DDT of the binary fuels H_2/C_3H_8-Air mixtures in the obstructed tube

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1 Introduction

The increasing consumption of the conventionally fossil-based fuels, and the relevantly environmental concerns, motivate the prospection and development of new energy sources. Due to its cleanliness and efficiency, hydrogen is under consideration as an alternative energy carrier. However, its lower ignition energy, wider flammability and higher propensity for leakage increase the explosion hazards in the stockage, transportation and distribution of hydrogen. In the industry, they are usually considered as resulting from the onset of a detonation wave or from the **Deflagration to Detonation Transition** (**DDT**) following the flame acceleration. In recently years, Bozier et al. [1], Cheng et al.[2-3], Chaumeix et al.[4], Matignon et al.[5], Medvedev et al.[6-7], Takita et al.[8] and Yoshida et al.[9] had verified that the addition of a small amount of inhibitors (e.g. propane or methane) had attenuated the H_2/Air mixtures detonation properties. It is therefore of particular importance to further study the characteristics of DDT phenomena in such binary fuels H_2/C_3H_8-Air mixtures in order to evaluate the potential risk of hydrogen industrial dangerous scenarios.

An effort is made in present paper to carry out an experimental investigation of the DDT phenomena of the binary fuel H_2/C_3H_8-Air mixtures in a stainless steel cylindrical tube at normal pressure and temperature. The studied mixture equivalence ratio Φ ranges from 0.7 to 1.8 and the H_2 molar fraction x varies from 0.5 to 1. The mixture compositions are given by:

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

The run-up distances to DDT, L_{DDT}, are measured. The variations of L_{DDT} with Φ, x, and the correlation $L_{DDT} = f(\lambda)$ are given, respectively. The criteria ($\lambda \leqslant d'$ [Peraldi et al.[10]]and $L > 7\lambda$ [Dorofeev et al.[11]], where L denotes the characteristic size, λ represents the detonation cell size and d' signifies the transverse dimension of the unobstructed passage in the channel with obstacles) to obtain DDT phenomenon are finally evidenced.

2 Experimental facilities

A typical sketch of experimental facilities is presented in Fig.1. All the experiments are carried out in a stainless-steel cylindrical tube with 52-mm inner diameter (I.D) and 8.7-m length at normal pressure and temperature. The tube is formed by two sections. Eleven piezoelectric pressure transducers (KISTLER 603B, 1 μs rise time) are used in the experiments. Nine transducers located along the first section (2-m length) are applied to obtain the pressure-times records in the period of flame acceleration at different axial location, and two others placed at the end of the second section (6.7-m length) are used to verify whether the self-sustained detonation wave is obtained at the end of the tube or not. The studied mixtures are ignited 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 close to the ignition point is placed in the tube in order to accelerate flame.

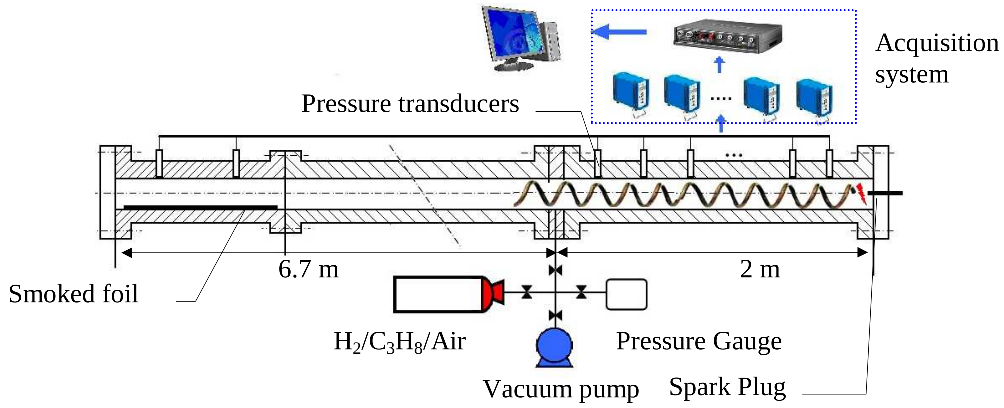

Figure 1. Sketch of experimental facilities.

