Influence of water sprays on a multi-cellular regular detonation

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1 Introduction

Detonation propagation in heterogeneous media is an age-old field, interesting researchers for both propulsion improvements and hazards prevention ([1], [2]). In this wide context, a more specific topic has been investigated by Thomas *et al.* ([3], [4]) where they highlighted conditions to mitigate detonations and deflagrations propagating in hydrocarbon-air atmospheres with submillimeter size water droplets (greater than $100\ \mu\mathrm{m}$). Their results revealed the strong influence of small droplets (lower than $30\ \mu\mathrm{m}$) in quenching those phenomena, and also defined a detonation quenching criterion. This criterion was based on a propagation velocity deficit of the mitigated detonation greater than 10 % compared to the theoretical detonation velocity in an equivalent dry atmosphere.
Furthermore, recent numerical ([5]) and experimental works ([6], [7]) confirmed the role of fine sprays in dampening a detonation. Jarsalé *et al.* [7] showed the strong influence of a $10\ \mu\mathrm{m}$ droplet water spray in enlarging cellular structures and thus slowing down the kinetic processes, without significantly impacting the detonation velocity propagation and the pressure profiles observed downstream of the detonation front.

Considering this latter work, this paper presents preliminary results dealing with a detonation propagation in ΦC_2H_4+$3O_2$+ZAr, for an equivalence ratio Φ ranging from 0.8 to 1.1, an argon dilution Z = 28 refering to a 90 % dilution in mass, and a fine water spray reaching an apparent density of approximately $130\ \mathrm{g/m^3}$. Pressure results, detonation velocities, cellular structures have been recorded and are analyzed, along with a spray characterization. As the study exposed in [7] describes the experimental apparatus involved in these experiments, and gathers results of ethylene-air detonation diluted with the same water spray (approximately same mass fraction, arithmetic and Sauter mean diameters), only a brief description of the set-up is recalled. Detonation features and behaviour in argon diluted mixture is compared with the mentioned work, and preliminary conclusions are drawn afterwards.

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2 Experimental considerations

2.1 The set-up and the flow rates

The experimental set-up consists of a $4\ \mathrm{m}$ height vertical stainless steel tube with a square section of $52 \times 52\ \mathrm{mm}^2$, where seven KISTLER 603B pressure transducers are placed at various positions, between 1.9 and $3.7\ \mathrm{m}$ from the bottom. A smoked plate is placed at a $3.40\ \mathrm{m}$ height on the inner surface of the tube to record the detonation cellular patterns. The injection process of both fuel and spray is performed by the bottom, ensuring an inline mixing. The ignition is performed with the help of a booster section, filled with a $C_2H_4 + 3O_2$ gaseous sensitive mixture generating a strong shock, transmitted to the experimented mixture. Since the last study [7], a new atomizer has been designed, and is composed of 4 atomizing units TDK NB-59S-09S, generating droplets by production of liquid film instabilities (at $1.7\ \mathrm{MHz}$). These units are fed with a constant power supply of $45\ \mathrm{V}$ and $0.6\ \mathrm{A}$ each. Different spray densities can then be produced.
The various flow rates involved are gathered in Table 1, along with their equivalence ratios. Two wet configurations were adopted during the test, with 1 and 2 atomization units running. Dry tests ($Y_{H_2O} = 0.0$) were also performed with another injector to obtain reference results. The flows involved allowed us to reach an argon dilution of $90.1 \pm 0.34\ \%$ in mass, and water mass flows of $199\ \pm 7\ \mathrm{g/h}$ ($Y_{H_2O} = 0.064\ \pm 0.001$) with 1 atomization unit running, and $294\ \pm 8\ \mathrm{g/h}$ ($Y_{H_2O} = 0.092\ \pm 0.001$) with 2 atomization units. Spray apparent density reaches $90\ \pm 4\ \mathrm{g/m^3}$ and $134\ \pm 5\ \mathrm{g/m^3}$ for 1 and 2 atomization units running respectively. Each test is repeated twice for reproducibility reasons.

Table 1: Mass flow rates in the tests. Φ refers to the equivalence ratio reached with each set of parameters.

Φ	$0.8\ \pm 0.04$	$0.9\ \pm 0.04$	$1\ \pm 0.04$	$1.1\ \pm 0.04$
$\dot{m}_{C_2H_4}$ (g/h)	$52\ \pm 4$	$59\ \pm 4$	$64\ \pm 4$	$72\ \pm 4$
$\dot{m}_{Ar}$ (g/h)		$2603\ \pm 26$		
$\dot{m}_{O_2}$ (g/h)		$223\ \pm 6$		

2.2 The spray characterization

A spray investigation was performed to obtain its properties before and after the injection in the test tube, and to verify its homogeneity. This investigation was achieved with an ARTIUM PDI-200 MD device using the Phase Doppler Interferometry method, on a related experiment reproducing two positions: the experimental tube botton ($\approx\ 20\ \mathrm{cm}$ above the atomizer) and the tube top ($5\ \mathrm{m}$ above the atomizer). Fig. 1 gathers the spray droplet and volume fraction distributions.

