Effect of initial temperature and temperature gradient on H_2/Air flame propagation in confined area

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1 Introduction

During severe accident in Pressurized Water Reactor (PWR), the interaction between the fuel rode and steam leads to the build-up of an explosive atmosphere inside the containment building [1]. This atmosphere is mainly composed of hydrogen, oxygen, nitrogen and water vapor. A gradient of both temperature and hydrogen concentration is usually generated from the primary circuit leak to the top part of the containment building. In case of an ignition by an energy source (electrical discharge spark, hot surface, etc.), a flame occurs and is capable to threaten the containment building. The flame propagation in such environment depends on geometrical configuration, turbulence level and initial mixture composition. The evaluation of the pressure loads which can be damaging are evaluated by using combustion models implemented in CFD and LP codes. These models have to be faced with reliable experiments. This paper aim is to present new data on H_2/Air flame propagation in a new facility through homogeneous and heterogeneous conditions of temperature and hydrogen concentration. The experimental work has been conducted over conditions relevant to severe accident in PWR: hydrogen molar fraction from 8 to 15, homogeneous initial temperature (298, 363, 413 K) and gradient of temperature (from 363 to 298K and from 298 to 363K).

2 Material and methods

A new experimental setup (ENACCEF 2) has been developed in ICARE laboratory to study flame propagation in confined area. It represents a vertical tube of 7.65 m of height with an internal diameter of 230 mm. It is composed of 9 switchable modules and can sustain 234 bar at 473 K. A schematic diagram of this facility is represented in Figure 1. Two visualization modules composed of sapphire windows (282*50 mm of optical access) can be implemented to operate Schlieren visualization or PIV measurement. In this case, the setup sustains 120 bar at 473 K. To promote flame acceleration phenomena, annular obstacles can be introduced inside the facility. In this study, obstacles are characterized by a

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Blockage Ratio of 0.63 (BR=1-(1/D)^2, where d and D are the internal diameters respectively of the obstacles and of the tube) and are implemented between 0.638 and 2.478 m of height. The ignition of the combustible mixture is produced at the bottom part of the facility via a spark ignition. 27 photomultipliers (Hamamatsu R928) located all along the height permit to obtain the flame front trajectory and to derive the flame propagation speed. Only radiations emitted by OH* radicals are detected thanks to optical filters (center wavelength of 306 nm). 10 pressure transducers (2 PCB 113B03 and 8 Kistler 601CA) are also implemented to record the pressure build-up during the combustion. The locations of these devices are also reported in Figure 1.

Figure 1. Schematic of the ENACCEF2 facility with the locations of the photomultipliers (■), the pressure transducers (■) and of the obstacles (■). The image has been rotated by 90°, the setup is vertical in reality.

The combustible mixture is constituted of hydrogen supplied by Air Liquide (purity>99.9999%) and laboratory dry compressed air. Before each run, the facility is vacuumed down below 80 Pa. Then the mixture is introduced at the desired composition up to a final pressure of 100 kPa with mass flow controllers (Bronkhorst, F-201CV) and three injection lines connected to the facility. In order to verify the initial composition, 4 gas sampling are operated prior to ignition and analysed with a gas chromatographer (SRA Instruments, Micro-GC) equipped with a HP Molsieve 5A column and a TCD detector. These sampling are operated at 1.35, 3.20, 4.75 and 7.11 m of height. In case of incomplete combustion, sampling and analysis are also conducted to confirm the quenching of the flame. Each module of ENACCEF 2 is equipped with its own electrical resistances system which permits to regulate the internal temperature from 298 to 473 K ($\Delta T=\pm 0.1K$). Therefore, an homogeneous temperature can be easily implemented all along the facility as well as a gradient of temperature. For each condition, three runs are conducted to verify the repeatability of the measurements. As an example, the Figure 2 plots the flame trajectory and the flame propagation speed obtained for the three runs conducted with a 11%mol.H_2+89%mol.Air flame at 298 K.

