FLAME FOLDING AND WRINKLING FACTOR FOR 2D AND 3D HYDROGEN-AIR FLAMES

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Abstract

An experimental study and theoretical analysis of laminar flame propagation in spherical 3D- and planar 2D-geometries for hydrogen-air mixtures was carried out in order to investigate an effect of flame instability, a flame structure and a mechanism of initial quasi-laminar flame acceleration prior turbulent flame acceleration and DDT. The theory of laminar flames and theoretical analysis based on solution of Sivashinsky-Michelson equation was performed to explain the experimental results. It was theoretically found, that the burning velocity increased by the factor of 1.2-1.6 due to the flame instability. This value was found to be exactly proportional to the flame area amplification and well confirmed by current experimental data in 2D- and 3D-geometries. Such a flame wrinkling leads to primary flame acceleration remaining the flame of laminar structure in general.

Introduction

Promptly after ignition, the surface of the flame wrinkles due to the Darrieus–Landau and the thermo-diffusive instability [1, 2]. A 2D - planar geometry has an advantage that independent of the boundary layer effect in transversal direction the structure of the flame instability in a radial direction will be freely developed and clearly distinguished. In 3D-geometry, internal flame structure is not visible from outside even with a schlieren system. In order to measure the wrinkling of the flame surface a schlieren imaging system and a laser tomography can be used.

Theory

The enormous potential of Sivashinsky equation [3] for the reproduction and modeling of the different flames instabilities has been demonstrated in [4-5]. The influence of different instabilities as Darrieus-Landau, thermo-diffusive and Rayleigh-Taylor on flame shape and dynamics of the flame for different hydrogen-air mixture has been investigated in [6] utilizing the Michelson method [4] and taking into account Lewis number Le and Zeldovich number β. The surface (Fig.1) obtained by numerical integration of Sivashinsky equation shows the dynamics of flame profile as heat map in which the local position of the flame relative to its average position is represented.

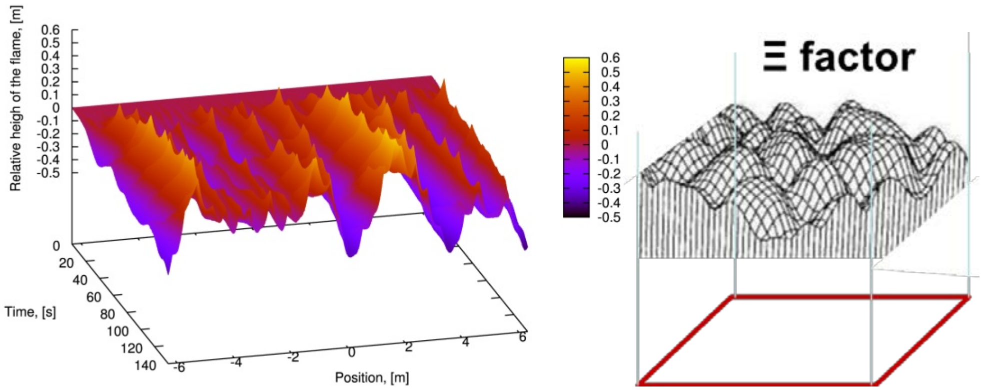

Figure 1. Results of the integration of the one dimensional Sivashinsky equation. Color scale is the position of the flame relative to the average position.

The ratio of real flame surface to planar one is defined by wrinkling factor Ξ. Effective flame velocity S_e accounts the enhancement wrinkling factor Ξ due to flame instability as follows $S_e = \Xi \cdot S_L$. So that the wrinkling factor Ξ is one of the major properties of flame behavior, responsible for potential flame acceleration. The wrinkling factors obtained in [6] by solving Sivashinsky equation for different hydrogen-air mixtures is very close to the ratio S_e/S_L (Table 1).

Table 1. Example of a table.

