Flame acceleration characterization in a vertical obstructed closed device: ENACCEF.

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INTRODUCTION

In the framework of nuclear safety, a severe accident can lead to a hydrogen leak in the reactor building which subsequently would raise a combustion hazard. In the case where hydrogen/air diluted mixtures can be obtained inside the flammability limits, a local ignition of the combustible mixture would give birth initially to a slow flame. However, rapidly this slow flame would accelerate strongly due to all the obstacles that would obstruct its path. This flame acceleration is responsible of high loads that can destroy the reactor's building. One of the major problems is to predict the level of flame acceleration due to the geometrical configuration and scale for a given mixture. Indeed the presence of obstacles will enhance first the combustible mixtures composition, it can accelerate, transit to detonation or be quenched after a certain distance. The regimes were well identified in the experimental work of Dorofeev's group [1, 2]. In the attempt of a better understanding of flame acceleration phenomena, different parameters were identified [3]: (i) intrinsic to the combustion itself, laminar flame velocity and flame thickness, (ii) turbulent flow, characterized by the integral length scale, and intensity of turbulence, (iii) flame instabilities, characterized by the Lewis number, Zeldovich number and the expansion ratio, (iv) gasdynamics of the compressible flow, reactant and product speed of sound.

The aim of the present work is to provide new experimental database on flame acceleration of hydrogen air based mixtures using a vertical obstructed tube in order to give a complementary insight over the fundamental parameters that where identified previously. We will give a first approach to the measurements of the fresh gas velocity induced by the flame propagation ahead of it, using a Laser Doppler Velocimetry coupled with the vertical facility.

EXPERIMENTAL SETUP

The flame acceleration facility, named ENACCEF, is a vertical stainless steel setup which totalizes a length of 4.9 m. It is constituted of two main parts. The bottom tube or acceleration tube (154 mm i.d., 3.2 m long, i.e. 62 dm³) is equipped, in its lower part, with 2 electrodes for the spark ignition. At a location of 1.9 m from the ignition point, 3 rectangular silica windows (40X300 mm optical path) are perpendicular to each other 2 by 2. The bottom tube is connected to the top tube or dome (750 mm i.d., 1.7 m long, i.e. 658 dm³) via a flange. Three silica windows (170 mm optical diameter) at the bottom of the dome allow for the visualization of the flame impingement in the larger tube. Sixteen photomultiplier tubes (Hamamatsu 1P28) equally spaced (250 mm) allow for the flame front detection and hence deducing the spatial flame velocity while 9 pressure transducers mounted flush with the inner surface of the tube record the pressure increase along the facility.

In order to measure the fresh gas velocity ahead of the flame front, a laser Doppler velocimetry system was coupled with the acceleration tube using the rectangular silica windows. The LDV is constituted of an argon ion laser at 488 and 514 nm (power 8 W) in order to measure simultaneously the velocity in 2 directions. However, because of the heavy reflections on the windows wall due to their thickness (40 mm), only the 514 nm laser ray was used. The velocity in the vertical direction (u_g) was derived using the TSI software INSIGHT.

The combustible mixtures were constituted of hydrogen distributed by Air Liquide (purity better than 99.95 %) and laboratory dry compressed air. Before each run, the whole facility was vacuumed down below 1 Pa. Then, the mixture is introduced in ENACCEF via flow meter controllers (MKS1179A) at the desired composition up to a final pressure of 100 kPa.

RESULTS

The studied mixtures were chosen according to the flame acceleration analysis based on the intrinsic properties of the combustible mixture, namely the expansion factor defined as the ratio between the unburned gas density and the burned one (σ). The different thermodynamic parameters and transport properties were calculated using CHEMKIN II package [4] on the basis of an adiabatic isochoric combustion. The Zeldovich number, β , is derived using an activation energy of 80.2 kJ.mol⁻¹ for H₂/air

mixtures (in the range of 10 - 13 %) [5]. Finally, the unstretched laminar flame velocity, S_l^0 , and the flame thickness defined as the hydrogen mass diffusivity in the mixture over the unstretched laminar flame velocity, δ , were estimated using RUN1DL code [6] and Marinov's model [7]. The different parameters are summarized in table 1.

Table 1: Properties of the different studied mixtures. Φ : equivalence ratio, σ : expansion factor, C_{sr} : speed of sound in the fresh gas (m.s⁻¹), C_{sp} : speed of sound in the products (m.s⁻¹), γ : specific heat ratio in the fresh gas, Le: Lewis number, β : Zeldovich number, T_F : adiabatic flame temperature at constant volume, S_l^0 : unstretched laminar flame velocity (m.s⁻¹), δ : flame thickness (µm).

