Detonation characteristics in tube filled with the binary fuels H_2/C_3H_8-Air mixtures

Guanbing CHENG, Ratiba ZITOUN, Pascal BAUER
Institut P' UPR 3346, Département Fluides, Thermique, Combustion, CNRS
1 Av. Clément Ader, BP 40109, 86961 FUTUROSCOPE CEDEX, FRANCE

1 Introduction

Due to no hydrocarbon and carbon dioxide in its combustion products, hydrogen can be widely used as an alternative energy carrier. However, its lower ignition energy, wider flammability and higher propensity for leakage make the potential explosion hazard possible during the industrial conservation or transportation of hydrogen. In general, a small fraction of inhibitor (e.g. propane or methane) being added into hydrogen, as one of solutions to handle the security of H_2/Air mixtures, can effectively attenuate the mixture detonabilities. It is therefore of importance to evaluate the detonation properties of the binary fuels H_2/C_3H_8-Air mixtures in order to assess the potential risk of dangerous industrial scenarios related to H_2-Air security.

To our knowledge, few attentions had been paid to detonation phenomena in such binary fuels with air mixtures. Takita et al.[1] investigated the detonation behaviors of stoichiometric blend fuels H_2/CH_4-Air, H_2/C_3H_8-Air and CH_4/C_4H_{10}-O_2 mixtures. They observed that the measured detonation velocities D agreed well with the CJ values. The detonability of H_2/C_3H_8-Air mixtures was similar to that of H_2/CH_4-Air mixtures, it decreases by adding CH_4 or C_3H_8 to H_2/Air mixtures. Afterwards, Yoshida et al. [2] measured the detonation cell size λ and velocity D of the stoichiometric binary fuels H_2/CH_4-Air, H_2/C_3H_8-Air and CH_4/C_3H_8-O_2 mixtures at ambient conditions. They also verified that the measured detonation velocities agreed well with the CJ ones. For H_2/C_3H_8-Air mixtures, they obtained the cell sizes λ varying from 25 to 75 mm when molar fraction y of C_3H_8 in the binary fuels H_2/C_3H_8 ranged from 0 to 1. λ increased with the molar fraction of C_3H_8 in case $y<0.3$, and seemed to be constant for $0.3<y<0.8$. Matignon et al. [3] investigated the detonation characteristics of binary fuels H_2/CH_4-O_2 and CH_4/C_2H_6-O_2 mixtures diluted by nitrogen. They observed that the detonation properties of such mixtures were generally governed by those of the heavier fuels, namely CH_4 and C_2H_6, respectively. Medvedev et al. [4] conducted experiments on detonation initiation conditions in the binary fuels H_2/CH_4-Air and H_2/C_3H_8-Air mixtures in the tube with 141-mm inner diameter (i.d) at ambient conditions. They also studied **Transition Deflagration Detonation** (***DDT***) for the same mixtures in a 54-mm inner diameter tube [5]. They pointed out that the limit of ***DDT*** relied on the components of the mixed fuels and the tube inner diameter. The works were carried out by Bozier et al. [6] and Sorin et al. [7] on detonation properties of binary fuels H_2/CH_4-Air mixtures in two tubes with different inner diameters. They obtained a plenty of data on the cell sizes λ and the run-up distance to ***DDT*** L_{DDT}. Their results confirmed the correlation obtained by Sorin et al. [8] between L_{DDT} and λ, $L_{DDT} \approx 40–50\lambda$. The addition of CH_4 in the H_2/CH_4 binary fuels reduced the detonability of H_2/Air and increased L_{DDT} accordingly.

