H_2 Gradient Effect on Premixed Flame Propagation in a Vertical Facility: ENACCEF

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Introduction

For environmental reason, hydrogen can be considered as a fuel of the future. However, the flammability domain is very large and the necessary ignition energy is only of few millijoules. The presence of hydrogen in air is potentially dangerous in confined environment. It can also be accidentally generated in nuclear plants. The expanding flame is intrinsically unstable. Numerous studies, for example Lee et al. (1985), Knystautas et al. (1986), showed that obstacles located along the path of expanding flames can cause rapid flame acceleration and deflagration to detonation transition. Generally, if the hydrogen quantity is less than 18 mol% H_2 in air, the detonation regime is not observed. However, in this case, the flame speed can increase up to 70 or 80 % of the burned gas speed of sound. This flame acceleration has considerable effect on the confinement and can destroy the building.

Flame acceleration has been largely studied for a homogeneous hydrogen distribution in the available containment volume (Yang et al. 1991, Dorofeev et al. 2001, Djebaïli-Chaumeix et al. 2005). However, very few data are available on the behaviour of the H_2/air flame in a non-uniform mixture (Whitehouse et al. 1996, Sochet et al. 1997). The present work aims at providing an experimental database on flame acceleration of lean H_2/ air based mixtures characterized by hydrogen gradient. The experimental work is completed by computations using TONUS CFD code (Rivière et al. 2004). The H_2 gradient establishment is controlled using GC gas sampling analysis and the results are compared to the modelling. Finally, the flame speeds measurements in the non uniform mixtures are compared to those for uniform mixtures.

Fundamental Issues

In the attempt of a better understanding of flame acceleration phenomena (Dorofeev et al. 1999, 2001), different parameters were identified: the laminar flame velocity, $S_L°$, and flame thickness, δ, the integral length scale, L_T, and intensity of turbulence, the Lewis and Zeldovich numbers, Le, β, the expansion ratio, σ, the product speed of sound C_{sp}. In homogeneous charged mixtures, previous works (Dorofeev et al. 2001, Djebaïli-Chaumeix et al. 2005) have shown that sufficiently large σ is necessary for potential development of fast flames, depending on either β(Le-1) or the burned gas Markstein length, Ma_b. Djebaïli-Chaumeix et al. (2005) have proposed the following relationships: $\sigma^* = 0{,}075\beta(Le-1)+4{,}38$ and $\sigma^* = 0{,}052Ma_b + 4{,}28$ which return a critical σ value close to 3.75 as recommended by Dorofeev et al. (1999, 2001) for uniform H_2/ air mixtures. In non uniform mixtures, Whitehouse et al. (1996) performed numerous tests changing the H_2 gradient and/or the ignition location (top or bottom of the 10.3 m^3 facility without obstacles). Different behaviours were identified depending on the hydrogen concentration and on the ignition point location. This study was performed in a smooth vessel. The main differences between homogeneous and non-homogeneous cases were observed when the lowest concentration of hydrogen in the vessel was below the downward propagation limit and concerned the peak combustion pressure, burn fraction and flame speed.

Experimental Facility: ENACCEF

Setup

The original vertical facility ENACCEF, that has been built, measures about 5 m high and can be equipped with repeated obstacles in the bottom part. It is divided in 2 parts: the lower one, acceleration tube, measures 0.15 m i.d. and 3.2 m long while the top one, the dome, is 0.75 m i.d. and 1.7 m long. The facility is highly instrumented (16 optical windows with PMT, 9 pressure transducers) to follow the flame propagation. The acceleration tube has 6 gas sampling location. The mixture is ignited by a spark discharge at the bottom-end using electrodes. Based on fundamental parameters assessments (Lamoureux et al. 2004), the studied H_2-air based mixtures (between 10 and 13 mol% H_2) are characterized by: $3.6<\sigma<4.2$, $9.1<\beta<12.6$, $0.34<Le<0.42$, $0.10<S_L°(m/s)<0.27$. In the present study, the tube was equipped with 9 ring obstacles (blockage ratio, BR=0.63) equally spaced by 154 mm between 0.7 and 1.95 m from the spark location. The facility is vacuumed down to 0.3 kPa before the premixed gas filling. The premixed gas composition is controlled by mass flow meters.

Non uniform mixtures

The effect of the mixture composition and the obstacles on the flame speed is analyzed in non-uniform charge (from 10 to 13 mol% H_2, from 13% to 10 mol%H_2 or from 18% to 8 mol% H_2). In order to produce the H_2 gradient in the lower tube, the 2 parts are isolated from each other by a thin terphane sheet (burst overpressure close to 25 kPa). Then, the facility is simultaneously filled with a premixed gas. The lower tube is filled up to 75 kPa with a mixture composition corresponding to the one expected at the bottom end while the dome is filled up to 100 kPa with a mixture composition corresponding to the one at the top end. 5 min after the sheet burst, gas sampling is done and the mixture is ignited. The 6 gas samplings are analysed using a GC apparatus with a relative uncertainty lower than 3% in mass. The total initial pressure is around 100kPa.