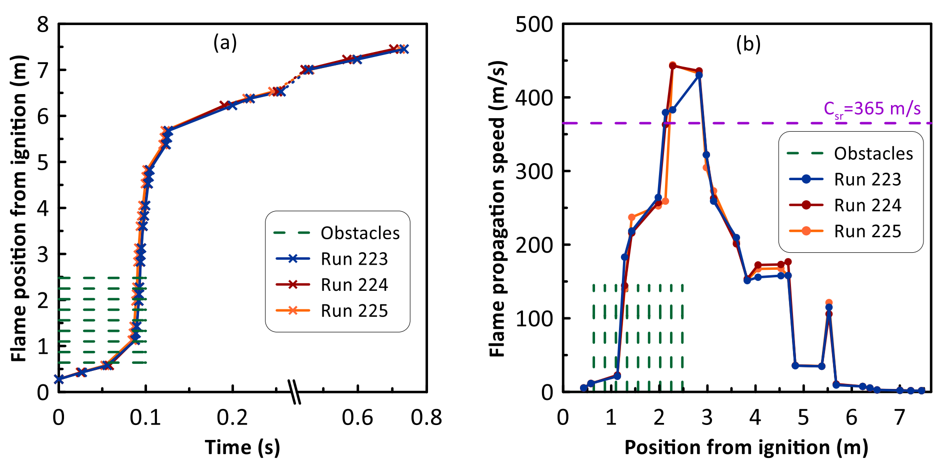

Figure 2. Example of flame trajectory (a) and flame propagation speed (b) obtained for three runs conducted in the same conditions (11%mol.H_2+89%mol.Air, T_{ini}=298 K, P_{ini}=100 kPa)

In this case, one can easily identify four steps of flame propagation. First, the flame undergoes a sharp acceleration until 2.5m of height due to the generation of turbulence in the obstacles region [2-3]. Therefore it reaches its maximum of propagation speed which is approximately 450 m/s in this case. Then due to the expansion of the flame front outside the obstacles, the flame velocity decrease to reach a plateau around 160 m/s. In the third phase, oscillations in the flame speed can be observed. This can be explained by interactions with a shock wave which is reflected at the top of the facility. Indeed, as one can see during the flame acceleration phase, the flame speed exceeds the speed of sound in the reactants (C_{SR}=365m/s). Therefore, the flame reaches the chocking regime [4] and a shock is generated in front of the flame. The propagation of this shock can be studied by analysing the pressure transducers signals as it is represented in Figure 3 (a). Due to its multiple reflections at the top of ENACCEF 2 and in the obstacles region, the shock and the flame interact several times as it appears in Figure 3 (b) which represents their trajectories. Note that the reflection point in the obstacles region is not identifiable with the pressure signals due to the noise. One can see these interactions are responsible of deceleration (shock and flame propagation in opposite direction) and acceleration (shock and flame propagation in same direction) of the flame. Furthermore, the shock propagation ahead of the flame is responsible of the increase in temperature and pressure. Considering a planar shock wave and calorifically perfect gases, shock parameters (pressure and temperature) can be calculated with the conservation equations [5] as it can be seen in equation (1) and equation (2). In these equations, P_2 and T_2 represent respectively the pressure and the temperature behind the shock, P_1 and T_1 represent respectively the pressure and the temperature ahead of the shock, M stand for the shock Mach number and γ for the specific heat ratio. Figure 3 (c) represents a comparison conducted between the calculated pressures P_2 behind the shock and the pressures measured experimentally at three different heights in ENACCEF 2. One can see a perfect agreement demonstrating the shock is planar.

