Further insight into the gas flame acceleration mechanisms in pipes. Part I : Experimental work

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Abstract

Some years ago, one of the authors (Proust, 2015) published the conclusions of a rather large experimental work devoted to the gas flame acceleration down a long pipe. It was concluded that the flame propagation could be represented by a constantly accelerating piston. The acceleration parameter seems to be primarily linked to the expansion velocity of the burnt product. Other parameters seemed of secondary importance questioning in particular the respective roles of the turbulence of the flame and of the instabilities.

Further experiments were performed using perfectly smooth and rough tubes (figure 1), varying the diameter of the pipe (150 and 250 mm) and the reactivity of the mixtures (methane-air and hydrogen air at various equivalence ratios). The smooth pipe is transparent enabling a direct visualization of the flame during the flame propagation and a refined resolution of the flame trajectory (in the steel pipes standard flame sensors were used). The pressure was measured at various locations but also the flow velocities in the boundary to try and detect any turbulence development. Only homogeneous and quiescent mixtures were studied and the flame was propagated from a closed ignition end toward the other open end. The results of the parametric study are presented in this paper.

Keywords: *premixed gaseous flame propagation, pipes*

1. Introduction

Coal mining industry remains one of the most high-risk industries in the world. Gas explosion accidents often happen following a leak of methane and ignition the flammable cloud formed in the mine infrastructures. The firedamp explosions generate important damages on critical equipment, injuries and dramatical deaths of people working in mines. As an example, there were 24 events related to methane hazard (explosions and ignitions) in Polish coal mines along the last 12 years. They caused the death of 62 miners and 75 were seriously injured. Losses in mining infrastructure and equipment were also significant. To improve the safety in mines and underground infrastructures, the European EXPRO project (prediction and mitigation of methane explosion effects for improved protection of mines infrastructures and critical equipment) was performed by the GIG institute, EMAGPL, KOMPWE in Poland, FSB in Spain and INERIS in France. One of the purpose of the project is to develop knowledge about the explosion process to determine the influencing parameters. Proust (2015) published an interesting review of explosion process and flame acceleration in tunnel and pipes. In this work, he exposed different mechanisms for flame acceleration:

- The most widely accepted mechanism so far is the continuous increase of the turbulence of the reactive mixture induced by the expanding burnt products pushing the reactants ahead (Borghi, 1988; Clarke, 1989). Due to friction at the wall, turbulence would be generated in proportion of the mean flow velocity. The burning velocity would increase inducing an increase of the expansion velocity of the burnt products, hence of the velocity of the reactants.;
- Deshaies and Joulin, (1989) explain thanks to a theoretical development that the gradual acceleration of the flow ahead of the flame due to burnt product expansion is produced by a series of compression waves. The temperature of the reactants ahead of the flame increases accordingly as well as the burning velocity. The flame then self-accelerates;
- A flame acceleration mechanism can also result from the flame front structuration generated by the pressure waves and their reflections on the extremities (Daubech, 2008).

Proust observed from his experiments that the flame propagation could be represented by a constantly accelerating piston. The acceleration parameter seems to be primarily linked to the expansion velocity of the burnt product. Other parameters seemed of secondary importance questioning in particular, the respective roles of the turbulence of the flame and of the instabilities.

The experimental results presented in this paper is a follow up of the examination of flame acceleration mechanisms. This work focuses on the influence of diameter and the roughness of straight long pipes closed at one end and opened at the other hand in the case of stoichiometric methane explosion.

2. Experimental set-up

The experimental device is a 24 m long pipe filled with a flammable mixture (Figure 1). The flammable mixture is prepared in a 2 m^3 spherical vessel using the partial pressure method and is injected in the tube. The initial pressure in the 2 m cube vessel is about 5 bar. The tube is swept by this mixture about 5 times its volume.

Tubes are made of transparent PMMA or steel. Two diameters are tested: 150 and 250 mm (Figure 2). The tube is closed on the side from which the gas is injected and the mixture ignited. The other extremity is covered with a plastic sheet drilled with the small hole to avoid a pressure rise-up of the tube during gas injection.

The instrumentation comprises:

- Three pressure sensors:
  - Near the ignition point, at 5.5 m and at 15.5 m from the closed end
- flame detection in steel pipes:
  - Flame probes: photovoltaic cells which catch the light produced by the flame (at 0.5, 4.5, 10.5 and 15.5 m from the ignition source)
  - Ionization probes in the first meter (4.5, 45 and 90 cm from ignition source - Figure 3)
- flame detection in transparent pipes:
  - Photron fast video camera
- Two Pitot probes (Proust, 2018) to measure flow velocity (Figure 3)

The flammable mixture is ignited by an electrical spark (100 mJ) located at the center of the closed end of the tube (Figure 1).

