Experimental study on turbulent flame speed of H_2-CO/air mixtures relevant to late phase accident scenario

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1 Introduction

During the late phase of an accident in a nuclear power plant, the interaction of corium with concrete leads to the release of H_2 and CO. The explosion of such a mixture would threaten the integrity of the containment. The assessment of the explosion risks is based on numerical simulations which must include the fuel characteristics. Bentaib et al. [1] showed that CFD codes, using turbulent flame models, were able to reproduce the maximum pressure generated by the combustion process, but have difficulties to well predict the flame propagation regimes and the rate of pressure increase. In order to improve and validate these codes, it is necessary to better characterize the transition between the laminar and the turbulent regime of the flame for a wide range of turbulence intensity. While the relationship between the propagation speed of a laminar flame front and the turbulence intensity is clearly defined, the acceleration mechanism of an expanding turbulent flame is more complex. In the framework of safety of explosions in nuclear power plants, several scaling laws for the normalized turbulent burning velocity have been obtained [2, 3, 4]. Nevertheless, these studies have identified a relationship between the velocity of the turbulent flame and the characteristics of laminar combustion only for H2/air mixtures. Studies devoted to the expansion of turbulent H2/CO/air flames [5, 6, 7, 8] remain quite rare. Most of them have been carried out for a relatively high equivalence ratio and in small vessels not corresponding to the conditions relevant for the late phase accident. In this context, the aim of this study is to characterize the turbulent flame propagation of H_2/CO mixtures in a turbulent spherical vessel in which a known and well-characterized turbulent intensity is created. The detailed experimental study was performed over a wide range of experimental conditions relevant to the late phase accident.

2 Experimental setup and methods

The experimental setup (Figure 1-a) consists of a stainless-steel spherical bomb (BS III) composed of two concentric spheres between which a heat transfer fluid can circulate allowing the regulation of the temperature inside the device. The outer sphere has an inner diameter of 640 mm and the inner vessel, corresponding to the spherical combustion chamber, an inner diameter of 563 mm to avoid perturbations due to the confinement. The setup is thermally isolated and designed to perform experiments for a maximum pressure of 200 bar and a maximum preheating temperature of 573 K. The enclosure is equipped with two pairs of diametrically opposed quartz windows of 200 mm in diameter. The turbulent flow is generated via 8 fans composed of 4 blades of 80 mm in diameter (Figure 1-b). The fans are mounted symmetrically around the circumference of the vessel deported of 83 mm from wall. The composition of the air and the fuel are respectively 20.9% O_2+79.1%N_2 and 50.03% H_2 + 49.97% CO. The composition of the introduced mixture is determined by the partial pressure method using a manometer MKS 690A Baratron (± 0.1 Torr). The initial temperature inside and on the wall of the combustion chamber is measured via two type K thermocouples (± 2 K). To ignite the mixture, an electric spark is generated by two 2mm diameter tungsten electrodes linked to a high voltage supply. The electrical spark signal is used to synchronize the temporal evolution of the flame with the pressure behavior. The pressure during the combustion is measured via a high frequency pressure transducer Kistler type 6001.

(a) (b) (c)

Figure 1: (a) View of the spherical bomb (BS III); (b) image of the fan used for the turbulent experiments.(c) Definition of the flame radius criteria for wrinkled flame.

The flame expansion is visualized via a Schlieren device using a 300 Watts Lot-Oriel xenon lamp. The Schlieren images are recorded with a high-speed camera Phatom V1610. The frame size and the exposure time are respectively fixed to 10 µs and 768 x 768 pixels². The edge of the flame is identified from a MATLAB image processing code and the area (A_f), included is this limit, is determined. The flame radius (R_f) is deduced from the total flame area as $R_f = \sqrt{A_f/\pi}$. For wrinkled flame, an average radius (R_{surf}) is calculated from an equivalent circle corresponding to the experimental zone as shown on Figure 1-c. Consequently, the laminar combustion speed (S_b) and the turbulent burning speed ($S_{b,T}$) are respectively derived from $S_b = dR_f/dt$ and $S_{b,T} = dR_{surf}/dt$. Finally, the unstretched velocity (S_b^0) was determined considering a non-linear variation of the flame speed with the stretch rate (κ) [9].