The left graph of Fig. 1 shows a similar droplet distribution between the tube bottom and the tube top. Both distributions provide the same arithmetic diameter $D_{10} \approx 10\ \mu\mathrm{m}$, and are well predicted by a log-normal fit in the range of 1 to $80\ \mu\mathrm{m}$. The Sauter mean diameters D_{32} are close to 98 and and $83\ \mu\mathrm{m}$ respectively. However as expected with this type of atomizer, larger droplets ($\geq\ 90\ \mu\mathrm{m}$) are generated and contain most of the liquid mass of the spray. Indeed as it is visible in the right graph of Fig. 1, more than 90 % of the liquid is carried by these large droplets. A slight discrepancy can also be found between the volume fraction distributions on Fig. 1. Hence one's should pay attention to these droplets as they are a potential reservoir of future fine droplets ($\leq\ 10\ \mu\mathrm{m}$) created by the shock induced secondary atomization.

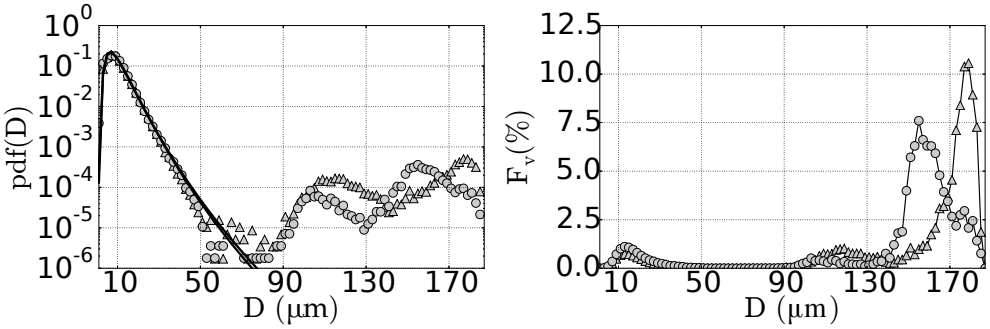


Figure 1: On the left, the experimental droplet size distribution obtained along with log-normal fits in solid lines, and on the right the droplet volume fractions. In the two graphs, $\triangle$ refers to the experimental tube bottom position ($20\ \mathrm{cm}$) and $\circ$ to the tube top ($5\ \mathrm{m}$). The spray characteristics are independant of the 1 or 2 atomization units configuration involved.

3 Results and discussion

3.1 Velocity analysis

The detonation velocity has been estimated from the pressure transducers located between 2.7 and $3.7\ \mathrm{m}$. A graph gathering the average velocities estimated for each equivalence ratio and each water mass fraction involved is represented in Fig. 2, with the maximum estimated uncertainties. We can see that the average velocities are in good agreement with the equivalent theoretical values. Differences between the experimental detonation velocity $\mathrm{D_{exp}}$ and the computed CJ detonation velocities $\mathrm{D_{CJ}}$ are lower than 3 % for the reference dry case. The addition of 6.4 % of water in mass increases this deficit up to 6 %. The addition of water also decreases the average detonation velocity $\mathrm{D_{exp\ -\ wet}}$ by 11 to 16 % in comparison with $\mathrm{D_{CJ\ -\ dry}}$ in a dry mixture, meaning a 170 to $240\ \mathrm{m/s}$ velocity drop.

The latter observations are in relative agreement with tests performed in ethylene-air-water spray mixtures [7], as a lower velocity drop of $90\ \mathrm{m/s}$ was observed with the addition of an analogous amount of water (in [7], $\mathrm{Y_{H_2O}} \approx 0.07$ and the spray apparent density is about $110\ \mathrm{g/m^3}$). Moreover, the deficits between theoretical and experimental data are slightly greater for each mixture considered. We can also observe that a sustained detonation can exist in $\mathrm{C_2H_4/O_2/Ar}$ despite a velocity difference slightly greater than 10 % between $\mathrm{D_{CJ\ -\ dry}}$ and $\mathrm{D_{exp\ -\ wet}}$, surpassing the criterion defined by Thomas *et al.* [3].

The latter observation suggests that the detonation quenching is nearly reached. This quenching has been experienced with a denser spray (9.2 % in mass), as velocities recorded are well under the theoretical detonation velocity. This observation is also confirmed with the study of the smoked plates and the pressure signals.

3.2 Detonation cellular structure

The average cell sizes were determined by measuring both group of individual cells and band spacings between triple points trajectories on the smoked plates. The corresponding graph is represented in Fig. 3a, where the typical tube dimensions are also represented. A good reproducibility is found between tests for the same experimental conditions.