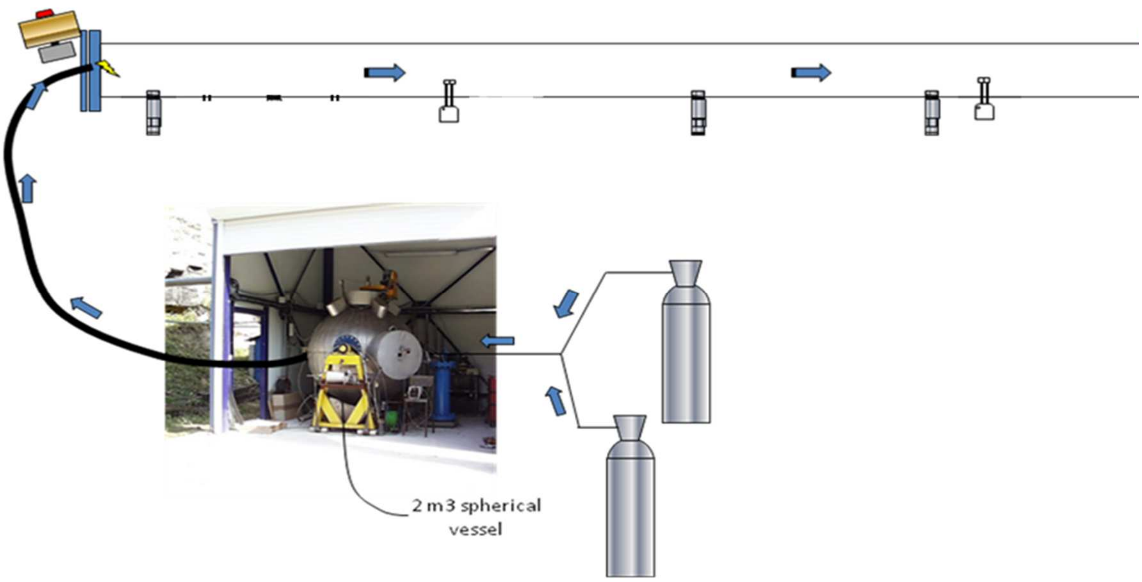


Figure 1 : Overall device

Figure 2 : 250 mm PMMA transparent pipe and 150 mm steel pipe

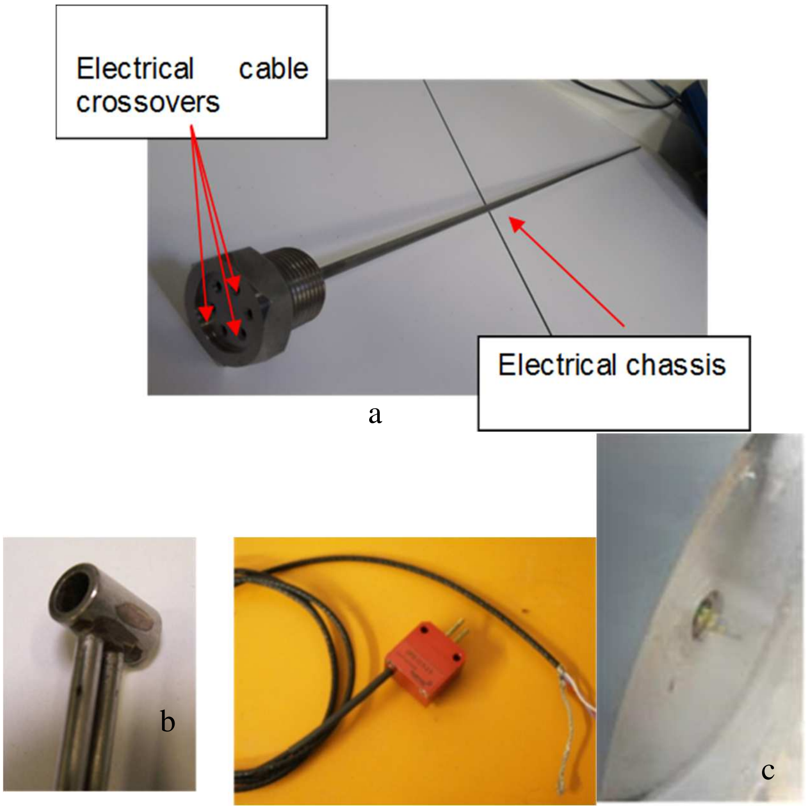


Figure 3 : Ionization probe (a), Pitot probe (b) and ignition source (c)

The tests are reproducible as the Figure 4 shows. The estimated errors on overpressure between two tests in the same configuration are around 5 % when the mixture is provided by the same batch and 10 % when the mixture is provided by two different batches.