Five different fuel molar fractions were selected to be representative of late phase accident conditions: 11 to 15% of H_2/CO in air at $P_{ini} = 0.1\ MPa\ (\pm 0.4\ kPa)$ and $T_{ini} = 295\ K\ (\pm 2K)$. The distance between the electrodes was fixed to 1 mm. The ignition energy was measured for each test. The turbulent flow was fully characterized in previous works using Particles Imaging in non-reactive conditions [10] For each conditions, four rotational speeds were used: 0, 1000, 2000 and 3000 rpm corresponding respectively to turbulent root mean square velocities of $u' = 0\ m/s, 0.31\ m/s,\ 0.67 m/s, 1.05\ m/s$. Finally, the laminar combustion properties were calculated using the software COSILAB® [11].

3 Results and discussions

3.1 Combustion regimes and flame expansion

The study of laminar flames made it possible to determine the fundamental flame speeds (S_L^0) and the unburn Markstein lengths (L_u) corresponding to the five studied mixtures. Being at constant pressure and temperature, the flame thickness, the Zeldovich number and the Lewis number depend only on the composition of the mixture. The effective Lewis number (Le_{eff}) for the binary mixture H_2/CO is calculated from the study of [12]. The set of experimental conditions used in this study are reported in Table 1.

Table 1: Experimental conditions.

$xfuel$	$S_L^0\ (m.s^{-1})$	$L_u\ (mm)$	$\delta_{(gradT)_{max}}\ (mm)$	Le_{eff}	β	u'/S_L^0
0.15	0.156	-0.53	0.872	0.7528	8.690	1.98-6.73
0.14	0.112	-0.83	1.005	0.7542	8.934	2.75-9.32
0.13	0.081	-1.25	1.299	0.7569	10.05	3.82-12.9
0.12	0.053	-2.39	1.629	0.7571	11.14	6.41-21.7
0.11	0.029	-3.83	2.683	0.7552	13.69	10.4-35.5

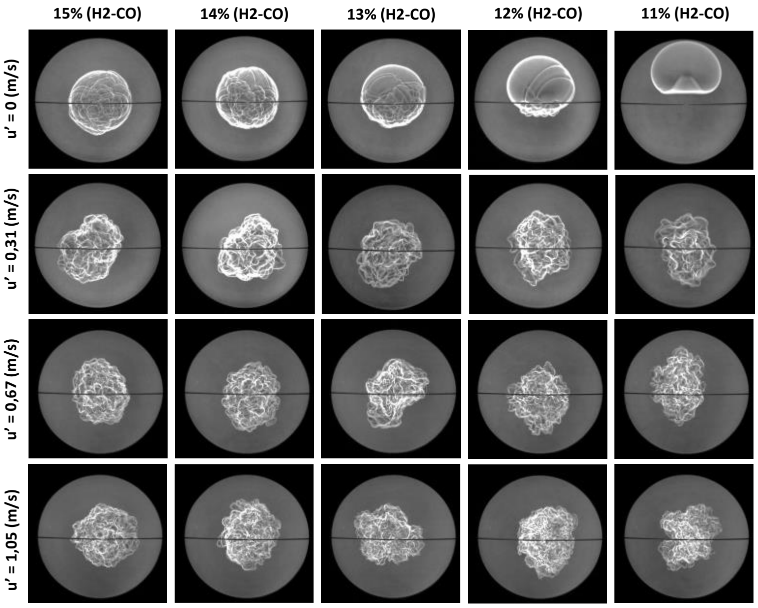


Figure 2: Flame visualizations for a mean radius of 50 mm.

Flame snapshots are presented in Figure 2. In the top line, flame visualizations obtained under non-turbulent conditions ($u' = 0$) are compared with turbulent conditions. For a large flame radius of 50 mm, the flame does not maintain a spherical geometry for all fuel content examined. For $x_{fuel} = 15, 14$ and 13%, the flame is wrinkled even for a non-turbulent regime. The flame front is affected by thermo-diffusive instabilities due to the high diffusivity of the fuel and the expansion of the burnt gases. For fuel molar fraction of 12% and 11%, the flame surface is mainly smooth and the flame propagates in the upward direction. For all mixtures, the increase of the turbulence level significantly modifies the flame structure. When u' is increased, one can see a change in flame morphology.

The turbulent combustion regimes were characterized using the Borghi diagram in Figure 3. In this classification, the different turbulent regimes are identified depending u'/S_L^0 versus $L_T/\delta_{(gradT)_{max}}$. The present study conditions cover the domain from ‘‘corrugated flames regime” to the ‘‘distributed reaction zone”. Most experiments are below the ‘‘distributed reaction zone”, delimited by the Damköhler number equal to 1. Only the leanest mixtures ($x_{fuel} = 12$ and 11%) are above or very close to this limit. These results indicate that the flames will certainly be heavily wrinkled.

