

Experimental study of the initial flame propagation of premixed H₂-air explosion in a channel.

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1 Introduction

This paper presents results from experiments on flame propagation in inhomogeneous and homogeneous hydrogen-air mixtures at 1 atm in a channel. The objective of the present work is to study the initial phase of the flame propagation and to determine the onset of flame instability (i.e. cellularity). Previously Sommersel et al. [1] have done experiments with ignition of inhomogeneous hydrogen-air clouds in the same set-up. They found that the hydrogen-air cloud behaves as a gravity current and the flow appears to be well described by Froude scaling.

When a hydrogen-air cloud is ignited by a spark the flame starts develop as a spherical flame, which becomes hemispherical when the flame reaches the wall. As the flame continues expanding the cellular instability appears on the flame surface. The cellular instability is initially suppressed by the strong curvature-induced stretch associated with the corresponding small flame radius. However as the flame expands further the stretch intensity get smaller. A state is reached at which cell development can no longer be suppressed and consequently cells will appear almost instantaneously over the entire flame surface. This state depends on the combined influences of the hydrodynamic and diffusion-thermal effects. The flame stretch rate, K , defines flame stretch as the rate of change of a flame surface element of area A , which can be simplified for the case of unconstrained spherical flames propagating outward at constant pressure from a point ignition source [2,3]:

$$K = \frac{2}{r_f} \left(\frac{dr_f}{dt} \right) \quad (1)$$

On the right hand side of the eq. 1, the term inside the parenthesis is the flame speed, also known as absolute speed (S_a). r_f is the flame radius. Addabbo et al. [3] and Bechtold and Matalon [4] successfully analysed the transition to cellularity in expanding spherical flames. They presented an explicit expression for the state of transition as represented by a critical Peclet number, Pe_c . eq. 2 shows the relation between Pe_c and the flame radius at transition, R_c , scaled by the laminar flame thickness of the mixture, δ_l .

$$Pe_c = \frac{R_c}{\delta_l} \quad (2)$$

This critical Peclet number is a function of concentration of the hydrogen-air mixture. Jomaas et al [5] used the critical Peclet number in their comprehensive study on the onset of instability of the positively stretched, outwardly propagating spherical flame in hydrogen-air mixtures at 5 to 20 bar. The flame instability increases the burning rate and the flame speed. Our study includes flame propagation and onset of flame instability in hydrogen-air mixtures at atmospheric pressure.

2 Experimental Setup

The experimental setup for the inhomogeneous explosion experiments consisted of a horizontal square steel channel, 1.7 m long, 0.1 m wide and 0.1 m high, as shown in Figure 1(a). The sidewalls were transparent and made out of glass. The channel was open in one end and closed in the other. The hydrogen gas was injected into the channel through a vertical 4 mm ID steel tube. The exit of the 4 mm tube was positioned 50 mm into the channel at the centreline and 0.1 m from the closed end. The hydrogen jet velocity was 26 m/s - 91 m/s. The hydrogen-air cloud expanded as a gravity current in the upper part of the channel. The ignition source was placed 0.5 m from the closed end at the top centreline on the top and ignition was continuously on. Thus when the flammable gas mixture reached the ignition source it instantly ignited. Schlieren technique was applied to capture the flame propagation. The high speed camera was a Photron Ultima APX-RS. The ignition system was a spark with a Siemens ZM 20/10 high voltage unit.