Results

H_2 gradients: modelling and experiments

Flame propagation was analysed with different H_2 gradients in the acceleration tube. **Fig. 1** shows the different H_2 gradients that were studied and the initial conditions are listed in Table 1. Numerical calculations with TONUS CFD code and for different hydrogen gradient were performed in order to evaluate the hydrogen distribution in the ENACCEF vessel. The used finite element solver is based on an asymptotic analysis of the compressible Navier-Stokes equations in the limit of low Mach number. Combustion numerical tests were also performed with TONUS CFD on the basis on distribution numerical results. The used combustion model is based on « forest-fire » model for flame tracking (CREBCOM model developed at

Kurchatov Institute: Dorofeev et al. 1998). The results obtained using the code were compared to the measurements obtained using CPG analysis.

Table 1. Mixtures composition filling the facility ENACCEF.

Tube (H_2, % vol.)	13	13	13	18	10.5	13	10.5
Dome (H_2, % vol.)	8	9	10.5	8	13	13	10.5
Run #	410	437	444	508	449	451	450

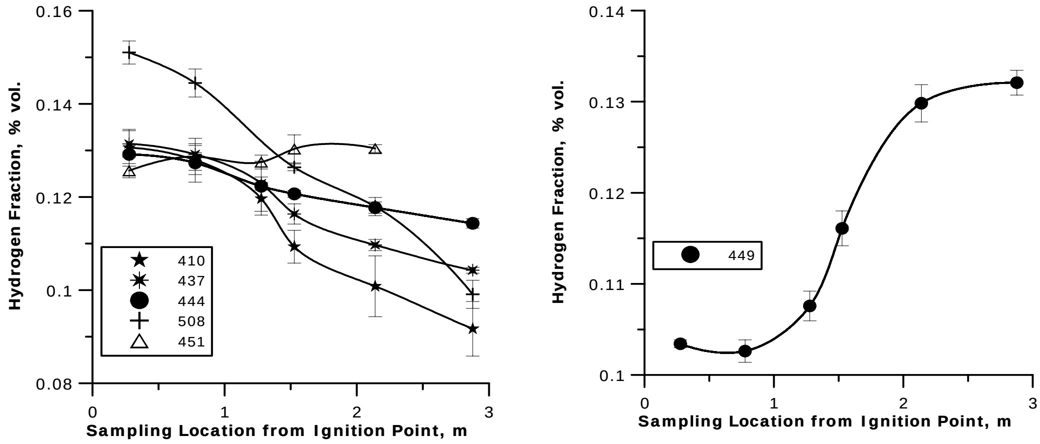

Figure 1. H_2 molar fraction according to distance from ignition point. Run# see table 1.

Flame speed measurements

When the acceleration tube is equipped with 9 ring obstacles, the maximum measured flame speed does not depend on the negative H_2 gradient, **Fig. 2**, but the velocity profile is very different in the dome. On the contrary, the maximum flame speed depends on the gradient when a positive H_2 gradient is established, **Fig. 3**. In the case of a positive gradient, the velocity along the tube is closer to the one obtained with a uniform concentration of 10.5 mol%H_2. The maximum velocity observed in the case of a positive gradient is lower than in the case of a negative one.

Conclusion

The present work constitutes a new contribution in the analysis of flame acceleration phenomena in closed and obstructed tubes. These new results concern the importance of non-homogeneous mixtures on the flame acceleration and the maximum velocity that is achieved by the flame during its propagation. The main results of this work are: (i) a flame of lean H_2/air can be strongly accelerated if the expansion ratio, σ, is greater than 3.75 ; (ii) the comparison between a flame propagating in a mixture with a negative H_2 gradient and a homogeneous one showed that the maximum velocity achieved by the flame is the same although it behaves differently once in the dome ; (iii) in the case of a positive gradient, the maximum flame velocity is lower than the one obtained in a homogeneous case with a hydrogen concentration corresponding to the average one. The discussion of H_2 gradient effect will be discussed in the final paper.

Acknowledgements

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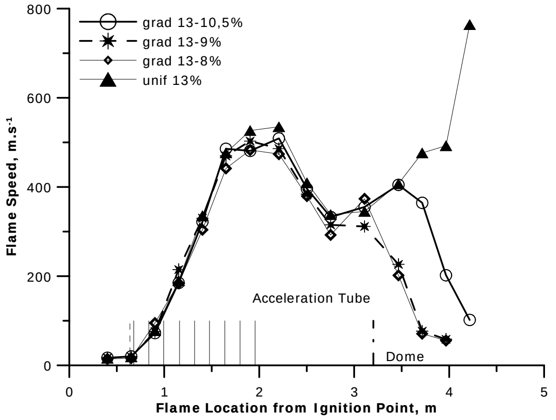

Figure 3. Flame speed vs. flame location in different negative H_2 gradients in the tube (9 ring obstacles, bottom ignition)

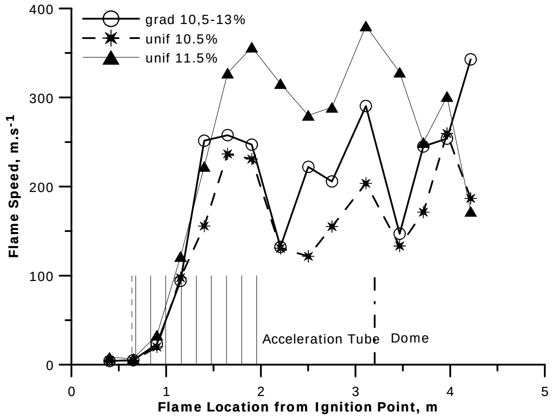

Figure 4. Flame speed vs. flame location in different positive H_2 gradients in the tube (9 ring obstacles, bottom ignition)

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