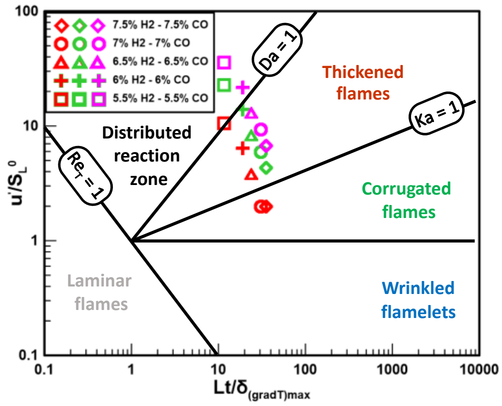
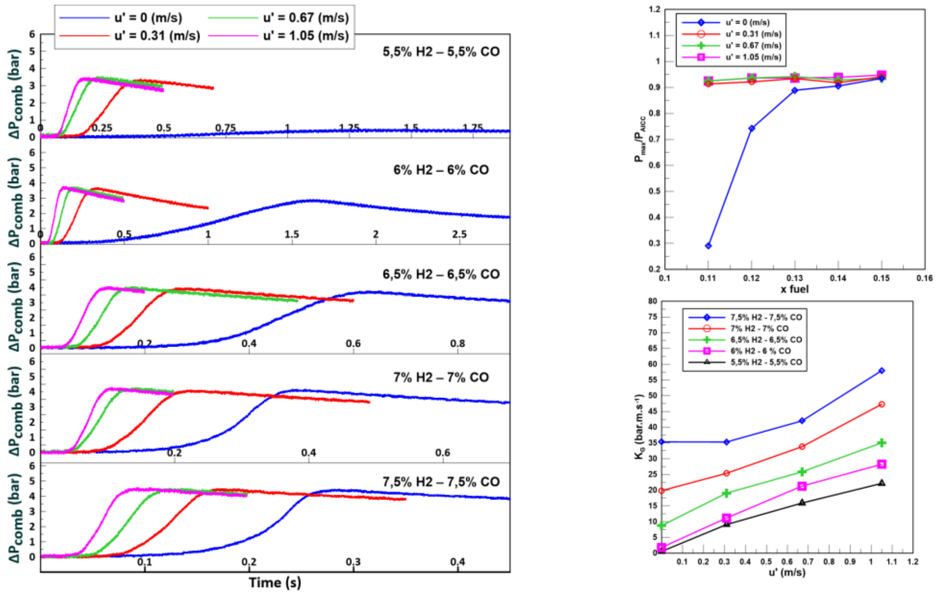


Figure 3: Experimental conditions reported on the Borghi diagram.

3.2 Combustion pressure and explosion index

The evolution of the overpressure (ΔP_{comb}) is shown in Figure 4-a. For all mixtures, the evolution of ΔP_{comb} is strongly affected by the presence of the initial turbulence. The maximum pressure (P_{max}) reached does not vary with the turbulence level when the fuel molar fraction varies from 15% to 11 %. The time to reach the P_{max} is reduced with increasing u' and this time interval decreases as the fuel molar fraction increases. P_{max} is compared to the pressure obtained for a complete and adiabatic combustion (P_{AICC}), estimated using COSILAB® [11], in Figure 4-b. In presence of initial turbulence, the ratio P_{max}/P_{AICC} remains around 93% over the whole range of tested conditions. The combustion is complete for all fuel conditions. On the contrary, P_{max}/P_{AICC} decreases with the decrease of $xfuel$ for the non-turbulent condition.



(b)

(c)

(a)

Figure 4: (a) Evolution of the overpressure, ΔP_{comb}, inside the vessel during the combustion of H2-CO/air mixtures initially at 1,013 bar and 295 K. (b) Evolution of the ratio P_{max}/P_{AICC} versus the fuel molar fraction in the air. (c) Evolution the deflagration index versus the fuel molar fraction in the air.

For x_{fuel} = 13% to 11%, the combustion is incomplete. From the determination of the maximum rate of pressure increase $(dP/dt)_{max}$, the deflagration index (K_G) can be deduced $K_G = (dP/dt)_{max} \cdot (V_{vessel})^{1/3}$. This index is a good indicator of the combustion intensity. K_G increases with x_{fuel} and quasi-linearly with u' (Figure 4-c). From a classification [13], for 0 < K_G < 200, the explosion intensity is characterized as low to moderate.