The present paper summarizes an experimental work on detonation characteristics of the binary fuels H_2/C_3H_8 - Air mixtures in the tube at ambient conditions. The detonation velocity D, pressure P and cell size λ are measured and presented as a function of the equivalence ratio Φ in the range of 0.7-1.8 and of the H_2 molar fraction x in the range of 0.5-1.0. The mixture composition and the H_2 molar fraction x are given by:

$$\Phi\,[x\,H_2 + (1-x)\,C_3H_8] + (5–4.5x)\,(O_2 + 3.76\,N_2); \qquad x = H_2/(H_2 + C_3H_8)$$

Correspondence to: guanbing.cheng@ensma.fr

The measured detonation velocity D and pressure P are compared with the theoretical ones calculated by software Gaseq. Evolution of measured cell size λ with l_i is determined, where l_i is the Zel'dovich-Neumann-Doering (*ZND*) chemical reaction-zone length computed by software Chemkin with the detailed chemical kinetic scheme Gri-mech 3.0.

2 Experimental facilities

The schematic of experimental facilities is shown in Fig. 1. The experiments are performed in a stainless-steel tube with 52-mm inner diameter (i.d) and 8.7-m length at ambient conditions. The tube formed by two sections is long enough to obtain a steady-state detonation wave at the end of the tube. Eleven piezoelectric pressure transducers (KISTLER 603B, 1 μs rise time) are used: nine of them located along the first section (2-m length) and two others placed at the end of the second section (6.7-m length) to verify whether the detonation is steady or not. A stainless-steel smoked foil with 50-cm or 100-cm length is placed opposite to the last two pressure transducers in the second section to measure the detonation cell size. The ignition is obtained by an automotive spark plug with about 15-mJ discharge energy. A Schelkin spiral with a blockage ratio B.R=0.5, a pitch equal to the tube i.d and a length of 2.1 m is placed close to the ignition point.

For Φ=1.1 and x varying from 0.5 to 1.0, several experiments are conducted in a stainless-steel tube with 92-mm i.d and 12-m length to check the values of detonation cell size obtained in 52-mm i.d tube, in particular the cell size of the order of 50 mm.