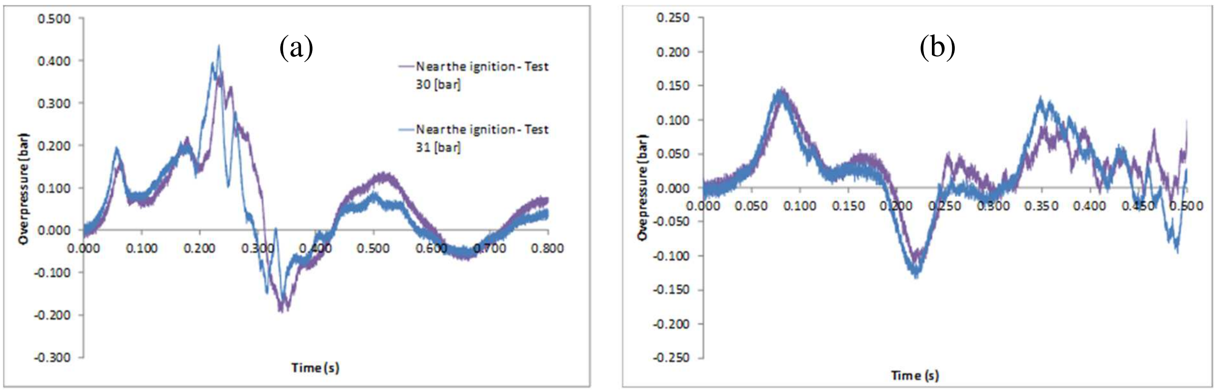


Figure 4: Overpressure signals for a test in 150 mm steel pipe for 10 % CH4-air mixtures provided by the same batch (a) and for a test in 250 mm plastic pipe for 10 % CH4-air mixtures provided by two different batch (b)

3. Analysis of a typical test

This section presents the typical result obtained with an explosion of a stoichiometric methane-air mixture in the transparent 250 mm tube.

Figure 5 presents the pressure signals measured in the transparent 250 mm tube near the ignition source, at 5.5 m and at 15.5 m from the ignition source. Figure 6 presents pictures of flame propagation when the transparent tube is captured on film in the middle of pipe. The flame is a paraboloid of revolution during its propagation.

Figure *7* presents the flame trajectory and the flame velocity. The flame trajectory is obtained thanks to a fast camera movie. A first pressure rise is observed up to 120 mbar at 75 ms. This first pressure peak P1 accurately corresponds to the first flame development of the flame from the ignition point to the side walls of the tube (Kerampran, 2000). This first elongation could be the establishment of Darrieus-Landau instability (Markstein, 1964). Then the flame stops and the pressure decreases. Afterwards, the flame is submitted to strong accelerations, decelerations and stops due to the interactions with the acoustic waves in the tube. Indeed, the typical acoustic frequency of the tube can be estimated with the formula f = n.c/4L where c is the sound velocity estimated around 340 m/s in stoichiometric methane air mixture, L is the length of the tube and n=(3p+1) where p is an integer starting at zero and represents the number of vibration harmonic. The frequency of the second harmonics is around10 Hz and the frequency of velocity oscillation is about 11 Hz. These interactions are also visible when the flame velocity and flow velocity (measured by pitot probes in the middle of a section of tube at 10 and 18 m -Figure 9) are compared showing a good matching of flame velocity and flow velocity oscillations.

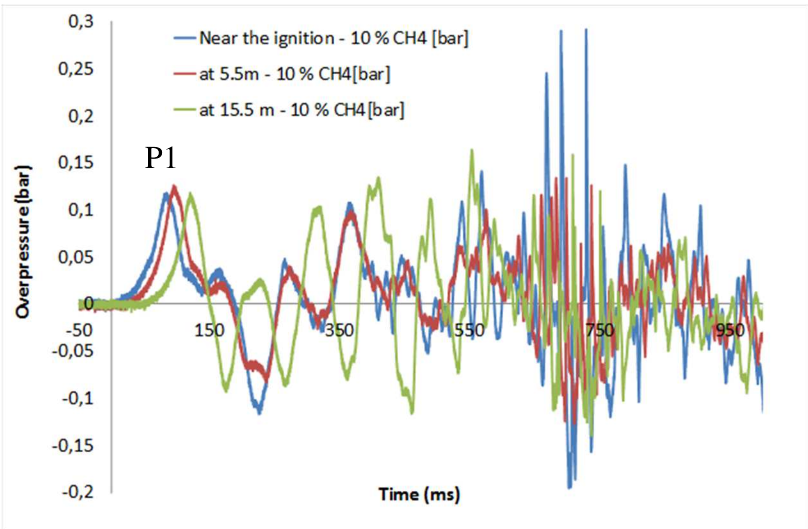


Figure 5 : Pressure signals measured in the transparent 250 mm tube near the ignition source, at 5.5 m and at 15.5 m from ignition source-stoichiometric methane air flame at ambient conditions

