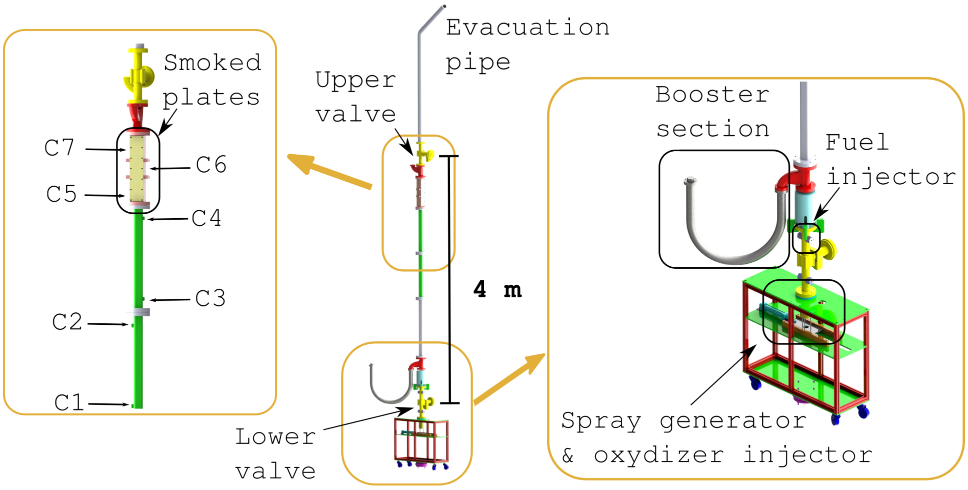

Figure 1: The 52x52 mm vertical detonation Tube set up.

The two injection systems of gaseous components and liquid water are placed in the lower part of the tube. In the upper part, seven KISTLER 603B pressure gauges are located along the tube and named ('Ci') in Fig 1, at a distance of 1.98, 2.48, 2.72, 3.12, 3.45, 3.59 and 3.66 m respectively from the lower valve. A glass soot plate of 52×408 mm, is placed at a distance of 3.40 m from the lower valve, where a self-sustained regime is supposed to be obtained.

2.2 Spray characteristics

The spray is produced with an ultrasonic spray generator: droplets are generated at an initial low velocity, by liquid film instabilities induced by metallic plate vibrations. Droplets are then carried along with air in the tube.

The spray characteristics have been measured by the Phase Doppler Interferometry technique (ARTIUM PDI-200 MD), in a 5 m height tube, with a 50 mm inner diameter, for mass flows equivalent to those in detonation experiments. Results of the experiments are summarized in Table. 1. Transient experiments reveal that the spray stays floating in the tube several seconds before falling down, after the spray generator has been switched off.

2.3 Experimental sequence

Several steps have been followed in order to perform each experiment. First the booster section is filled with a stoechiometric C_2H_4/O_2 mixture at 100 kPa. Two BROOKS mass flow controllers adjust the oxydizer and fuel flows to meet the equivalent ratio set point, and for 5 minutes, fuel, air and spray are

Air mass flow (g/s)	Liquid mass flow (g/h)	D_{10} (μm)	D_{32} (μm)	LWC (g/m^3)
0.93 ± 0.06	156 ± 25	8.5 ± 0.7	127.4 ± 2.4	35.7 ± 6.1
0.93 ± 0.06	274 ± 6	12.2 ± 1.9	119.0 ± 12.9	104.5 ± 21.2

Table 1: Spray characteristics. D_{10} and D_{32} are respectively mean diameter and Sauter diameter. Liquid Water Contents (LWC) are in good agreement with estimations made with a mas balance.

flowed in the tube. At the end of the injection, the upper and lower pneumatic valves are closed, and to initiate the detonation, an electric ignitor is triggered in order to generate a detonation wave in the booster section, which is then transmitted in the test tube. The detonation initiation is completed within 2-3 s after the end of injection.