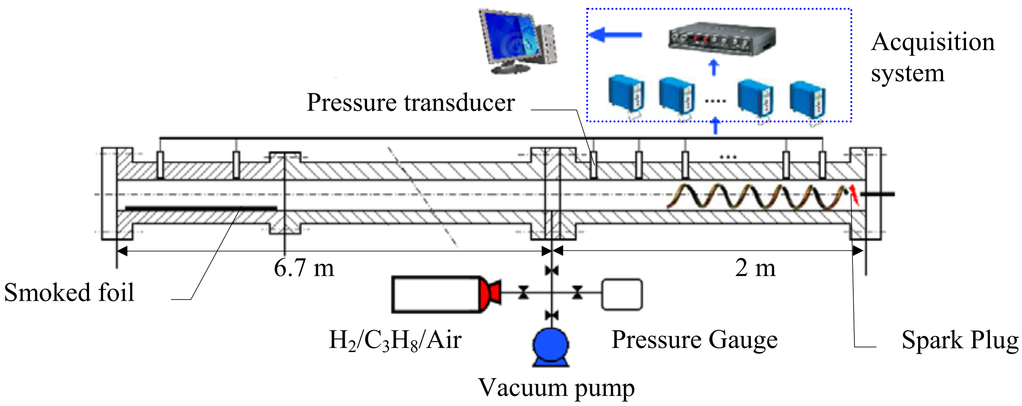


Figure 1.Scheme of experimental facilities

3 Results and discussion

3.1 Detonation velocity and pressure

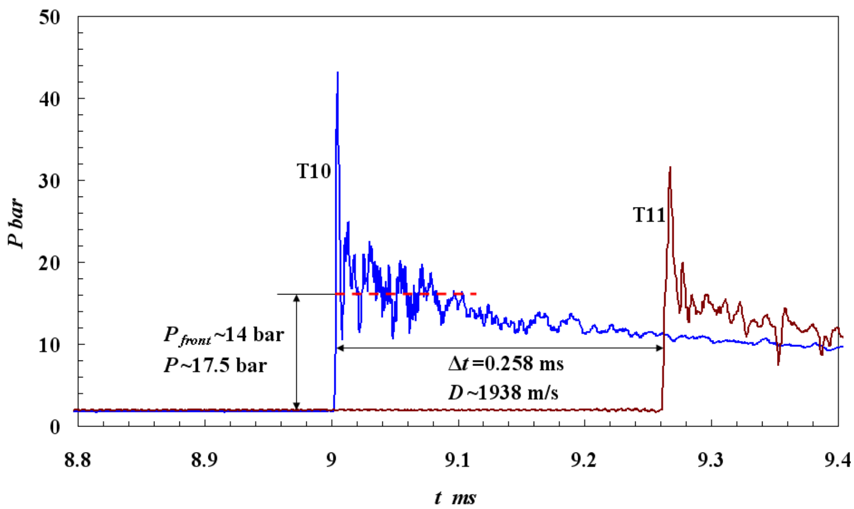


Figure 2. Pressure signals: Φ=1.1, x=0.95, P_0=1 bar

The pressure signals of two pressure transducers (T10 and T11) located at the end of the tube are shown in Fig. 2. According to the time-of-arrival of detonation wave, the experimental detonation velocity D is determined. The detonation pressure P is calculated by means of the relation $P = P_{front}/0.8$, where P_{front} denotes the back plateau pressure. In order to make comparison between the measured velocities and their CJ values, the variations of D/D_{CJ} with x are plotted in Fig.3. The measured detonation velocities are in good agreement with theoretical ones within ±3%. Also are demonstrated in Fig.4 the variations of P/P_{CJ} with x. The ratio P/P_{CJ} varies from 0.8 to 1.2. The discrepancy between P and P_{CJ} is more important probably because of the method of determining the peak pressure.