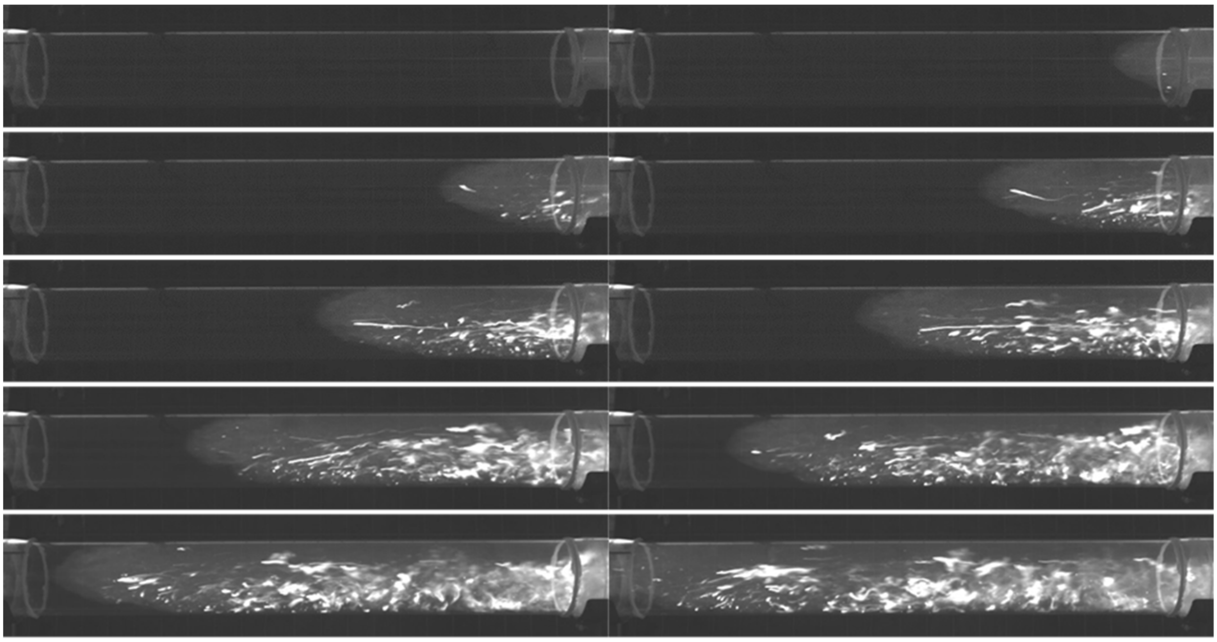


Figure 6: Pictures of flame propagation when the transparent tube is captured on film in the middle of pipe (5 ms between two pictures) -stoichiometric methane air flame at ambient conditions (250 mm tube)