$[H_2]$ Vol. %	Ξ	S_L [m/s]	S_e [m/s]	S_e/S_L
8	1.34	0.06	0.09	1.49
9	1.33	0.08	0.12	1.50
10	1.34	0.11	0.17	1.58
12	1.34	0.19	0.28	1.48
15	1.38	0.34	0.54	1.58
20	1.46	0.9	1.43	1.59
25	1.52	1.6	2.95	1.84
30	1.49	2.19	3.84	1.75
40	1.42	2.88	4.87	1.69
50	1.4	2.59	4.23	1.63
60	1.38	1.86	2.91	1.56

Dynamics of the wrinkling factor demonstrated two different behaviors [6]. For very lean mixtures, up to 12 % vol H_2 an initial plateau exists, representing a regime in which the thermo-diffusive instability accounts for the most of the excess of surface. This regime is followed by a more or less fast transition that culminates in a regime in which larger surface wrinkling factor due to Darrieus-Landau instability is reached. For richer mixtures above 12 % vol H_2 the transition to saturation is fast and has no visible transient to the final stage led by Darrieus-Landau instability. Another interesting fact is the almost similar value Ξ = (1.33÷1.52) that the surface wrinkling factor finally reaches for all the concentrations of H_2 (Table 1).

Objectives

The main purpose of the current work is to experimentally investigate the effect of instabilities on the hydrogen flame behavior in a planar 2D- and a spherical 3D-geometry. The main interest of this work is to investigate how the flame instability affects dynamics of the flame propagation and whether the flame acceleration would occur in such configurations leading to the transition from deflagration to detonation (DDT).

Experimental details

2D-experiments were performed a thin layer of H_2 – air mixtures with a center ignition. The experimental facility consists of two glass plates assembly, hydrogen-air intake and exhaust system, an ignition system, an optical schlieren system combined with a high speed camera, data acquisition and control system.
The glass plate assembly was made of two transparent Quartz plates with spacers placed in between to keep parallel gaps of 2, 4 and 6 mm. Experiments were carried out in a squared frame with dimensions of 500 x 500 mm. The mixture within the glass plate assembly was ignited in the center using a spark electrode igniter. The exposure time of a test mixture was set about 30s prior ignition to eliminate the effect of initial turbulent motion. The spark energy was less than 10 mJ. Hydrogen-air mixtures in the range 10-50% H_2 were investigated in the current work. Mass flow rate controllers were used to inject premixed composition directly into the gap. The mixture was isolated around the peripheral sides by a weak plastic foil (~5 mkm). The weakness of the foil provides simultaneous opening to the ambient atmosphere at the perimeter to keep constant combustion pressure of 1 bar. All experiments were performed at ambient conditions of 1 bar and 293 K.

Experimental results and discussions

Figure 2 shows a sequence of flame contours at different times for a very lean mixture of 14%H2 in air. The thermo-diffusion and Darrieus–Landau instabilities lead to the development of a double-mode cellular structure of the flame surface. The primary thermo-diffusion instability appears almost immediately after the ignition, leading to quite random, relatively small-size mode of cellular structure. Then, the large-size mode of very regular cellular structure due to Darrieus–Landau instability develops with a growing cell size similar to the flower petals. Since the Markstein number becomes positive for hydrogen-air mixtures above 20%H2 it changes the sensitivity of the flame to thermo-diffusion instability. In Fig. 3, very smooth flame surface can be seen for mixtures with 30 and 50% H2 in air at the initial stage of the process. Only after a flame radius of the order of 10-15 cm, the cellularity of the flame surface appears due to Landau-Darrieus instability. The wrinkling factor $\Xi = P/P_m$ (Fig.2, right) was evaluated as a ratio of real flame area A (proportional to the perimeter P) to the mean value $P_m = 2(\pi \cdot A)^{1/2}$. The maximum value $\Xi_{max} = 1.7$ is very close to theoretical one for lean mixtures. Very close values in the range 1.4-1.7 were found for all tested lean hydrogen-air mixtures from 10 to 20%H2. For mixtures with positive Markstein number, the saturated value of wrinkling factor has not reached because of limited space of the system.