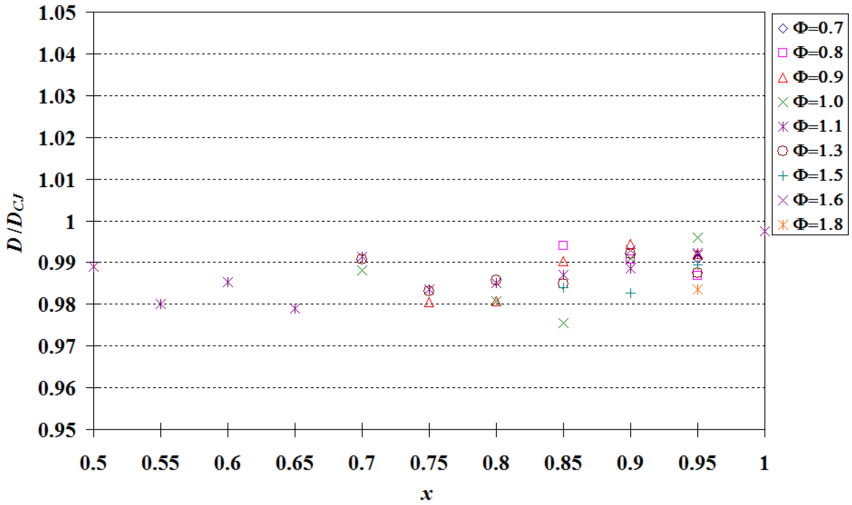


Figure 3. D/D_{CJ} vs. x

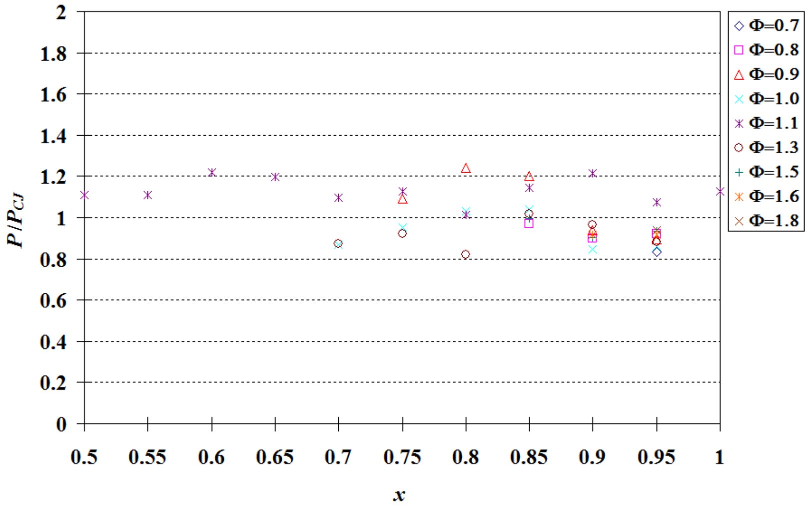
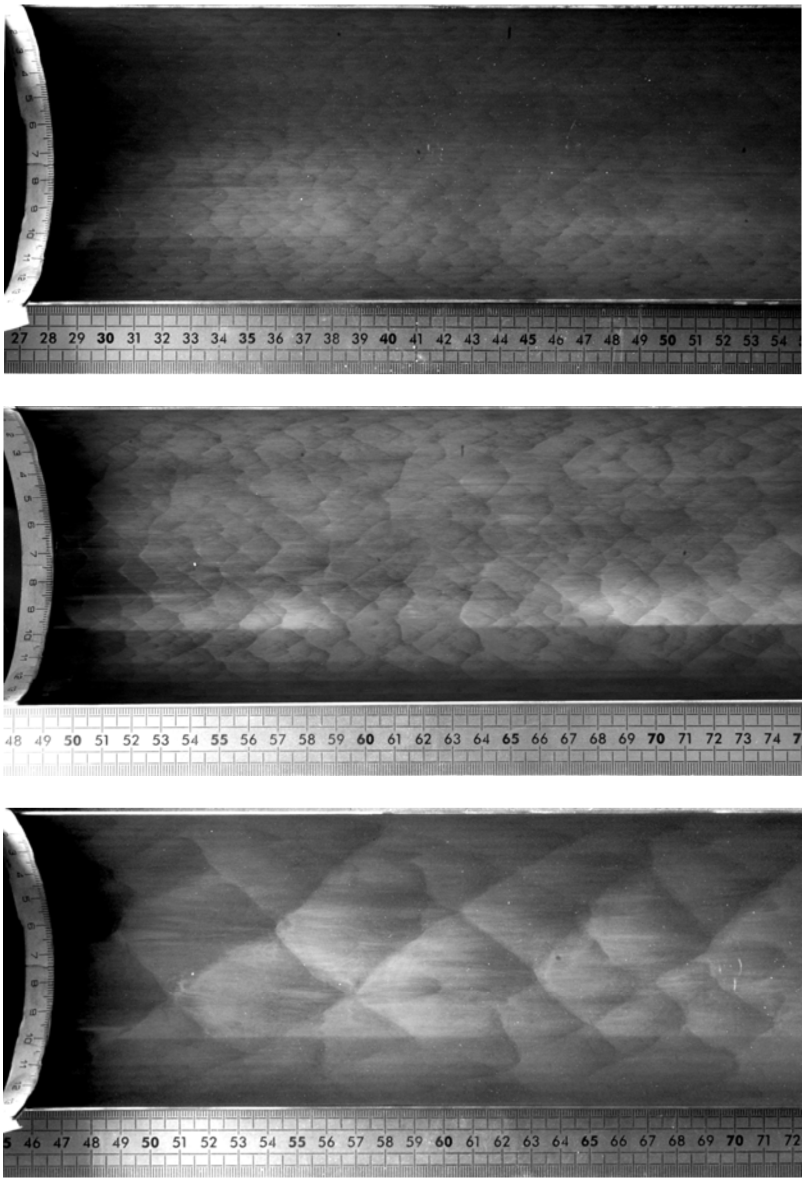


Figure 4. P/P_{CJ} vs. x

3.2 Detonation cell size

By means of the smoke foils placed at the end of the tube, we can measure the detonation cell size. Fig.5 shows the typical records of trajectories of the triple points of detonation front on the smoked foils for three mixtures with Φ=1.1, x=1.0, 0.95 and 0.5 in 92-mm i.d tube at ambient conditions. Due to their various origins and to the irregular structure of cell size shown on the smoke foils, the inaccuracies cannot be satisfactorily computed. The discrepancies are estimated from the dispersion of different experimental results at a given initial condition. To reduce the experimental errors as possible, the tests are repeated at least three to four times for each mixture. The discrepancy is of the order of 25%.