Dry mixtures exhibit the smallest detonation size, with more than 5 cells in the channel. The typical U-shape of the average cell size measured is also visible, as observed with ethylene-air mixtures. Besides,

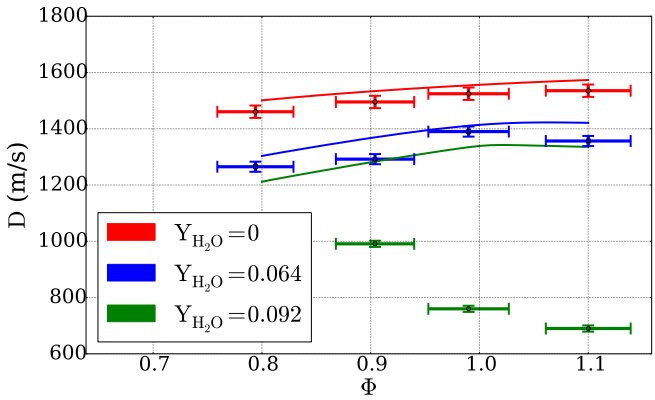
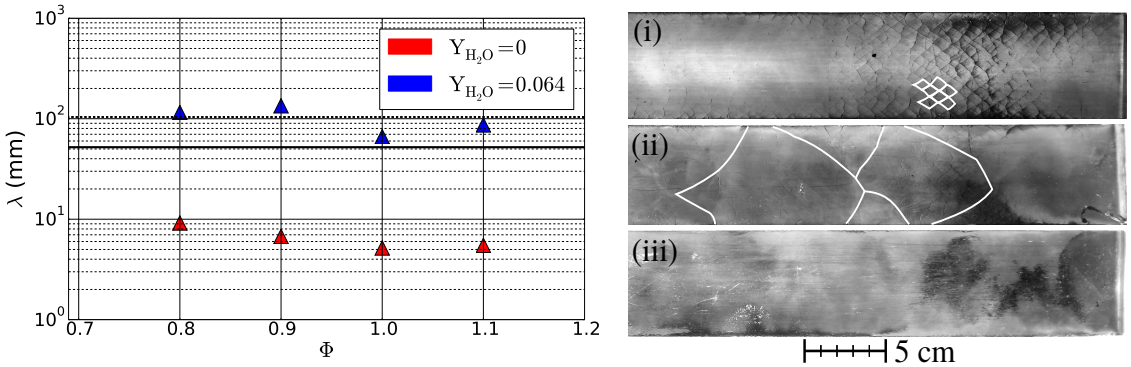


Figure 2: The average detonation velocities (D) obtained for the various equivalence ratios Φ and water mass fractions, represented with symbols and their maximum experimental uncertainties. Solid lines represent the computed detonation velocity performed with TDS [8], considering a mixture of C_2H_4/O_2/Ar with liquid water.

the addition of water generates a cell enlargement, by a factor of 12 to 20 compared to the dry mixtures, producing a transition from a regular multi-cellular detonation to an irregular cellular of half-cell detonation regime, as displayed on Fig. 3b. Dry mixtures reveal quite regular cells patterns (see smoked plate (i)), whereas water addition triggers a loss of cell regularity (smoked plate (ii)) and eventually leads to the detonation failure (smoked plate (iii)). This detonation failure has also been observed with an equivalence ratio Φ of 0.9 and 1.1 in the case of a 9.4 % addition in mass of water.



(a) (b)

Figure 3: On the left : Average cell size λ estimated for the various equivalence ratio Φ and water mass fraction tested. The plain line refers to the tube size (52 mm) and the dashed line to twice this size. On the right : Cellular structures printed on smoked plates in the case of ΦC_2H_4+3O_2+ZAr mixture at Z=28 and $\Phi = 1$ for a dry test (i), a test with $Y_{H_2O} = 0.064$ (ii) and with $Y_{H_2O} = 0.092$ (iii). Cells are highlighted in white lines.

Induction lengths, which refer to the distance between the shock front and the thermicity peak, were also calculated with the ZND-Toolbox [9] using the Cantera library [10], for detonations propagating in dry C_2H_4/O_2/Ar mixtures at a velocity calculated with TDS [8]. Preliminary calculations reveals that the increase of the induction length does not exceed a factor of 5, between a detonation propagating at the ideal dry

gaseous detonation speed D_{CJ}, and a detonation propagating at a lower velocity D for the same dry mixture (D in the range of $1300 - 1420$ m/s, which refers to the TDS velocities calculated in $C_2H_4/O_2/Ar$+liquid water mixtures).

