# Experiments on Flame Propagation Regimes in a Thin Layer Geometry

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## 1 Introduction

Flame propagation regimes, the mechanisms of flame acceleration and DDT transition in different geometries were very recently investigated. An influence of a specific layer geometry was investigated in a thin 2D-layer [1-2]. The layer thickness was changed from 2 to 6 mm in between two squared plates of different size 20x20 cm$^2$ and 50x50 cm$^2$ and 1x1 m$^2$. Different hydrogen-air and hydrogen-oxygen mixtures were tested with respect to investigate the flame dynamics and to evaluate the flame instability characteristics. The thermal-diffusion and Landau-Darrieus instabilities were leading to the development of a double-mode cellular structure of the flame front. The primary thermal-diffusion instability appears almost immediately after the ignition, leading to quite uniform, relatively small-size mode of cellular structure. Then, a large-size mode of cellular structure due to Landau-Darrieus instability develops with a growing cell size similar to the flower petals. In total, the planar flame finally accelerates 1.4 times compared to the laminar flame speed only due to the flame wrinkling and folding [2-4].

Another mechanism of laminar flame acceleration is so called "finger" flame behavior, when the flame dynamics is governed by the geometry factor or increasing flame area with a distance. As the gap size decreases, the specific area of the flame gets higher, causing the burning velocity to increase for 2D-geometry as follows [1-2]

$$S_f = \frac{dx}{dt} = \frac{A}{A_0}\sigma S_L = \left(1 + \frac{x}{h}\right)\sigma S_L \tag{1}$$

where $A$ is the visible flame area which is proportional to the flame radius $x$ in a layer with a constant gap $h$; $A_0$ is the initial flame area; $\sigma=\rho_u/\rho_b$ is the expansion ratio of combustion products compared to the unreacted mixture; $S_L$ is the fundamental laminar flame speed. This means that for "finger" flames in a layer geometry, the visible flame velocity is inversely proportional to the gap size $h$. In general, such a mechanism does not allow to exceed the speed of sound for flame propagation velocity.

Then, additional mechanisms of flame acceleration like shear layer or boundary layer producing turbulent flow ahead the flame might also be involved into the further flame acceleration to sonic velocity and even to detonation. It was found the minimum size or so called run-up-distance to DDT should not be less than 20 cm from ignition point [1-2]. Significant effect of a shear layer at the interface between the test mixture and surrounding atmosphere on DDT was discovered in the tests. Additionally, the run up distance to detonation might be reduced due to the turbulence produced by rough side walls or due to obstructions.

The main goal is detail measurement of $H_2$/air combustion behavior including flame acceleration (FA) and DDT in a closed layer geometry in order to provide experimental data for numerical code validation for combustion processes in a layer of hydrogen–air mixtures. Critical conditions for different flame propagation regimes with respect to the safety depending on channel gaps and obstructions are investigated.

## 2 Experimental Details

A series of hydrogen combustion and detonation experiments was done in a layer geometry to model an enclosure with a thin gap between two plates. The facility was vertically installed a front of reflecting screen. The relative position of light source, high speed camera (Fastcam SA1.1, Photron), test facility and reflecting screen should provide required distances for optical system to get proper quality of schlieren images

The experimental facility itself consists of a rectangular channel with the inner dimensions of 900x200x (1-10) mm³ (LxWxh), which is made of PVC frames to fix the gap *h* = (1, 2, 4, 6, 8, 10) mm between two Plexiglas windows and to keep isolated the test mixture from ambient atmosphere (Fig. 1). Principal positions of igniter (red cross), three pressure sensors (blue diamonds) and gas inlet (black ring, top left) and outlet (black ring, bottom right) are shown in Fig. 1. Wooden profiles were used as flanges to fix together all elements of the assembly by 24 metal C-clamps. Two Plexiglas windows of 12 mm thickness were used as side walls. They played a role of transparent windows for optical access as well. Another important reason was the possibility to mount pressure sensors and a spark plug directly to the windows.

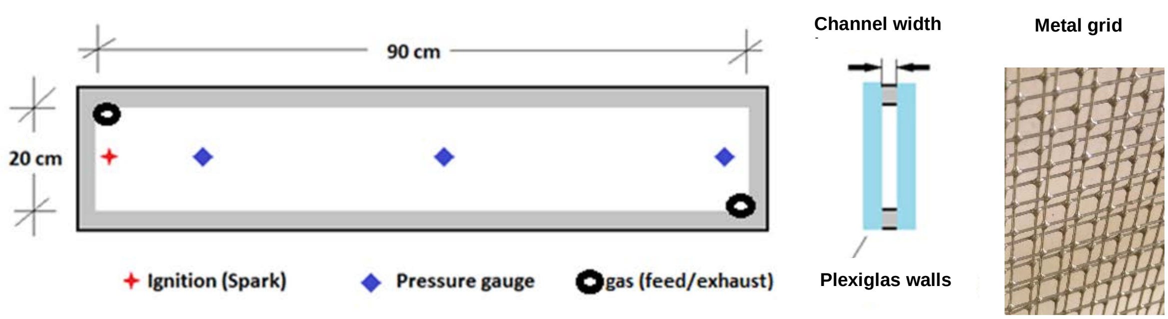


Figure 1. Scheme of the channel with narrow gap. Metal grid consists of 2 layers of metal net 6.5x6.5x0.6 mm.