The variations of the cell size λ with x for Φ=0.9, 1.0 and 1.1 are shown in Fig.6. The error bars in Fig.6 represent the standard deviations of cell sizes for three equivalence ratios. It can be observed that λ increases with a decrease in *x* or an addition of propane, as similarly seen in Fig.5. For Φ=1.0, our results are in good agreement with those of Yoshida at al.[2]. For Φ=1.1, the cell size seems to reach a plateau corresponding to the cell size value of C_3H_8-Air mixtures. This trend is also observed by Yoshida at al.[2]. The results obtained in a 92 mm i.d tube are also plotted in Fig.6. The cell size and its evolution with *x* are the same as those obtained in the smaller tube.



(a) x=1.0

(b) x=0.95

(c) x=0.5

Figure 5. Examples of records on the smoked foils for the binary fuels mixtures
(Φ=1.1; P_0=1 bar; I.D=92 mm)

The cell size λ is plotted in Fig.7 as a function of the equivalence ratio Φ for different *x*. From Fig.7, the studied mixtures are less (more) sensitive than H_2-Air (C_3H_8-Air) mixtures. For a given *x*, a classical U-shaped curve $\lambda = f(\Phi)$ is obtained. The measured average cell sizes vary from 20 to 50 mm, and its minimum is reached at a rich-side of the curves. The cell size increases with introduction of propane for a given equivalence ratio. It implies that addition of propane reduces the detonability of the H_2/Air mixtures. The detonability of such binary fuels mixtures seems to be controlled by the heavier fuel (C_3H_8). For example, 5% of C_3H_8 in the binary fuels H_2/C_3H_8 represents 54% of molar mass.