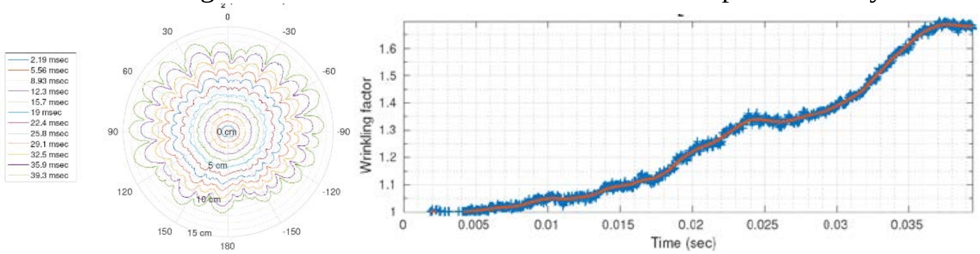

Figure 2. Flame dynamics and wrinkling factor for lean H_2 – air mixture (14% H_2 in air) in a 6-mm gap layer

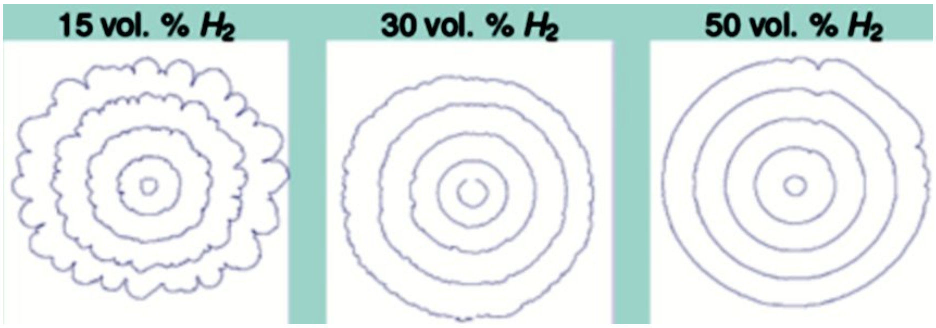

Figure 3. Flame propagation for lean H_2 – air mixture (15, 30 and 50% H_2 in air) in a 6-mm gap layer

Very similar flame structure for 3D-geometry was experimentally obtained using laser tomography [7]. The winkled flame structure, amplification (wrinkling) factor of the surface, AF_{Surf} and the speed, AF_{Speed}, from paper [7] are plotted as a function of the radius of the flame for four different molar fraction of hydrogen in air in Figure 4. The maximum values for flame surface wrinkling factor AF_{Surf} =1.4-1.6 is very close to that for 2D-geometry (ses Fig. 2). Approaching to stoichiometric mixture, the surface wrinkling factor establishes in the range 1.2-1.4.
The flame front velocity was calculated by taking the difference between the instantaneous radius of the flame front, r_f and igniter position, r_o divided by the actual time difference. The stretch-free laminar burning velocity were obtained by linear extrapolation of a plot of the laminar burning velocity S_L as a function of the stretch rate K (Fig. 5). The laminar burning velocity S_L is first calculated by dividing the flame front velocity S_F by the expansion factor σ and stretch rate K.

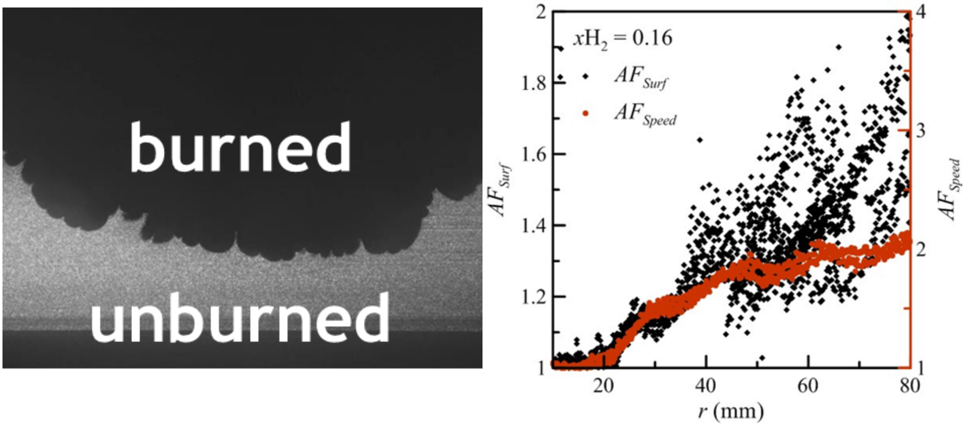

Figure 4. Laminar burning velocity as a function of stretch rate K for H_2 – air mixtures: 2D case current work (left); 3D case Chaumeix et al. [7] (left).