3 Experiments

3.1 Initial conditions

In these investigations, the initial mixture is composed of C_2H_4 (N25 quality) and air coming from the compressed air network which are at room's pressure and temperature. Water is used for the liquid spray. Table 2 gathers all the mass flow parameters.

Equivalence ratio (Φ)	$\dot{m}_{C_2H_4}$ (mg/s)	$\dot{m}_{air}$ (g/s)	$\dot{m}_{H_2O}$ (g/h)	Y_{H_2O}
0.9	57	0.93	0	0
0.9	57	0.93	156 ± 25	0.039 ± 0.003
0.9	57	0.93	274 ± 6	0.07 ± 0.005
1.02	68	0.99	0	0
1.02	68	0.99	156 ± 25	0.039 ± 0.003
1.02	68	0.99	274 ± 6	0.07 ± 0.005
1.12	68	0.86	0	0
1.12	68	0.86	156 ± 25	0.039 ± 0.003
1.12	68	0.86	274 ± 6	0.07 ± 0.005

Table 2: Initial conditions in the various tests, Y_{H_2O} being the water mass fraction

3.2 Results and discussion

Detonation velocities

For each experiment, the mean detonation velocity have been obtained by averaging velocities between the pressure gauges. Velocities calculated between the two first gauges showed that the detonation has already reached a self-sustained regime. Furthermore, for each set of parameters, two experiments have been performed, and show reproductible results. Experimental velocities are plotted against the equivalence ratio in Fig. 2, with also computed velocities for similar mixtures, performed on TDS [8]. Calculations of CJ state were made by considering water droplets completely evaporated before CJ plane.

As expected, Fig. 2 shows a global decrease of the detonation velocities as water is added and equivalence ratio is decreased. Experimental velocity deficit with CJ speed at $Y_{H_2O} = 0.039$ is about 1.6 -2.6 % (considering a CJ state without water in initial conditions). At $Y_{H_2O} = 0.07$, the deficit observed is about 3.3 to 5.1 %. Moreover at $\phi = 1.02$, with $Y_{H_2O} = 0.07$, only one detonation has been observed on the two experiments performed.

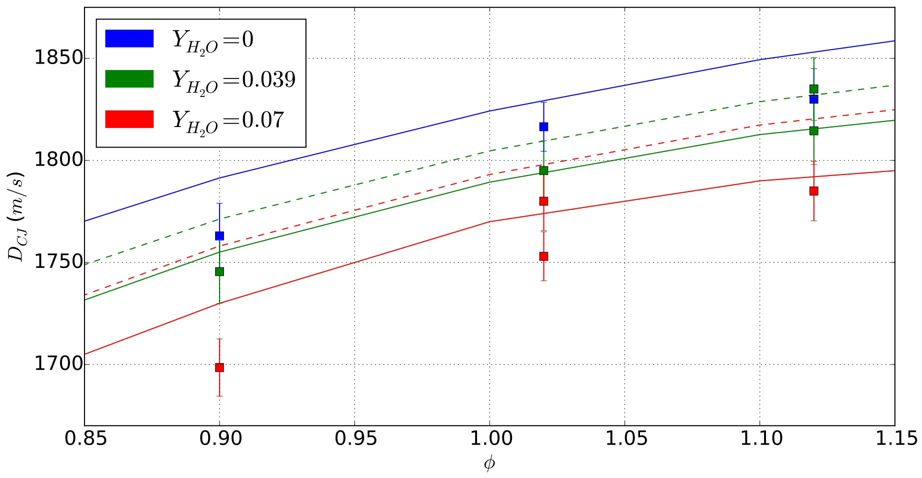

Figure 2: Detonation velocities (symbols with errobars) as a function of the equivalence ratio. Lines refer to theoretical CJ values, with solid lines containing liquid water in initial phase and dashed lines gaseous water in initial mixture.