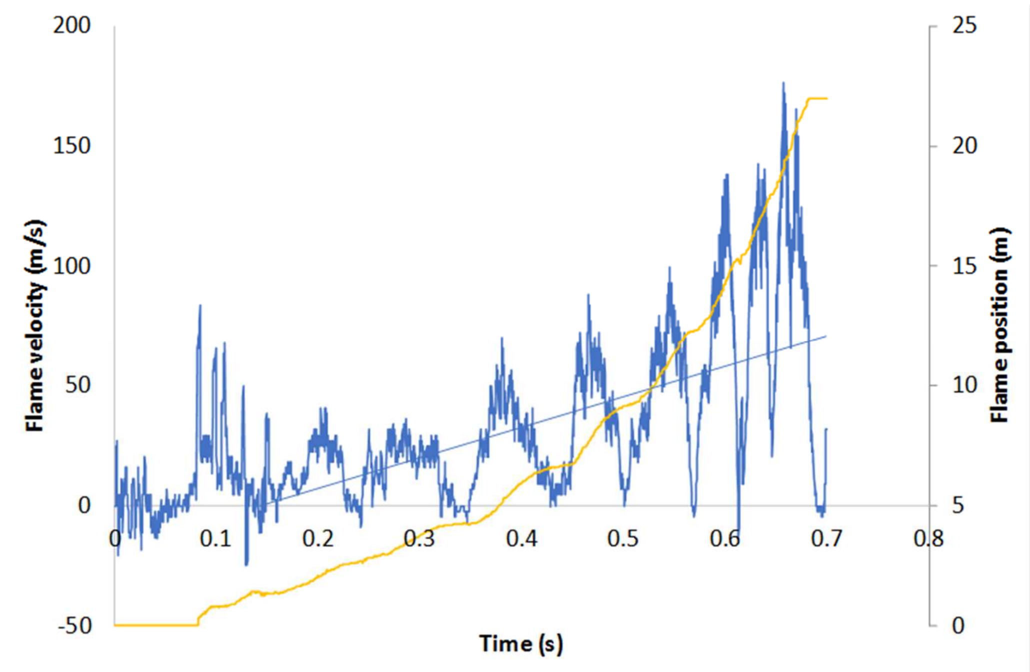


Figure 7 : Flame trajectory (orange curve) and flame velocity (blue curve) -stoichiometric methane air flame at ambient conditions (250 mm tube)

The flame velocity shows strong oscillations at a frequency increasing as function of the flame position in the pipe (Figure 8). The blue line in the Figure 7 seems to show that the flame progresses at a mean velocity which increases. Thus, the flame seems to have, on average, a uniformly accelerated movement as suggested earlier (Proust, 2015). Note also that the amplitude of the oscillations of the flame velocity increase during the flame propagation. The value of this average acceleration is about 130 m/s^2.

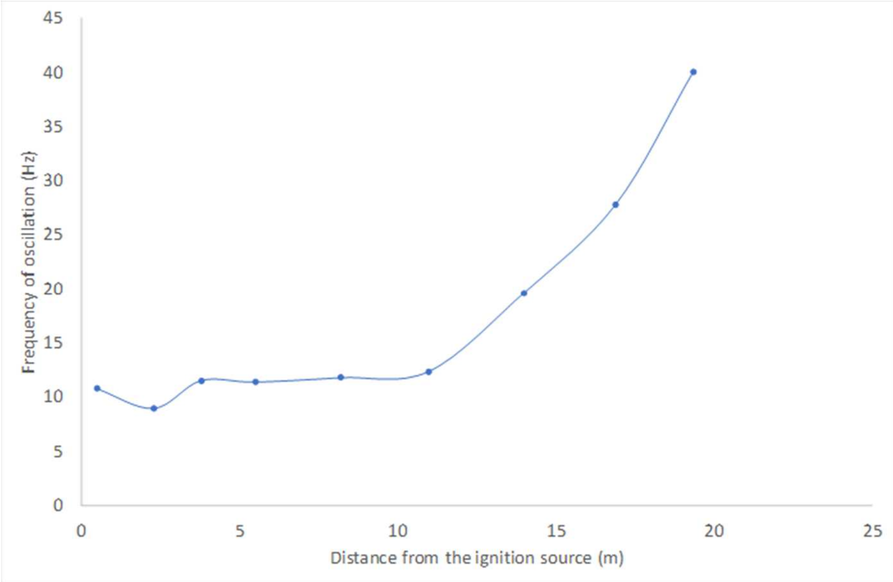


Figure 8 : Frequency of oscillation versus distance from ignition source -stoichiometric methane air flame at ambient conditions (250 mm tube)

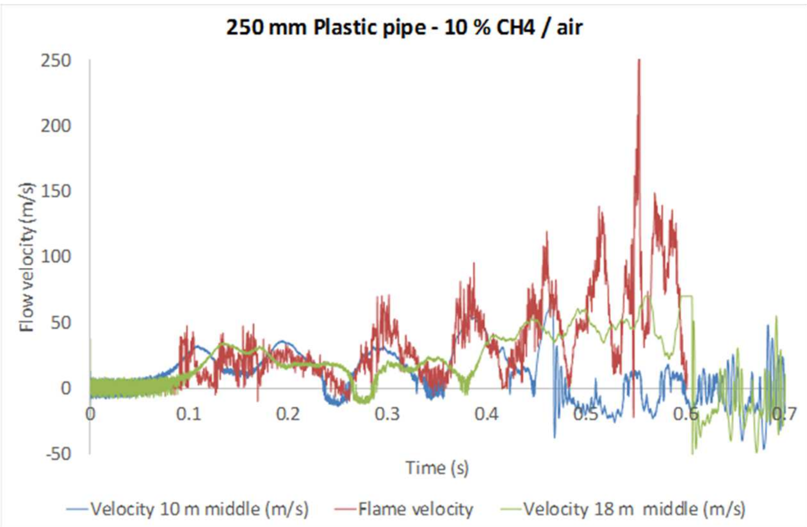


Figure 9 : Comparison between flame velocity and flow velocity (measured by pitot probes at 10 and 18 m). -stoichiometric methane air flame at ambient conditions (250 mm tube)

4. Nature of the flow

Specific measures of flow velocity are realized with pitot probes at 10,5 m from the ignition source one on the axis of the pipe and the second near the wall at 0.5 cm from the wall. The principle of the Pitot probes (Figure 3) is to create a break point where the flow line has a null velocity. The dynamic pressure is also null at this point, the total pressure is measured to which the "static" pressure measured by a pressure point downstream of the flow is subtracted from.