3.3 Turbulent flame speed

Figure 5 shows the evolution of the turbulent burning speed ($S_{b,T}$) normalized by the unstretched burning speed (S_b^0) versus the radius of the flame. The ratio $S_{b,T}/S_b^0$ increases with u' and with decreasing the fuel mole fraction over the entire radius range. These results show that the initial turbulence has a greater influence on the leanest conditions. The experimental data are used to verify the applicability of the combustion model to turbulent expanding spherical flames. The result are compared with the widely used correlation of Zimont [2] and of Goulier et al [3], developed for H2/air mixtures, in Figure 5. The Zimont correlation [2] fails to predict the ratio $S_{b,T}/S_b^0$ profile versus the flame radius and overpredicts the flame speed because it does not consider the size of the flame. The correlation proposed by Goulier et al. [3] takes into account both the flame radius and the Lewis number. For $u' = 0.31\ m/s$. this correlation is able to well predict the profile of the $S_{b,T}/S_b^0$ ratio over the entire domain of flame radius for 13% to 15% of fuel. However, a slight deviation is observed versus the flame radius for 11 and 12% of fuel. As u' increases, a difference is observed. From 13% to 11%, this difference becomes very important. In this case the correlation proposed by Goulier et al. is no longer valid.

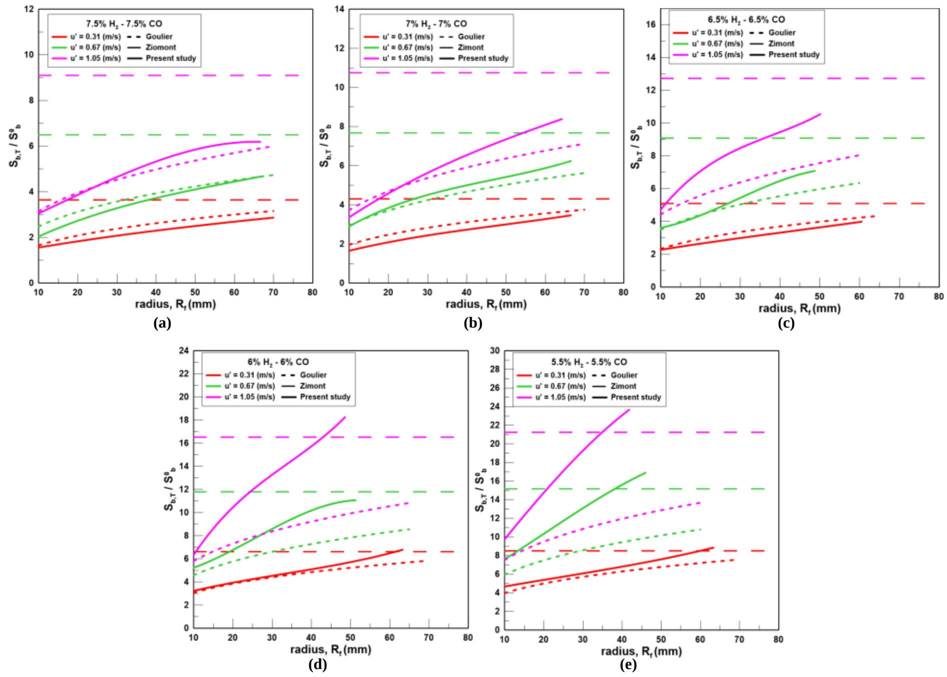


Figure 5: Comparison of the normalized burning speed versus the flame radius obtained in the present study with the correlation proposed by Zimont [2] and Goulier [3] for different fuel molar fraction: (a) 15%, (b) 14%, (c) 13%, (d) 12% and (e) 11% of H_2/CO.

4 Conclusions

This study presented new results concerning turbulent flame speed and combustion overpressure of lean H_2/CO/air mixtures obtained in a spherical vessel (BS-III) at CNRS-ICARE. The experiments were performed for a fuel molar fraction of a binary H_2/CO (50/50) in air in a range between 11 and 15%. The influence of the turbulence intensity, fixed at 0.31, 0.67 and 1.05m/s, on the propagation speed and the combustion pressure has been assessed. Under non-turbulent conditions, the combustion is incomplete for the leanest mixtures. On the contrary, in the presence of initial turbulence, the combustion is complete and flame extinction does not occur, even locally as expected for u'/S_L^0 values above 20. Finally, the experimental results were compared to the correlations of Zimont and Goulier et al. The correlation proposed by Zimont failed to describe the turbulent flame speed. The correlation of Goulier et al has proven to be more appropriate for low turbulent intensities and for larger values of $xfuel$. However, when u' increases and $xfuel$ decreases this result is no longer valid. Further correlation should be developed to consider H_2/CO mixtures for the validation of CFD codes.

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