As discussed in introduction, the presence of roughness promotes the flame acceleration and reduces the run-up-distance to fast sonic flame or even to detonation. To do that, one or two layers of fine grid (size 6.5 mm x 0.6 mm) were placed inside the channel. The efficient blockage ratio depending on gap size changes from BR = 0.6 for 1- and 2-mm channels to BR=0.12 for 10-mm channel (Table 1). Another variable was to change the blockage by filling entire gap with a metal grid (100%), to fill only a quarter of the channel (25%) or to keep the channel free of any obstructions (0% - smooth channel).

Flame propagation of hydrogen combustion was investigated for stoichiometric $H_2$ – air mixtures. Mass flow rate controllers were used to inject premixed composition directly into the gap. The test mixture was injected from the top by replacing air through the bottom outlet lines until the exhausted gas becomes the same as injected mixture. All experiments were performed at ambient conditions of 1 bar and 293 K. The mixture within the glass plate assembly was ignited in the centerline (Ign. A) or in the corner (Ign. B) using a spark igniter (Fig. 1).

Table 1: Blockage ratio of channels with metal grid

| Channel width, mm | 1 | 2 | 4 | 6 | 8 | 10 |
|---|---|---|---|---|---|---|
| Blockage ratio | 0.6 | 0.6 | 0.3 | 0.2 | 0.15 | 0.12 |
| Note | 1 layer | 2 layers | 2 layers | 2 layers | 2 layers | 2 layers |

## 3 Experimental Results and Analysis

69 tests have been processed to extract characteristic velocity and maximum combustion pressure. Figure 2 shows two examples of slow and fast (detonation) flame propagation regimes. Slow subsonic deflagration was more typical for smooth channel (0% blockage). The flame accelerates due to the flame instability and turbulent flow ahead the flame, see Fig. 2 (left). The visible flame velocity never exceeds the speed of sound. Fast flame propagation regimes as sonic flame or detonation mainly occurred in fully obstructed channel (100% blockage). The cellular structure of detonation can be resolved in Fig. 2 (right).

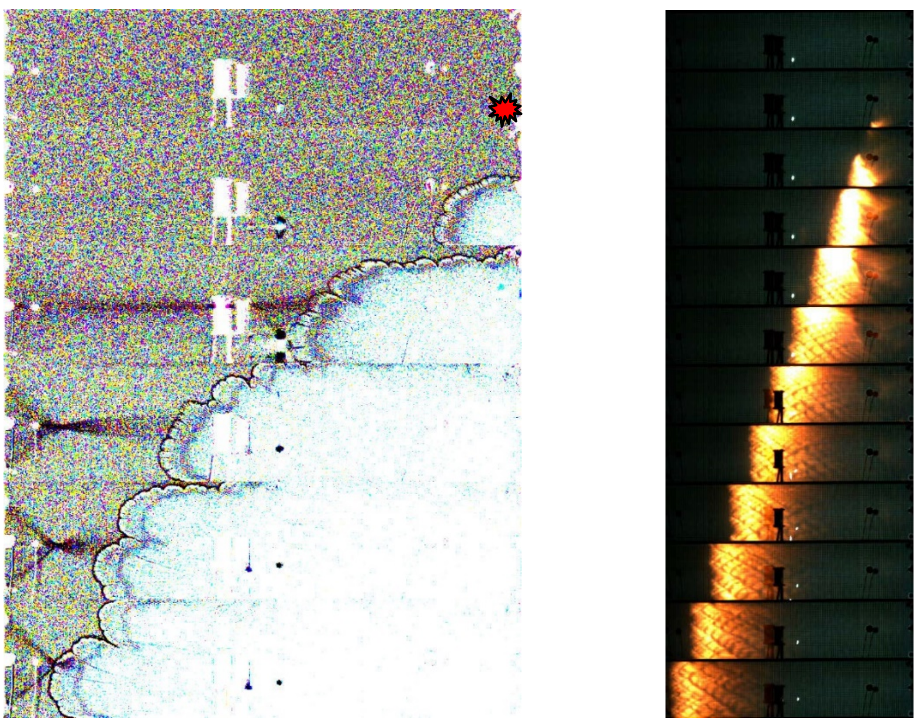

Figure 2. Slow (left, 0% blocked, 3000 fps) and fast-detonation (right, 100% blocked, 20000 fps, time step 0.05 ms) flame propagation regimes for 30 % H2 in air in a 6-mm channel