The Pitot probes linked with a differential pressure transducer, allows to measure the difference of the dynamic pressure and then to deduce, thanks to the Bernouilli's principle, the velocity of the flow and the fluctuations in the flow. Figure 10 and Figure 11 presents flow velocity measured in the 250 mm plastic and steel pipes and in the 150 mm steel pipe.

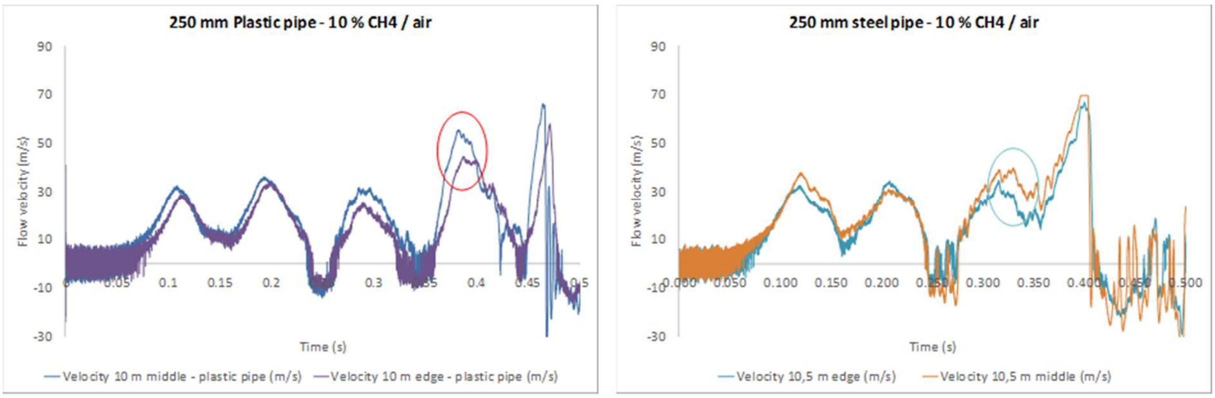


Figure 10 : Velocity in plastic and steel pipes in the middle of a section and near the edge at 10 m from ignition source - stoichiometric methane air mixture at ambient conditions (24 m long)

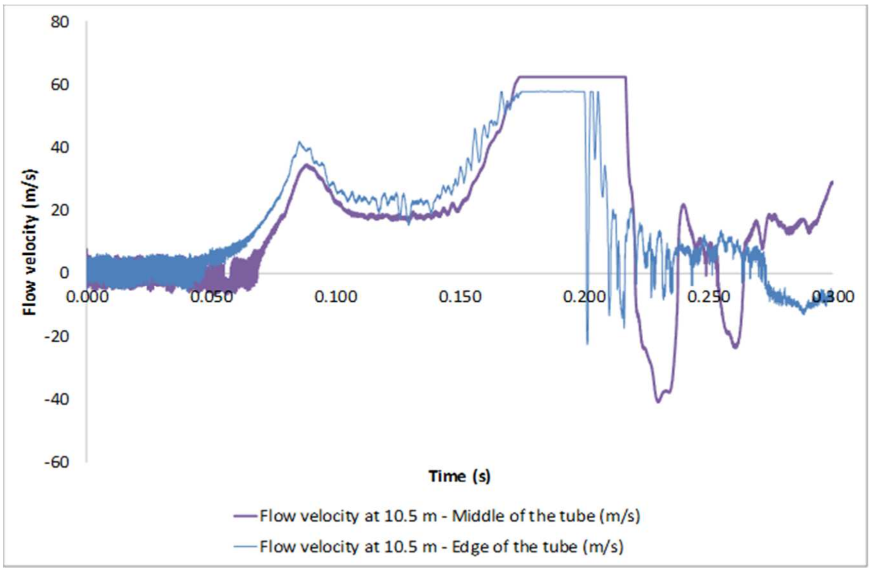


Figure 11 : Flow velocity measured by pitot probes in 150 mm steel pipes- stoichiometric methane air mixture at ambient conditions (24 m long)

In these cases, the velocities in the middle of the cross section and near the wall are on the same order of magnitude and are nearly superposed. Those results can be compared with flow velocities measured with the same pitot arrangement inside a 300 mm steel pipe in which a steady state air flow of 25 m/s is obtained using a fan (Figure 12). Note the flow velocity in similar to that measured in the present explosion tests. In the fan driven flow, a strong velocity gradient is measured near the wall of pipe which can be shown to result from the wall known boundary layer. Such phenomenon is not detected in the explosion tests. The flow velocity measured during the fan driven flow test and the explosion test are measured with the same sensor, with the same response frequency. Considering now the structure of the flows (Figure 13), the fan driven flow can be into a time average velocity, about 24 m/s; and a random fluctuation part, which amplitude is about 1 m/s with a high frequency composition (tens of Hz at least) . This fluctuating part is typically that of an established turbulent flow in a pipe (intensity of the turbulence ≈1/24 = 4% - Hinze, 1975). In comparison, the velocity signal from the explosion tests is much smoother with a very low frequency signal (5 Hz) which is very far from that of any turbulence.