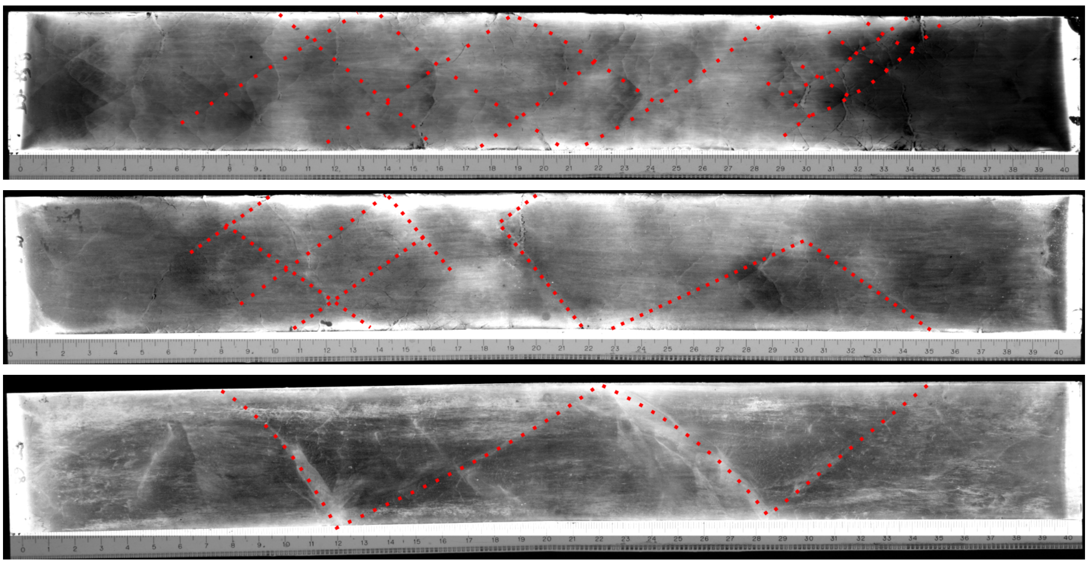

Figure 3: Detonation cellular structure on smoked foils, for $\phi = 0.9$. From top to bottom: $Y_{\mathrm{H_2O}} = 0$, $Y_{\mathrm{H_2O}} = 0.039$ and $Y_{\mathrm{H_2O}} = 0.07$

Detonation cellular structure

Cellular structures recorded on the smoked plates placed in the higher part of the tube are shown in Fig. 3. Cell sizes determination were made by averaging the measured individual cell width (λ) found on the smoked plates, thus error bars take into account the user accuracy in determining the cell shape. Wide range of cell sizes could be observed on plates, due to intrinsic irregular cellular detonation structure of the C_2H_4/air mixture. As expected, for a given equivalent ratio, adding water droplets enlarge cell width.f

Cell size measurements are plotted against equivalent ratio in Fig. 4. A good agreement between our cell sizes and available data for $Y_{\mathrm{H_2O}} = 0$ ([9],[10],[11]) is found, even if cell size measurements in

[10]-[9] were estimated from critical tube diameter transmission. When adding water to reach $Y_{\mathrm{H_2O}} = 0.07$, transitions from multi-cell ($\lambda \approx$ 20-25 mm at $\phi = 1.02$ and $\phi = 1.12$) to one-cell detonation regime are observed ($\lambda \approx$ 35-55 mm), as well as from one-cell ($\lambda \approx$ 35-40 mm) to half-cell regime ($\lambda \approx 106$ mm) at $\phi = 0.9$.