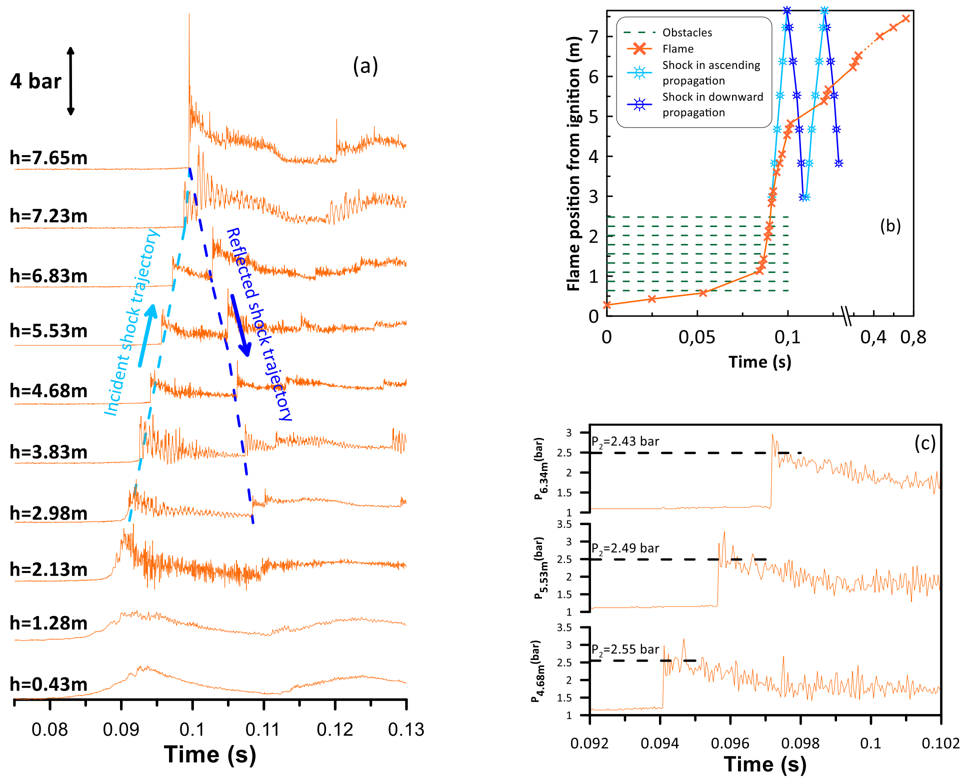

Figure 3. Example of pressure signals (a) flame and shock trajectory (b) and shock parameters (c) obtained for 11%mol.H_2+89%mol.Air mixture (T_{ini}=298 K, P_{ini}=100 kPa)

$$\frac{P_2}{P_1} = \frac{2\gamma M_1^2 - (\gamma - 1)}{\gamma + 1} \quad (1)$$

$$\frac{T_2}{T_1} = \frac{\left(\gamma M_1^2 - \frac{\gamma-1}{2}\right)\left(\frac{\gamma-1}{2} M_1^2 + 1\right)}{\left(\frac{\gamma+1}{2}\right) M_1^2} \quad (2)$$

3 Impact of molar fraction of hydrogen

Hydrogen molar fraction has been varied from 8 to 15% in the H_2/Air mixtures investigated in this study. The impact of %mol.H_2 on flame speed in ENACCEF 2 is represented in Figure 4 (a). Every flame speed profile represented corresponds to an average operated on 3 runs conducted in the same conditions. One can see that mixtures with a hydrogen molar fraction of 8 and 10% correspond to quenched flames. Indeed, an extinction of the flame is always obtained at the end of the obstacles region (2.2 m). From 11 to 15% mol.H_2 the flame speed profiles present 4 steps of propagation as already describes in the previous section. It is noticeable that flame propagation speed increases with the molar fraction of hydrogen in the reactive mixture. As an example, the maximum flame speed vary from 433 to 604 m/s when %mol.H_2 increases from 11 to 15. For these hydrogen molar fractions, flames transit to the choking regime during the acceleration phase in the obstacles region. Furthermore, the shock propagation speed, and so the pressure and temperature behind the shock, increase with the molar fraction of hydrogen as it is represented in Figure 4 (b). It has to be noted that the last pressure and temperature indicated at 7.65 m of height correspond to the shock parameters behind the shock which has been reflected at the top part of the facility. It is also noticeable that the height for which occurs the first interaction between the flame and the reflected shock increases with %mol.H_2. It can be observed in Figure 4 (c) that the first interaction occurs at 4.95 m for11%H_2, 5.66 m for 13%H_2 and 6.22 m for 15%H_2. Note in Figure 4 (b) and Figure 4 (c) that curves represent singles runs and not averages on three runs.