Dynamics of flame propagation were obtained from image processing of high speed movies and maximum combustion pressure for different blockage and layer thickness. The influence of layer thickness on combustion behavior was investigated for fixed blockage of the channel. For smooth channel the velocity never exceeds 80 m/s. It increases a bit with a layer thickness increase but never approaches to the speed of sound (Fig. 3). Maximum combustion pressure for smooth channel (0% blockage) changes in the range 1-2 bar and agrees well with characteristic velocity less than speed of sound (Fig. 4).

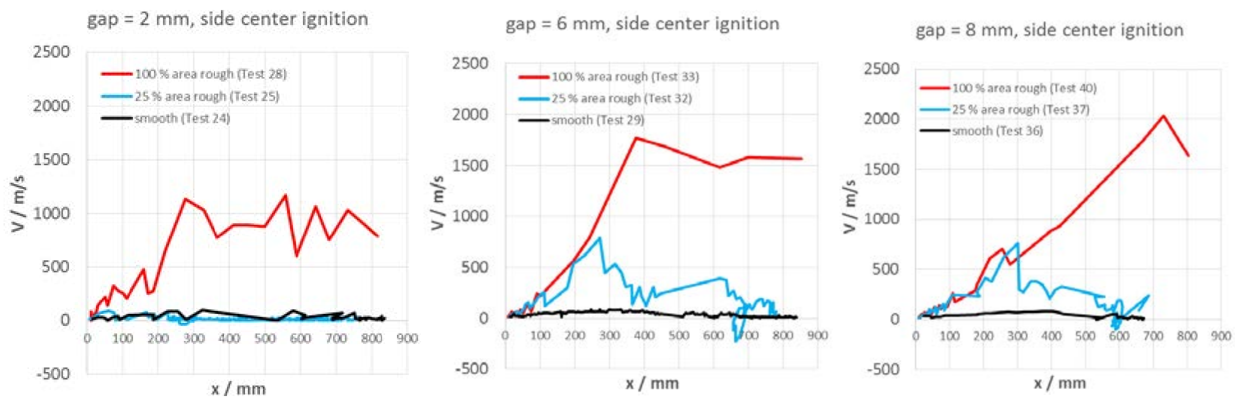


Figure 3. Dependencies of local flame propagation velocity for 2, 6 and 8-mm gap vs. distance obtained by image processing.

The blockage of 25% leads to more efficient initial flame acceleration after ignition. The flame accelerates until the channel is blocked, then velocity decays to the level of <80 m/s typical for smooth channel. For the layer thickness > 4 mm, the local velocity may reach speed of sound or even higher values in the range of 1000-1500 m/s but detonation never occurs for 25% blockage. For thinner layers the velocity never exceeds 80 m/s. Maximum combustion pressure agrees well with dynamics of flame propagation for 25% blockage. Since the local velocity reaches 1000-1500 m/s, the maximum combustion pressure in these cases also increases to 3-4 bar. For the layers thinner than 4 mm, the maximum combustion pressure never exceeds the level of 0.5 bar (Fig. 4).

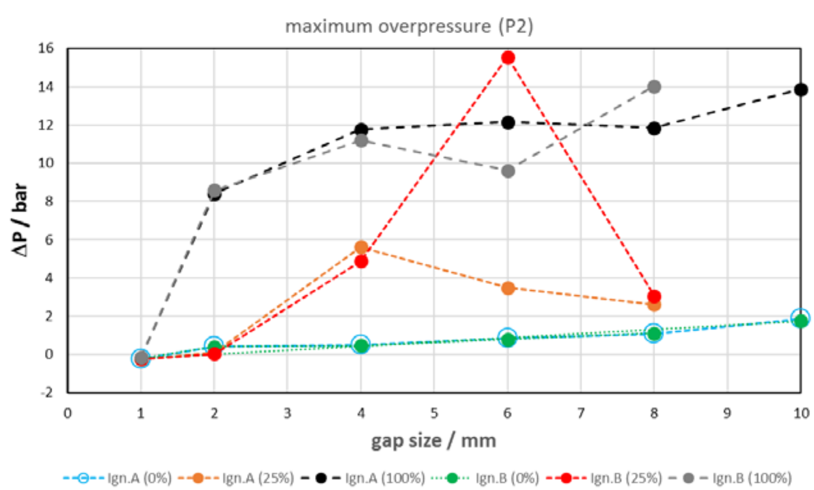


Figure 4. Dependencies of maximum overpressure vs. gap size obtained by image processing.