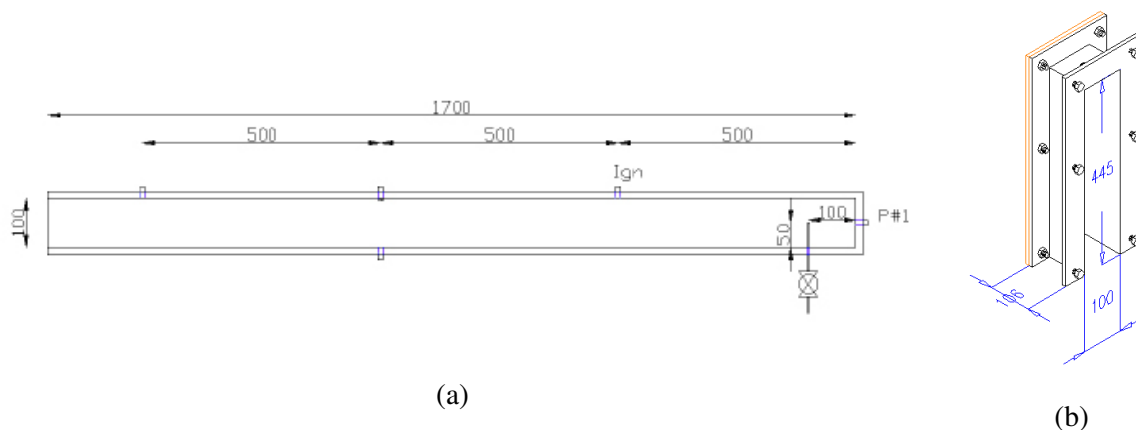


Figure 1. Experiment setup for (a) inhomogeneous H₂-air (b) homogeneous H₂-air.

The experiments with homogeneous gas were carried out in a vertical square channel, 0.45 m high, 0.10 m wide and 0.10 m long and open at the bottom end. The setup is shown in Figure 1(b). The premixed hydrogen-air mixture was injected into the channel through a vertical 4 mm ID steel tube positioned 150 mm below the closed end wall. The hydrogen-air was released upward. The ignition source was placed at the top and at the centre of the closed wall. The gas was ignited after the channel was filled with a homogeneous hydrogen-air mixture.

3 Results and discussion

For the experiments with inhomogeneous mixtures the hydrogen release rates were 20 dm³/min to 70 dm³/min. Figure 2 shows the flame development for a release rate of 70 dm³/min. The flame started as a spherical flame at the spark. As the flame reached the upper wall it became hemispherical. Initially the hemispherical flame was stable however as the stretch rate got smaller due to increased flame radius (eq. 1), the instability appeared on the flame surface after 12 ms.

Experiments with homogeneous hydrogen-air mixtures were carried out with equivalence ratios (ϕ) of 0.52, 0.75, 1.00, 1.25, 1.50 and 2.38 and at 1 atm. Figure 3 shows the flame development for $\phi = 0.75$. The flame radius r_f was measured from the high speed Schlieren pictures. The stretch rate was calculated by eq. 1 and plotted as a function of time as shown in Figure 4.

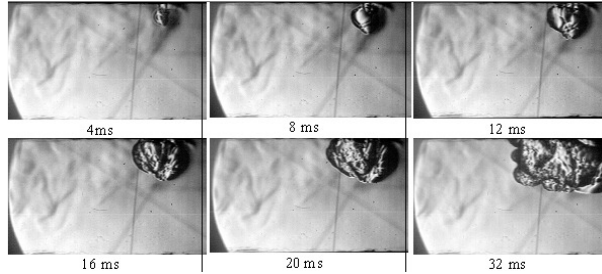


Figure 2. Flame propagation
Inhomogeneous hydrogen-air mixture
Release rate of 70 dm³/min

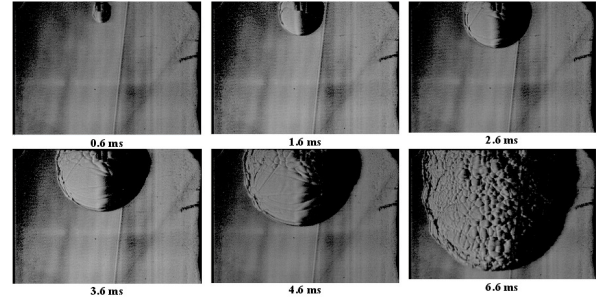


Figure 3. Flame propagation $\phi=0.75$
Homogeneous hydrogen-air at 1 atm

The onset of instability occurred between 3.8 ms and 6.0 ms for all the experiments. For $\phi = 0.52$, the onset of instability occurred between 5.6 and 6.0 ms. For the other equivalence ratios, the onset of instability was between 3.8 ms and 4.4 ms. The critical Peclet number for different equivalence ratios was estimated from eq. 2. A comparison of estimated critical Peclet number with experimental and calculated critical Peclet number by Jomaas et al. [5], is shown in Figure 5. The data from our experiments at 1 atm fits well with the theory of Jomaas et al. for $\phi \leq 1.0$. For rich mixtures the critical radius become larger than the width of the channel, hence the critical radius we measured was influenced by the channel width and therefore smaller than the real critical value.