4 Impact of temperature

The impact of temperature has been investigated in both homogeneous and heterogonous conditions. For homogeneous conditions, three temperatures were studied: 298, 363 and 413K. The impact of the initial temperature on speeds of flame and shock with a 13%H_2+87%Air reactive mixture is presented in Figure 5. First of all, one can notice that flame propagation regime is not modified when the initial temperature varies. However the height for which occurs the transition from subsonic to supersonic flame increases with the temperature. Indeed as it can be observed in Figure 5, this transition occurs at 1.43 m at 296 K, 2.12 m at 363 K and 2.16 m at 413 K. The maximum flame speed also increases with the temperature. At 296 K this speed is approximately 521 m/s, while at 363 and 413 K it is respectively 595 and 608 m/s. The height for which occurs the first interaction between the flame and the shock decreases with the temperature. Indeed in Figure 5 the sharp decrease of flame speed after the obstacles occurs at 4.69 m at 413 K, at 4.83 m at 363 K and at 5.53 m at 413 K. It is also interesting to note that during the first steps of acceleration up to the third obstacles, the flame velocity decreases with the temperature due to the density of the gases which decrease. Finally it appears in Figure 5 (b) that shock velocity is increasing with the temperature.

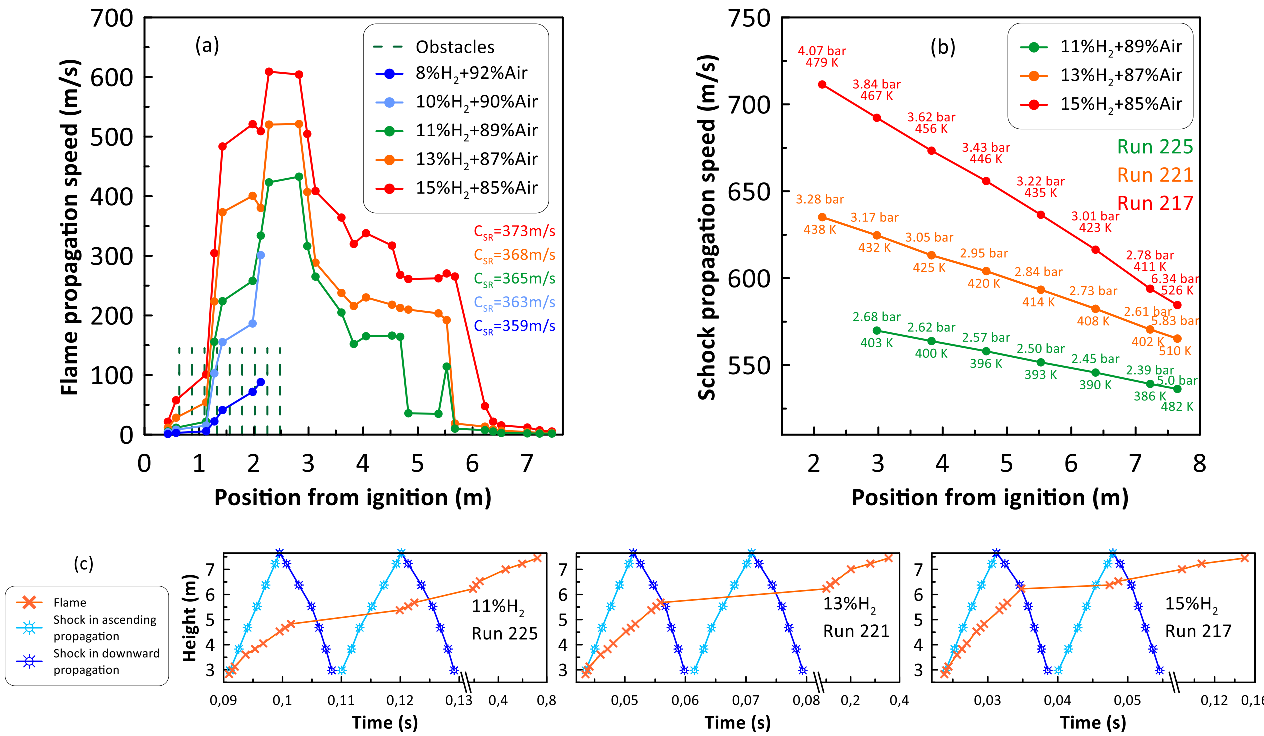

Figure 4. Impact of hydrogen molar fraction on flame propagation speed (a) shock propagation speed (b) and trajectories of flame and shock (c) in ENACCEF 2 (T_{ini}=298 K, P_{ini}=100 kPa)