3 Results and discussion

3.1 Determination of the run-up distance to DDT L_{DDT}

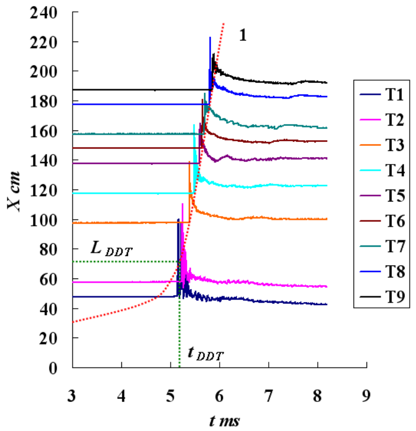

Figure 2. A typical example of DDT pressure-time records for the mixture Φ=1.0; x=0.95.

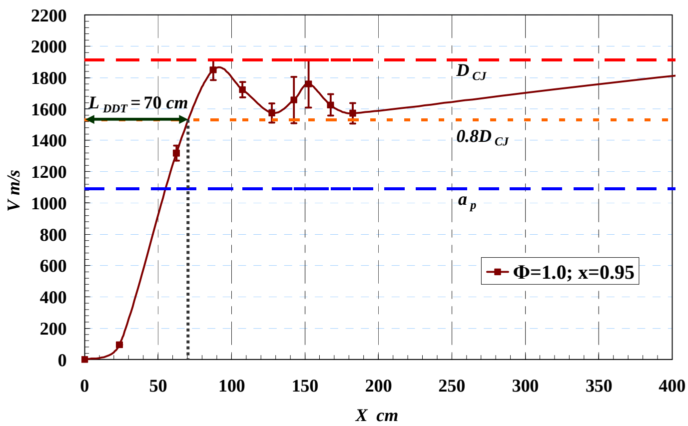

Figure 3. An example of determination of the run-up distance to DDT L_{DDT} for the mixture Φ=1.0; x=0.95.

A typical DDT pressure-time records of nine transducers in the 2-m length first section is presented in Fig. 2 for the mixture Φ=1.0, x=0.95. X denotes the distance of different transducers from the ignition point, T denotes the pressure transducers and 1 indicates the trajectories of the flame, shock or detonation fronts. The average velocities V are deduced from the front time-of-arrival measured by the transducers, so the diagram V-X can be correspondingly plotted in Fig.3. D_{CJ} represents the theoretical CJ velocity, 0.8D_{CJ} signifies the front velocity at the exit of spiral and a_p shows the sound speed in combustion products. According to Figs. 2 and 3, three stages of flame propagation can be observed: 1) Low-velocity flame propagation following ignition; 2) Flame acceleration and fast deflagration or the choking regime and 3) DDT phenomena. From the diagram V-X, the run-up distance to DDT L_{DDT} can be determined with the horizontal coordinate of the intersection point between the straight-line of 0.8D_{CJ} and the profiles of the front velocity V. The measured quasi detonation velocity is always slightly smaller than D_{CJ} because of the momentum losses on the spiral and the heat losses on the tube wall during the flame, shock or detonation propagation.

3.2 Variations of L_{DDT} with x, Φ

The variations of the run-up distance to DDT L_{DDT} with Φ, x are shown in Figs 4 and 5, respectively. L_{DDT} increases when x decreases or propane is added in the H_2-Air mixtures. From Fig.5, we can observe that the L_{DDT}-Φ curve shows a classical U-shaped form. For a given x, L_{DDT} is always minimum for the stoichiometric or slightly rich equivalence ratios (Φ=1.0-1.2). As for a fixed Φ, L_{DDT} varies from 60 to 180 cm. This indicates that the addition of propane in such binary fuels increases the chemical induction length, and decreases the H_2-Air mixture sensitivity. The run-up distance to DDT L_{DDT} accordingly increases. In addition, as observed in [2] on variations of the detonation cell size λ of the studied mixtures with x and Φ, it is seen that the studied mixtures represent the detonation characteristics of H_2-Air mixtures in case of $0.8 \leqslant x \leqslant 1$, and propane plays a dominant role in such binary fuels when x varies 0.5 to 0.8, because propane molar mass is heavier than hydrogen.