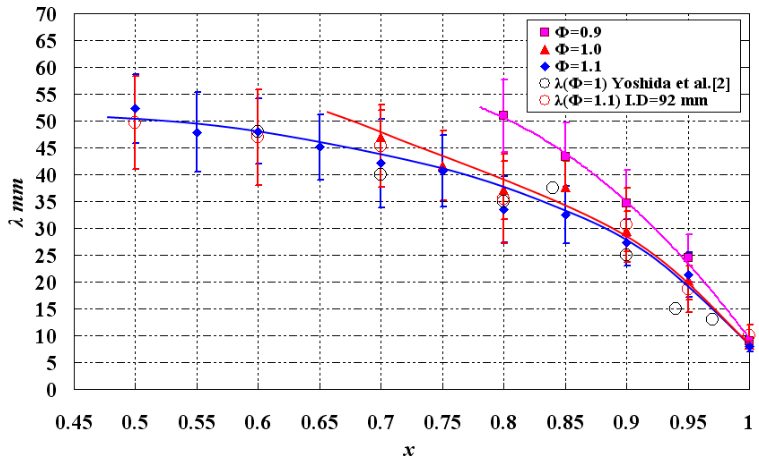


Figure 6. Variation of cell size with x

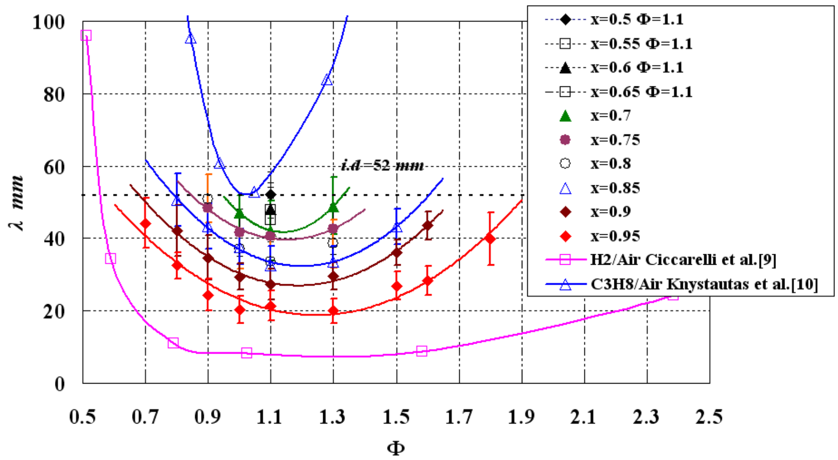


Figure 7. Evolution of cell size with equivalence ratio

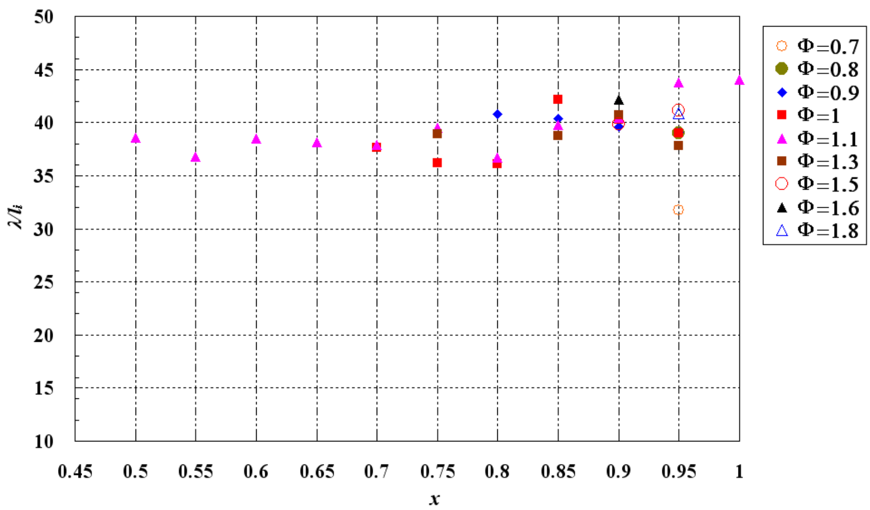


Figure 8. Evolution of λ/li as a function of x

3.3 Evolution of λ with l_i

In order to assess the detonation behaviors of the studied mixtures, we correlate the measured cell sizes λ with the *ZND* chemical reaction zone length l_i calculated by Chemkin with the detailed chemical kinetic scheme Gri-mech 3.0. The evolution of the ratio $K=\lambda/l_i$ as a function of x is presented in Fig. 8. We observe that the ratio K varies from 35 to 40 within $0.5<x<0.8$. For $0.8<x<1$, the ratio K ranges predominately from 40 to 45. It seems to tend toward a constant and appears to be independent of x and Φ.

4 Conclusions

An experimental investigation on detonation characteristics of the binary fuels hydrogen (H_2)/propane (C_3H_8)-Air mixtures is conducted in a stainless steel tube with 52 mm inner diameter and 8.7 m length at ambient conditions with equivalence ratios Φ ranging from 0.7 to 2.0 and the H_2 molar fraction x varying from 0.5 to 1. The detonation velocity, pressure and cell size are measured. The measured velocities and pressures agree well with the CJ ones. The velocity deficit does not exceed 3% and the ratio P/P_{CJ} varies from 0.8 to 1.2. The measured average detonation cell sizes vary from 20 to 50 mm. The minimum cell size always occurs at the rich-side of the mixtures. Introduction of propane to H_2/Air mixtures reduces the mixture detonability. Subsequently, a relationship $\lambda/l_i = f(x)$ can be constructed. The ratio λ/l_i varies from 35 to 45 and seems to be independent of x and Φ. In addition, we carry out several experiments in the 92-mm i.d tube to validate the cell size obtained in the 52-mm i.d tube.

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