Assuming a linear correlation, the influence of the flame front stretch on the laminar flame speed can be specified by Markstein length L_M:

$$S_L(K) = S_{L,s} - L_M \cdot K \tag{1}$$

where $S_L = S_f/\sigma$, and $S_{L,s}$ are the stretched and free of stretch laminar flame velocities, A is the visible flame area for flame radius r_f and a layer thickness h, $A = 2\pi r_f h$, K is the stretch rate calculated for 2D-planar case as follows

$$K = \frac{1}{A}\frac{dA}{dt} = \frac{1}{r_f}\frac{dr_f}{dt} \tag{2}$$

The stretch rate in a planar geometry (Eq. 2) is two times smaller compared to a spherical 3D-geometry [7].

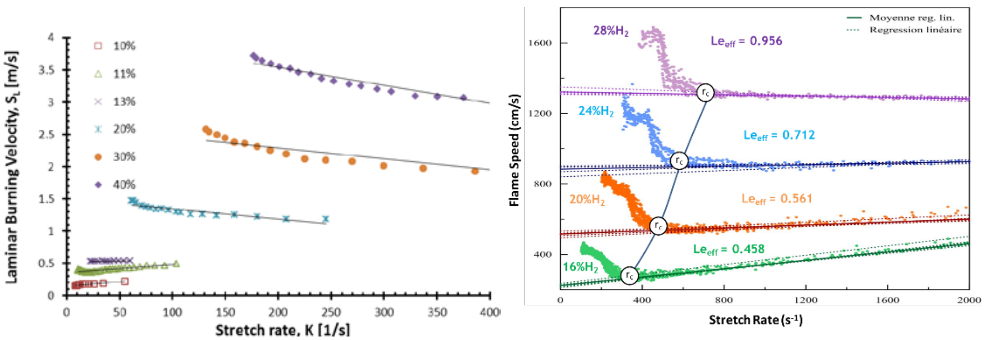

Figure 5. Laminar burning velocity as a function of stretch rate K for H_2 – air mixtures: 2D case current work (left); 3D case Chaumeix et al. [7] (left).

The linear extrapolation of the curve (Fig. 5) represents the stretch-free laminar burning velocity $S_{L,s}$ as the y-intercept of the line fit, whereas the slope of the line gives the Markstein length, L_m. Figure 5 (left) shows the relationship between laminar burning velocity S_L and the stretch rate K for different H_2 – air mixtures for a peripherally open planar configuration at a gap size 6 mm. Right plot shows the same dependence for 3D case [7]. A critical flame radius r_c in Fig. r when the flame velocity abruptly increases corresponds to the moment when the Darrieus–Landau instability appears producing well developed regular cellular structure.

Conclusions

Hydrogen flame behavior in two-dimensional geometry was experimentally investigated. Hydrogen combustions of H2 – air mixtures were carried out within the gap between two transparent quartz plates spaced by 2, 4 and 6 mm.
To analyze the influence of flame instabilities, the stretch-free laminar burning velocity of the flame and Markstein length were determined via post-processing of optical measurement. Negative Markstein lengths were obtained for lean H2 – air mixtures (< 15% H2). The results also show that the laminar burning velocity strongly depends on H2 concentration and gap size.
The appearance of the cellular structure for H2 – air mixtures was found as a result of two main intrinsic instabilities of the flame, thermal – diffusive instability and hydrodynamic instability, namely Landau – Darrieus instability. Wrinkling of the flame due to the flame instability and enhanced flame area result in a flame velocity amplification factor Ξ = 1.2-1.5, which is the same as found by derivation of the Sivashinsky eqation in [6]

References

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