Figure 12 : Flow velocity measured in a 300 mm steel pipes (20 m long) in which the flow is established using a fan

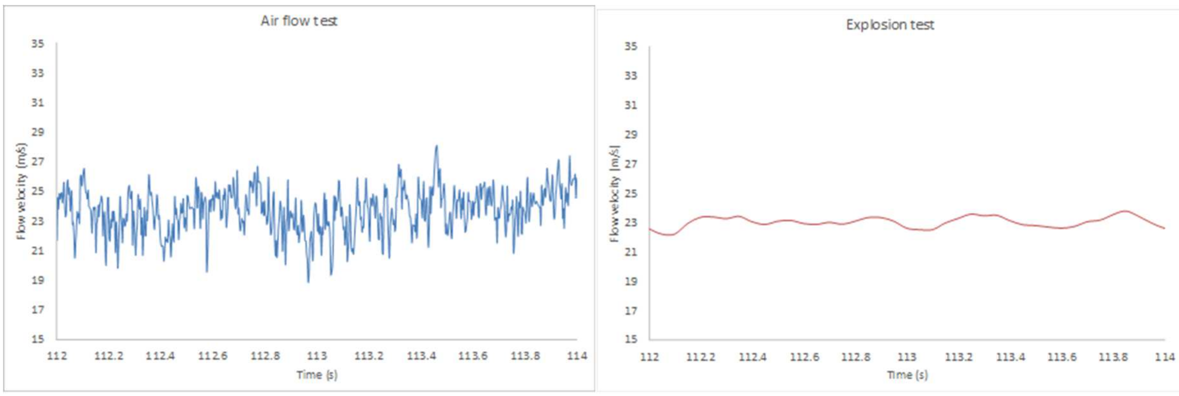


Figure 13: Focus on the velocity signals in air flow tests (Figure 12) and in explosion tests measured in the centre of pipe

This analysis strongly suggests that the flow in front of a flame propagating in a pipe is very different from a standard established boundary flow: a flat velocity profile, with very limited boundary, and as a consequence hardly turbulent seems to be produced like a “plug flow”.

5. Parametric investigations

The influence of diameter, roughness of pipes and initial conditions was investigated.

5.1 Influence of the pipe diameter

The impact of the tube diameter was experimentally studied in the 24 m long transparent tube with diameters of 150 and 250 mm for stoichiometric methane/air mixture (Figure **14**) The common point is the presence of the first peak of overpressure (P1) but the rest of the signal differ significantly with a second significant bump in the smaller tube, much less obvious in the larger pipe.

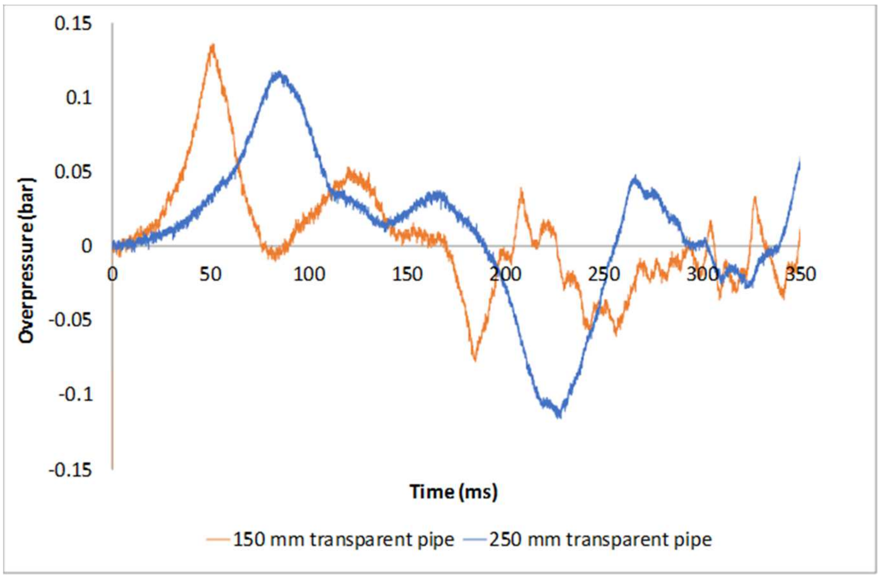


Figure 14: Impact of the tube diameter in the 24 m long transparent tube with diameters of 150 and 250 mm for stoichiometric methane/air mixture