The strongest combustion regimes is realized for 100% blockage. In all cases with a layer thickness >4 mm the detonation of stoichiometric hydrogen-air mixture with corresponding maximum pressure 12-16 bar is occurred (Fig. 4). For 2 mm layer thickness, sonic flame propagation is usually observed with a velocity

~1000 m/s and corresponding pressure 7-8 bar. For 1 mm layer thickness only slow subsonic flame or flame extinction occurs due to energy losses and steam condensation (Fig. 5). Due to the strong heat losses in a narrow channel and an additional influence of metal grid the global flame extinction occurred near the center of the channel. As longer the flame propagates, the more heat losses leading to steam condensation and loss of overpressure. Near mid of the channel, the flame finally stops propagating due to global extinction.

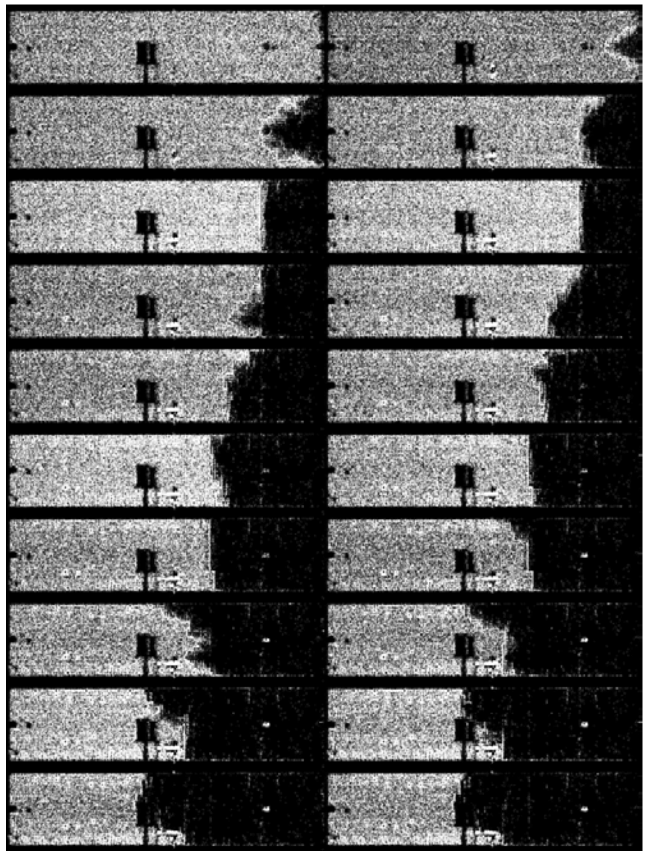

Figure 5. Global flame extinction: 1-mm layer, 100% blockage, Ign. A, 3000 fps (every 25$^{th}$ frame).

Six categories of flame propagation were classified, based on experimental data analysis. The main criteria to choose the category were the maximum combustion pressure and the maximum flame propagation velocity relatively speed of sound. Another criterion was the flame instability and heat losses due to steam condensation leading to local extinction in narrow channels even for stoichiometric hydrogen-air. In some experiments a transient regime may occur. For instance, rather high local pressure of 10 bar occurred but it doesn't lead to steady detonation because of limited width of the channel compared to detonation cell size.

a) Non-ignition

b) Ignition & local extinction

c) Ignition & slow deflagration

d) Ignition & fast deflagration

e) Ignition & detonation

f) Ignition & local explosion

Table 2: Diagram of state of combustion regimes

| Layer thickness / Geometry | 1-mm | 2-mm | 4-mm | 6-mm | 8-mm | 10-mm |
|---|---|---|---|---|---|---|
| BR=0 | c | c | c | c | c | c |
| BR=25% | c | c | d/c | f | d/c | - |
| BR = 100% | b | d | f | e | e | e |

All the data on flame propagation regimes based on velocity and pressure measurements were put in Table 2. The safety domain with lower maximum combustion pressure and flame velocity is colored in green and blue.

## 4 Conclusions

The experiments on different combustion regimes for stoichiometric H2/air mixture were performed in a closed rectangular chamber with dimensions of 20 x 90 x h $cm^3$, where *h* is the gap size (*h* = 1, 2, 4, 6, 8, 10 mm).

Three different layer geometries were used: (1) a smooth channel without obstructions; (2) the channel with a metal grid filled 25% of space and (3) 100% of channel space filled with a metal grid.

Critical conditions for five different flame propagation regimes as function of the layer thickness and a presence of obstructions were evaluated from experimental data analysis.

It was found that in a smooth channel, without obstructions, the flame is not available to accelerate to sonic velocity and to detonation. The only metal grid may lead to the efficient flame acceleration to speed of sound and DDT in a channel thicker than 4 mm.

In a 1 mm channel with 100% filled with a metal grid, the strong effect of steam condensation, leading to local flame extinction was discovered.

## References

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