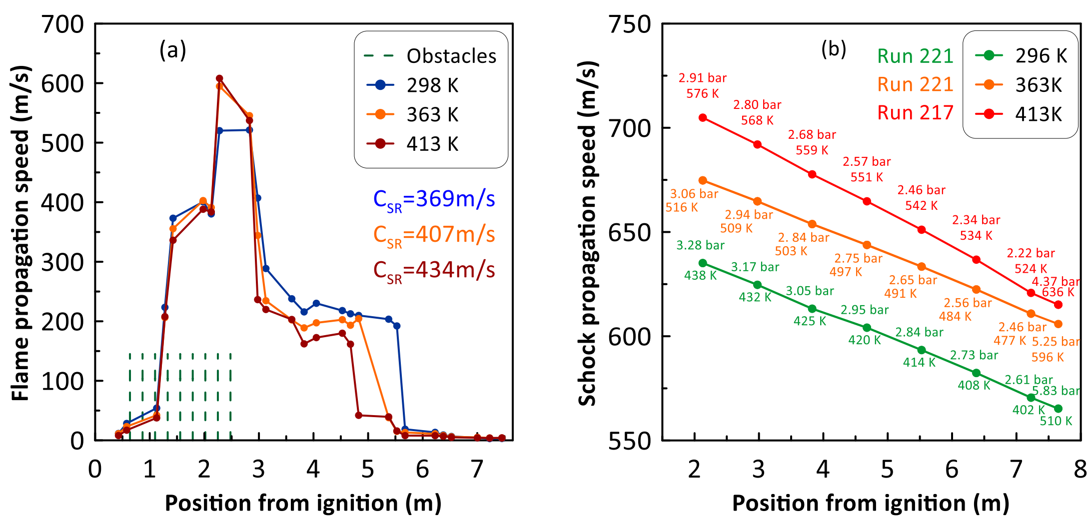

Figure 5. Flame speed profiles (a) and shock speed profiles (b) obtained in homogeneous temperatures in ENACCEF 2 (13%H_2+87%Air, P_{ini}=100 kPa)

In case of temperature gradient, temperature rising from 296 to 363 K in ENACCEF 2 has been investigated. Flame speed profiles in gradient and homogeneous conditions for a reactive mixture of 15%H_2+85%Air are compared in Figure 6. As one can see, these profiles are similar and do not present important differences. Indeed the first steps (0 to 2.5 m of height) and last steps (4 to 7.65 m of height) of flame propagation in gradient conditions are similar respectively to the first steps of propagation at 363 K and the last steps of propagation at 298 K.

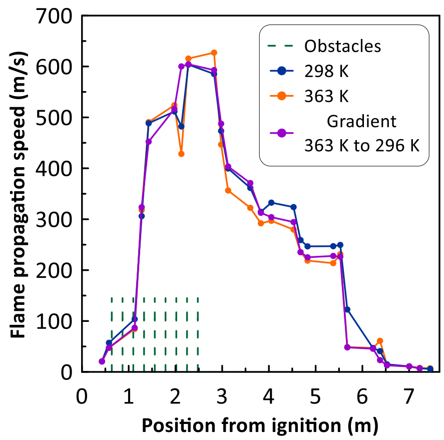

Figure 6. Comparison between flame speed profiles obtained in homogeneous and heterogeneous conditions of temperature in ENACCEF 2 (15%H_2+85%Air, P_{ini}=100 kPa)

4 Conclusion

H_2/Air flame propagation has been studied in a new facility (ENACCEF 2) to provide new data in confined area relevant to severe accident in PWR. Impact of hydrogen molar fraction was studied. It is established that the chocking regime is obtained from 11%mol.H_2. Below this molar fraction, only quenched flames are observed. The impact of initial temperature was also studied. In homogeneous conditions, it is demonstrated that increasing the temperature increase the maximum flame speed and decrease the height for which an interaction between the flame and the reflected shock occurs. In temperature gradient conditions (from 363 to 298 K), it is shown that the flame speed profile is similar to the one obtained in homogeneous temperature at 363 K during the first steps of propagation and similar to the one obtained in homogeneous temperature at 298 K during the last steps of propagation. In this study, experiments in positive gradient (298 to 363 K) were not conducted. The study will be completed in a near future. Furthermore, the impact of hydrogen concentration gradient on flame propagation in ENACCEF 2 will be also investigated.

References

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