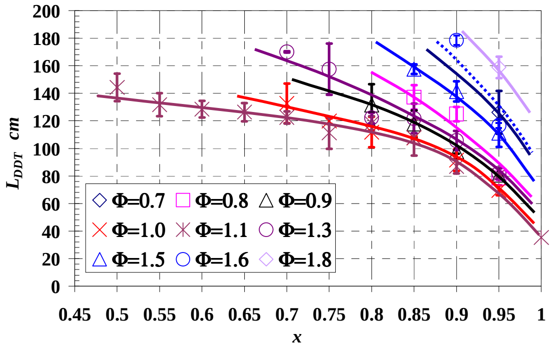

Figure 4. Variations of L_{DDT} with x.

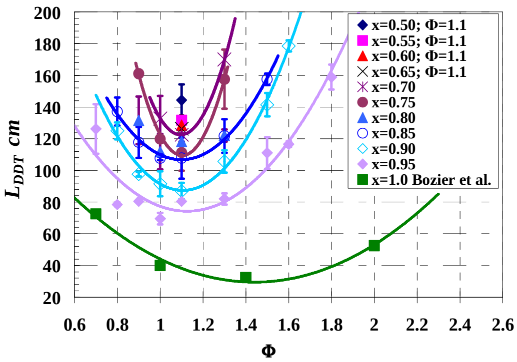

Figure 5. Variations of L_{DDT} with Φ.

3.3 Correlations L_{DDT} with λ

For conventional C_nH_m-Air/H_2-Air mixtures, a relation between L_{DDT} and λ has been evidenced ($L_{DDT}\approx$(30-40)λ) by Sorin et al.[12-14]. On the basis of our experimental results, a similar correlation is observed. In Fig. 6 is represented variation L_{DDT} as a function of the detonation cell size λ for the studied mixtures. It is observed that the ratio L_{DDT}/λ varies from 25-40 and seems be independent of x. Our results are in good accordance with those obtained in [12-14]. Therefore, the correlation $L_{DDT}\approx$(25-40)λ can be considered as an estimate to L_{DDT} for the studied mixtures.

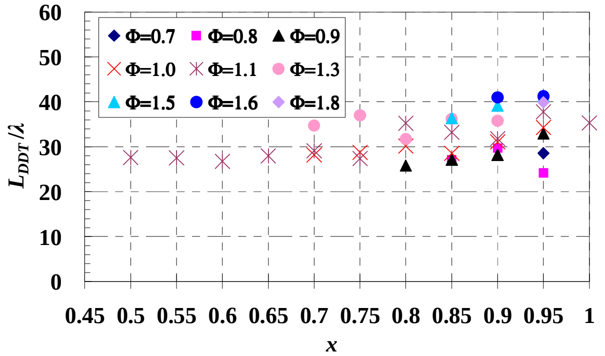

Figure 6. Evolution of L_{DDT}/λ with x.

3.4 Criteria of $\lambda \leqslant d'$ and $L > 7\lambda$

In order to obtain the onset of detonation in channels with obstacles, the criteria $\lambda \leqslant d'$ [Peraldi et al.[10]] and $L > 7\lambda$ [Dorofeev et al.[11]] are necessarily satisfied. L is generally defined as follows:

$$L = \frac{I.D + S}{2(1 - d'/I.D)} > 7\lambda$$

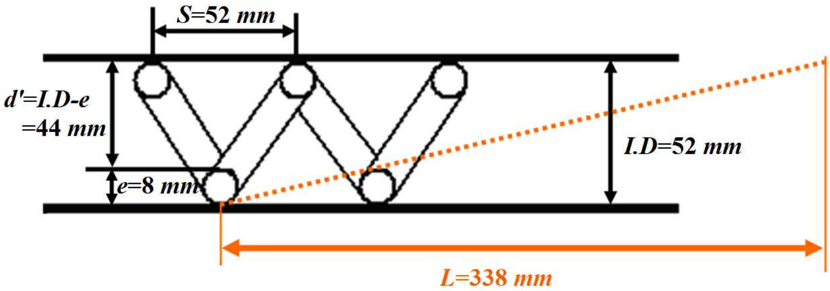

Figure 7. Sketch of Schelkin spiral geometrically characteristic size *L* and transverse dimension *d'* of the unobstructed passage in the I.D=52 mm tube.

Where *L* denotes the characteristic size, λ represents the detonation cell size and *d'* signifies the transverse dimension of the unobstructed passage in the channel with obstacles. In present paper, the geometrical characteristics of the Schelkin spiral are depicted in Fig. 7. *e* signifies the thickness or external diameter of spiral. Therefore, *d'*(*d'=I.D-e*) is on the order of 44 mm. The geometrically characteristic size *L* is deduced from the above formula and is about 338 mm. Therefore, the variations of the ratios d'/λ, and $L/7\lambda$ can be plotted in the Figs 8 and 9 as a function of the molar fraction of hydrogen *x*. From both figures, it is seen that the ratios d'/λ, varies from 0.8 to 4.5, while $L/7\lambda$ ranges from 0.92 to 6.2. Namely, both ratios d'/λ, and $L/7\lambda$ are nearly higher than 1. So, the criteria to achieve DDT phenomena are fulfilled for the studied mixtures.

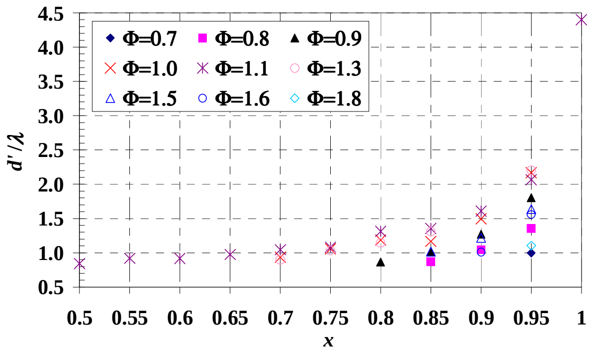

Figure 8. Variations of ratio d'/λ with *x*.

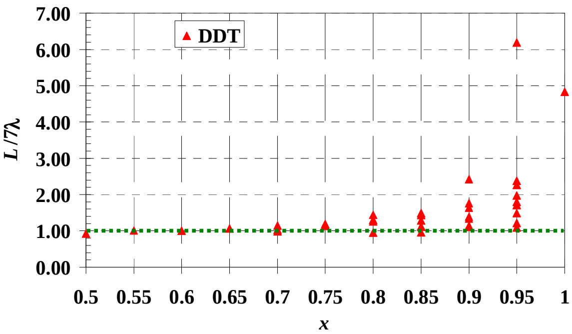

Figure 9. Variations of ratio $L/7\lambda$ with *x*.

4 Conclusions

An experimental investigation of Deflagration-to-Detonation Transition (***DDT***) phenomena in the binary fuels hydrogen (H_2)/propane (C_3H_8)-Air mixtures is carried out. All the experiments are performed in a stainless steel cylindrical tube with 52-mm inner diameter and 8.7-m length at normal pressure and temperature with equivalence ratio Φ ranging from 0.8 to 1.8 and H_2-molar fractions *x* varying from 0.5 to 1. A classical Schelkin spiral is used to promote the flame acceleration and the onset of detonation. The run-up distances to DDT, L_{DDT}, are measured. The variations of L_{DDT} with Φ, *x* and the correlation $L_{DDT}= f(\lambda)$ are given, respectively. The criteria ($\lambda \leqslant d'$ and $L>7\lambda$) to obtain DDT phenomenon are validated.