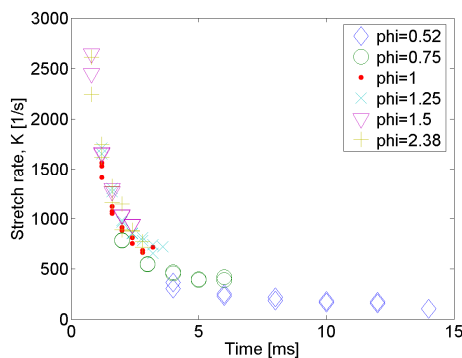


Figure 4. Flame stretch vs. Time
Homogeneous hydrogen-air mixtures

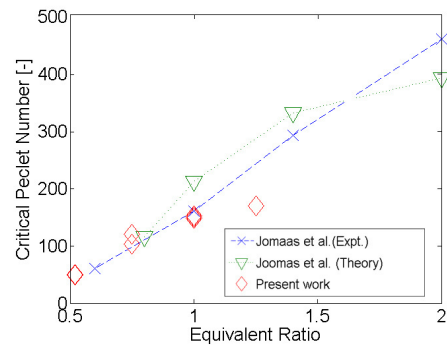


Figure 5. Critical Peclet Number vs. ϕ
Homogeneous hydrogen-air mixtures

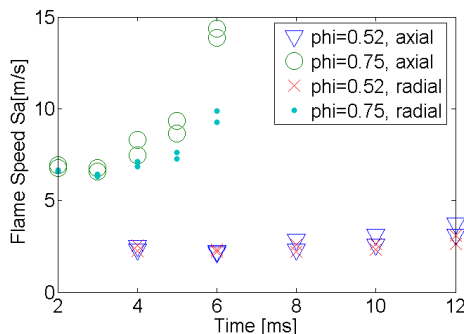


Figure 6. Flame Propagation vs. Time
Homogeneous hydrogen-air mixtures

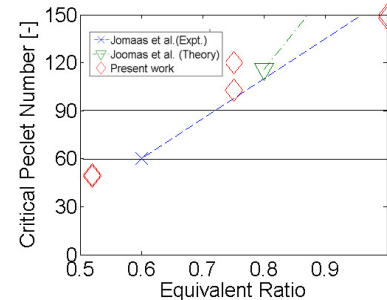


Figure 7. Critical Peclet number vs. ϕ
Inhomogeneous hydrogen-air mixtures

Figure 6 shows the flame speed for $\phi = 0.52$ and 0.75 . In Figure 6, 'axial' refers to the flame speed in vertical direction. 'Radial' refers to the flame speed towards the side walls (i.e. horizontal). At equivalence ratio 0.52 and 0.75 , the onset of instability was at around 6 and 4 milliseconds, respectively. It can be seen in Figure 6 that the flame speed increases with the flame radius. Compared with the laminar flame speeds we observed an increase of about 50% and 100% in the flame speeds for $\phi = 0.50$ and $\phi = 0.75$. This increase is about the same for lean hydrocarbon-air mixtures (1.6 – 1.8 times the laminar flame speed) observed by Lind and Whitson [6] and cited by Matalon [7]. However in our case, the increase in the flame speed may be affected by the walls in the late phase.

The critical Peclet number for the experiments with inhomogeneous gas cloud was estimated based on the onset of the flame instability. The critical Peclet numbers for flow rates between $20\text{ dm}^3/\text{min}$ and $70\text{ dm}^3/\text{min}$ were 60 to 90 . These values for the Peclet number correspond to $\phi = 0.60$ ($20\text{ vol}\%$) and $\phi = 0.72$ ($23\text{ vol}\%$), respectively. This indicates that the front of the hydrogen cloud has approximately the same concentration when ignited. This observation is in accordance with the observations made by Sommersel et al. [1].

4 Conclusion

Laboratory experiments with flame propagation in inhomogeneous and homogeneous hydrogen-air mixtures at 1 atm . have been carried out. The objective was to study the initial phase of the flame propagation and to determine the onset of flame instability. The flame stretch rate was estimated and the time of onset of flame instability was found from the high speed Schlieren video images. The critical Peclet number was estimated and our results agreed with earlier data for 5 atm . reported by Jomaas et al. We observed an increase of flame speed due to the flame instability. The increase was about 50% for $\phi = 0.50$ and 100% for $\phi = 0.75$. The onset of flame instability was also observed in the inhomogeneous hydrogen-air mixtures.

References

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