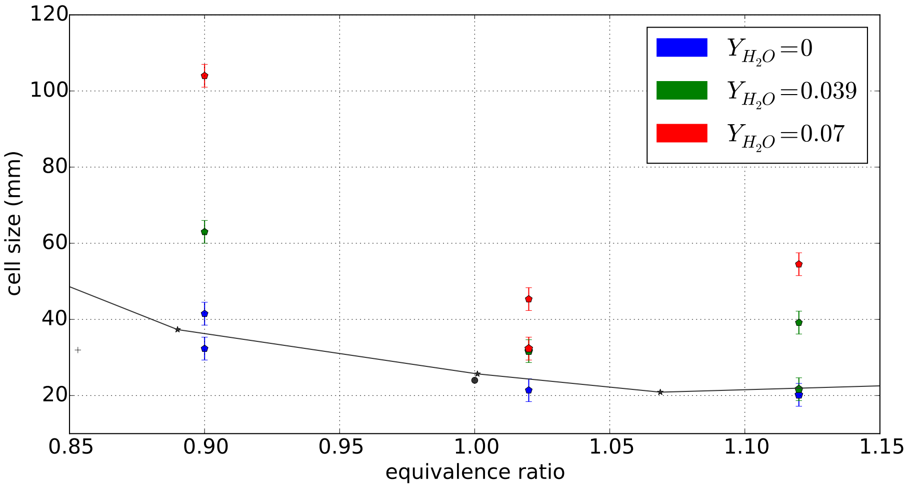

Figure 4: Detonation cell width (λ) on smoked foils against equivalence ratio (ϕ). Data from litterature are displayed on solid line.

Pressure signals

Experimental estimations of the CJ pressure have been performed following Desbordes et al. The results show a ratio of $P_{\text{CJ,theo}}/P_{\text{CJ,exp}} \in [0.69, 0.73]$, which is slightly lower than the value of 0.77 suggested in [12] for a cylindrical tube.

Furthermore, the hydrodynamic thickness (L) has been estimated following [13], with analyses of the fluctuations decay, downstream the incident shock. In the pure gaseous case (no water added), an approximate average thickness of 25-40 cm has been found, which matches the litterature ([14], [15] and [13]). In the multi-cell regime ($\phi = 1.02 - 1.12$), $L/\lambda \approx 18$ whereas in the one-cell regime ($\phi = 0.9$), the ratio decreases $L/\lambda \approx 6$. Results are in relative agreement with those found by Edwards et al. [15] ($L/\lambda \approx 4$) and by Lee and Radulescu, who observed a ratio $L/\lambda \approx 6$ for an unstable detonation. Indeed, in our case, the initial pressure is higher, and Vasiliev et al. quoted a growth of this ratio as it is increased. Moreover, water addition ($Y_{H_2O} = 0.07$) tends to decrease the average L/λ ratio to 4 at $\Phi = 0.9$, and to 8 and 6.5, for $\Phi = 1.02$ and 1.12 respectively. With the addition of liquid water for the lean case $\phi = 0.9$, a net increase of L from 25 cm to 42 cm is observed, which is not clearly visible for richer mixtures.

4 Conclusion

New spray detonation experiments were conducted in a 52 mm square tube. Detonations of C_2H_4/air mixtures have been investigated for $0.9 < \phi < 1.1$ and $Y_{\mathrm{H_2O}} < 0.07$, with liquid water droplets of 10 µm mean diameter. Pressure signals, detonation velocity and detonation cellular structure were recorded. They show that the velocity deficit is very small, compared to the CJ speed. Nonetheless, noticeable cell size increase is observed, when liquid water is added. Initially, these detonations seem to behave more like gaseous detonations with water diluent. However, it is not known yet if all the liquid water is vaporized at the end of the reaction zone. Investigations also highlight the sensitivity of cell size parameter, for, as velocity decreases by 3.3-5.1 % in comparison with CJ speed, detonation regime can change from multi-cellular to half-cell behavior. This change in the regime of the detonation propagation is significant, as it exposes a slowdown in the global kinetics of the oxidation process. This is also corroborated by the growth of the hydrodynamic thickness as the liquid content is increased. Authors will try to estimate how much liquid water is vaporized in the reaction zone and determine what is the influence of water addition on chemical kinetics.

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