The mainly conclusions are:

1) For the studied binary fuels/Air mixtures, L_{DDT} varies from 60 to 180 cm when *x* varies from 1 to 0.5.
2) L_{DDT} increases when *x* decreases or propane is added in the H_2-Air mixtures. For a given *x*, L_{DDT} is always minimum for the stoichiometric or slightly rich mixtures.
3) A correlation between L_{DDT} and λ is obtained: $L_{DDT} \approx$ (25-40) λ.
4) The criteria ($\lambda \leqslant d'$ and $L>7\lambda$) to obtain DDT phenomenon are satisfied. The ratios d'/λ, varies from 0.8 to 4.5, and $L/7\lambda$ ranges from 0.92 to 6.2.

References

[1] O.Bozier, R.Sorin, R.Zitoun, D.Desbordes. (2009). Detonation characteristics of H_2-natural gas-air mixtures. Proc. European Combustion Meeting, Vienna, Australia. Paper 167.

[2] G. Cheng, R. Zitoun, P. Bauer. (2011). Detonation characteristics in tube filled with the binary fuels H_2/C_3H_8-Air mixtures. Proc. 23rd ICDERS, Paper 129.

[3] G. Cheng, R. Zitoun, Y. Sarrazin, P. Bauer. (2011).Deflagration-detonation transition in tube filled with the binary fuels H_2/C_3H_8-Air mixtures. Proc. European Combustion Meeting, Cardiff.

[4] N. Chaumeix, S. Pichon, F.Lafosse, C.-E. Paillard. Role of chemical kinetics on the detonation properties of hydrogen/natural gas/air mixtures. Inter. Journal of Hydrogen Energy 32(2007)

[5] C. Matignon. (2000). Etude de la détonation de deux mélanges stoechiométriques($H_2/CH_4/O_2$ /N2 et $CH_4/C_2H_6/O_2$ /N2) Influence de la proportion relative des deux combustibles et de la températur initiale élevée, PhD thesis, University of Poitiers, Poitiers, France.

[6] S.P.Medvedev, SV.Khomik, H.Olivier, BE.Gelfand. (2005). Examination of the DDT triggering in an obstructed tube. Proc. 20th ICDERS, paper 134.

[7] S.P.Medvedev, AN.Polenov, SV.Khomik, BE.Gelfand.(2009).DDT test of binary fuel-air mixtures in an obstructed channel. Proc. 22nd ICDERS, paper 36.

[8] K.Takita, T.Niioka , Shock waves 6(1996):16-66.

[9] A.Yoshida, Y.Okuda, T. Yatsufusa, T.Endo, S.Taki, S.Aoki, Y. Umeda. (2005). Detonation properties of mixed-fuel-and-air gas mixtures. Proc. 20th ICDERS, paper 77.

[10] O. Peraldi, R. Knystautas, J.H.S. Lee.(1986). Criteria for transition to detonation in tubes. Proc. 21st Symposium on combustion.

[11] S.B. Dorofeev, V.P.Sidorov, M.S. Kuznetsov, I.D. Matsukov, V.I. Alekseev. (2000). Effects of scale on the onset of detonations. Shock waves 10(2000):137-149.

[12] R.Sorin, O.Bozier, R.Zitoun, D.Desbordes. (2009). Deflagration to detonation transition in binary fuels H_2/CH_4 with air mixtures. Proc.22nd ICDERS, paper 186.

[13] R.Sorin, R.Zitoun, D.Desbordes. Optimization of the deflagration to detonation transition: reduction of length and time of transition. Shock waves.15(2006):137-145.

[14] R.Sorin. Etude et optimisation de la Transition Déflagration Détonation en tube des mélanges stoechiometriques H_2/O_2 /N_2 et (CH_4, C_2H_2 , C_2H_4 C_3H_8) /O_2 /N_2 et de sa Transmission à un espace de plus grand dimension, PhD thesis, University of Poitiers, Poitiers, France, 2005.