The experiments performed with ethylene-air and water spray mixtures [7] revealed that the cell growth is only of a factor of 2 to 3 with a similar water mass fraction addition, and is also of the same order of magnitude for the induction length growth when a velocity deficit is considered in the calculations. Thus the influence of the liquid water spray seems to be more important on a regular multi-cellular detonation than on a 2 or 3-cells irregular detonation (ethylene-air), as it almost extincts it. In the conditions of near extinction, the induction length growth also may not match anymore the equivalent cell size growth.

3.3 Pressure analysis

The seven pressure transducers located all along the tube allowed us to record the detonation pressure signals. A superimposition of three typical unfiltered pressure signals is presented in Fig. 4, for a detonation in a near stoechiometric mixture ($\Phi = 1$), taken at the C6 position (≈ 3.5m from the tube bottom). It highlights the visible effect of water addition on the detonation pressure signals, as for $Y_{H_2O} = 0.064$ larger fluctuations are generated in comparison with the dry case. Moreover the addition of this amount of water also noticeably lowers the average pressure level downstream of the front shock. A delay in the reflected shock arrival is also visible when we compare the two pressure signals of $Y_{H_2O} = 0.0$ and $Y_{H_2O} = 0.064$. As previously noticed, the detonation quenching is observed on the pressure signals for the addition of $Y_{H_2O} = 0.092$, with the propagation of a weaker shock followed by a possible combustion indicated by the pressure plateau.

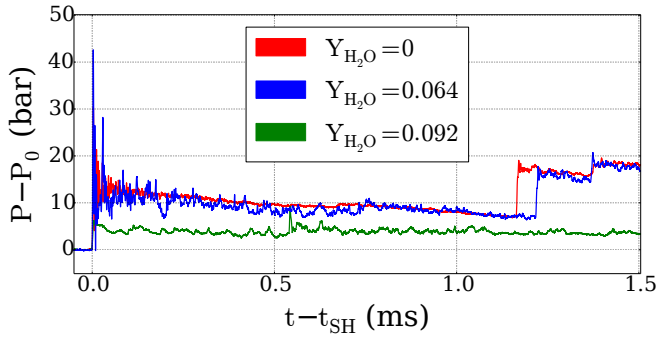


Figure 4: Pressure signals recorded at the C6 position on the tube for 3 different water mass fractions, at an equivalence ratio $\Phi = 1$. The time $t - t_{SH}$ represents the time elapsed after the detonation front shock arrival on the transducer.

The experimental pressure values estimated range between 0.71 and 0.78 P_{CJ} for mixtures with $Y_{H_2O} = 0.0$, by using the same method exposed in [7]. These values relatively agree with the 0.75-0.78 factor found in the literature for ethylene-air-water spray mixtures ([7]).

We have also estimated the hydrodynamic thickness and the values range from 8 to 15 λ in the case of the addition of ΦC_2H_4+$3O_2$+ZAr+water spray ($Y_{H_2O} = 0.064$), for all the equivalence ratios. Those values are higher than the ones found in the literature for regular mixtures (1-4 λ in [11]) and irregular mixtures (5-7 λ in [7], 6 λ in [12]). The values in [12] and [7] were obtained for a smaller 2-cell and 2.5 to 1 cell structures respectively. In our case, the estimation is obtained with a half-cell detonation structure in a square channel.

3 Conclusions

The detonation experiments conducted at an initial atmospheric pressure in ΦC_2H_4+$3O_2$+$28Ar$ mixtures (Φ ranging from 0.8 to 1.1), laden with water sprays (approximately $90\ \mathrm{g/m^3}$ and $130\ \mathrm{g/m^3}$), highlight interesting features. Indeed a significant velocity decrease reaching 170-240 $\mathrm{m/s}$ is observed with the addition of 6.4 % in mass of water, and is associated to a very strong enlargement of the cell structure (ten to twenty times), linked to a worsening of the cellular structure regularity. The addition of this amount of water has also a noticeable influence on the pressure decrease downtsream of the leading front shock, and increase the global pressure fluctuations. The detonation extinction limits lie between 6.4 and $9.2\ \%$ in mass of water.

We need to mention that the mixtures we used in our experiments and analysis have very different reaction heat releases (approximately 880 $\mathrm{kJ/kg}$ for C_2H_4/O_2/Ar diluted at 90 % and 2400 $\mathrm{kJ/kg}$ for C_2H_4/air). However, some observations can be done. Indeed for dry cases, the detonation cellular structure is found to be more regular with argon dilution in comparison with nitrogen dilution, as expected. The spray injection generates a decrease of the detonation velocity of more than 10 % for C_2H_4/O_2/Ar mixtures. As a comparison, the experiments with more irregular detonation in dry air seem to show a smaller decrease in the detonation velocities.

Further experiments will be carried out to check the first observations made in this paper, and to see whether the conclusions can be extended to C_2H_4/O_2/Ar mixtures with higher reaction heat releases (i.e. smaller dilutions).

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