| Mixture | Φ | σ | C_{sr} | C_{sp} | γ | Le | β | β (Le-1) | $T_{\rm F}$ | S_l^0 | δ |
|---------------------|------|------|----------|----------|-----|------|------|----------------|-------------|---------|-----|
| 13%H ₂ | 0.36 | 4.21 | 366.8 | 752.2 | 1.4 | 0.36 | 5.69 | -3.66 | 1614 | 0.203 | 456 |
| 11.5%H ₂ | 0.31 | 3.88 | 363.9 | 693 | 1.4 | 0.35 | 6.05 | -3.94 | 1476 | 0.144 | 566 |
| 10.5%H ₂ | 0.28 | 3.66 | 362 | 670.6 | 1.4 | 0.34 | 6.32 | -4.15 | 1383 | 0.092 | 944 |

Different regimes of flame propagation were observed when the acceleration tube was equipped with 9 equally spaced (154 mm) annular obstacles between 0.7 and 1.95 m from the ignition point. Figure 1 shows the evolution of the flame velocity along the vessel derived from the photomultiplier tubes. When the mixture is constituted of 10.5% H₂ in air, the flame velocity increases up to 220 m.s⁻¹ at the end of the obstructed area and then stabilizes between 150 and 200 m.s⁻¹. With a mixture of 13%H₂ in air, the maximum velocity at the exit of the obstructed area reaches 510 m.s⁻¹ before it drops around 400 m.s⁻¹. As it was expected, the mixture containing 13% H₂ in air which has an expansion factor of 4.21 has the potential to strongly accelerate and reach the choked regime, while the 10.5% H₂ in air mixture accelerates only mildly. Going from a smooth tube to a highly obstructed one (BR = 0.0 to 0.63) increases the maximum spatial flame velocity as it is shown on figure 2.

In the flame acceleration phenomena, one has to take into account the velocity fluctuations in the flow field which are generated by the flame itself. It would be very helpful if one can measure this quantity instead of derive it from different models which are more or less predictive. To do so, an attempt has been done to measure the flow velocity ahead of the flame front as the flame approaches the visualization section by using LDV measurements. Figure 3 shows the evolution of the fresh gas velocity (at 1.9 m from the ignition point). Whereas the spatial flame velocity increases up to 900 m.s⁻¹ at the end of the obstructed area, the velocity in the fresh gas ahead of the flame front reaches 80 m.s⁻¹.



Figure 1: Spatial flame velocity versus distance when the acceleration tube is filled with 9 annular obstacles (BR=0.63) equally spaced (154 mm) between 0.7 and 1.95 m from ignition point.





Figure 2: Spatial flame velocity versus distance in a mixture of 13%H₂ in air. Effect of blockage ratio of 9 annular obstacles equally spaced (154 mm) between 0.7 and 1.95 m from ignition point.

Figure 3: Spatial flame and fresh gas velocities versus time in $13\%H_2+87\%$ air mixture at normal temperature and pressure. The acceleration tube is filled with 9 annular obstacles (BR=0.63) equally spaced (154 mm) between 0.7 and 1.95 m from ignition point.

CONCLUSIONS

This study focuses on flame acceleration of lean hydrogen air mixtures. A first attempt has started on the characterization of the flow field ahead of the flame front using Laser Doppler Velocimetry. Different mixture compositions and obstacles configurations were adopted in order to establish a new database.

Dorofeev S. B., Kuznetsov M. S., Alekseev V. I., Efimenko A. A., Bezmelnitsun A. V., Yankin Y. G., Breitung W., Effect of scale and mixture properties on behaviour of turbulent flames in obstructed areas, Report FZKA-6268. Karlsruhe: Forschungszentrum Karlsruhe [preprint IAE-6127/3, RRC Kurchatov Institute, Moscow], 1-26 (1999).
Dorofeev S. B., Kuznetsov M. S., Alekseev V. I., Efimenko A. A., Breitung W., Evaluation of limits for effective flame acceleration in hydrogen mixtures, J. of Loss Prev. Proces. Ind., 14, 583-589 (2001)

³ OECD State of Art Report on Flame acceleration and Deflagration to detonation transition in nuclear safety, Common Report (1999).

⁴ Kee R. J., Rupley F. M., Miller J. A., Chemkin II: A fortran Chemical Kinetics Package for the analysis of gas phase Chemical kinetics, SAND89-8009 (1989)

⁵ Lamoureux N., Djebaïli-Chaumeix N., Paillard C.-E., Mesures de vitesses fondamentales de combustion par la méthode de la bombe sphérique. Mélanges H₂-air-CO₂-He à température ambiante et H₂-air- vapeur d'eau à 80°C, private communication (2002).

⁶ Rogg B., RUN-1DL : The Cambridge Universal Laminar Flamelet Computer Code, in: Reduced kinetic mechanisms for applications in combustion systems, Appendix C, N. Peters and B. Rogg (Eds), Springer-Verlag, Berlin-Heidelberg (1993).

⁷ Marinov N., Westbrook C. K., Pitz W. J., in Transport phenomena in combustion, vol. 1, S. H. Chan (Ed), Taylor and Francis, Whashington DC (UCRL-JC-120677) (1996).