It is known that the first peak corresponds to the first flame elongation, the overpressure in the 150 mm tube (around 130 mbar) is on the same order of magnitude than in the 250 mm tube (around 120 mbar). This value seems to be independent from the pipe diameter, which is consistent with Proust results (Proust, 2015). From the first peak P1, the flow velocity produced by the flame can be deduced: $P1=\rho.c.U_{flame}$ (Kerampran , 2000 : ρ : density of gases, U_{flame} : flame velocity, c : sound speed) . A maximum value of 25 m/s is calculated. Note that in the present configuration, this estimation can be compared to the flow velocity measured at 10 m from the ignition. Further, if the burnt product can be considered to be at rest behind the flame front, the flow velocity should be close to the flame velocity. In transparent tubes, the flame velocity can be estimated visually. When all these informations are confronted together a consistent result is obtained (Figure 15) demonstrating the flame and flow dynamics are correctly captured.

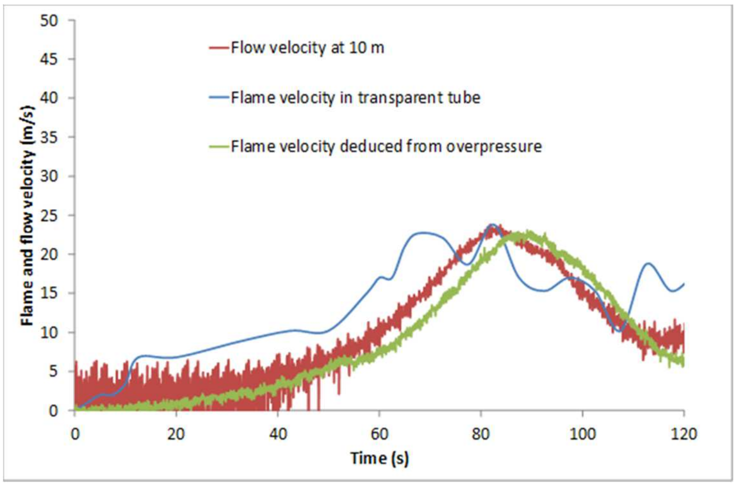
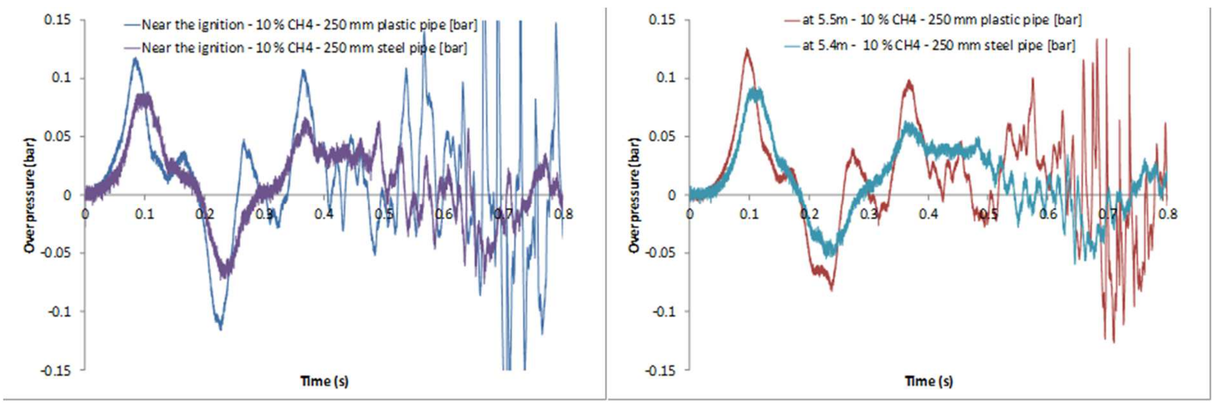


Figure 15 : Comparison between the flame velocity measured in transparent tube for which the first flame development is similar, the flow velocity measured by pitot probe at 10 m and the flame velocity deduced from the overpressure- stoichiometric methane air mixture at ambient conditions (250 mm pipe -24 m long)

The maximum flame velocity, 25 m/s, is much large than the expansion velocity $E.S_{lad}$ (E : expansion ratio of burnt gases, S_{lad} : laminar flame speed). The ratio between both parameters is a flame folding factor (flame area to cross section) which amounts 10, consistently with previous findings (Daubech, 2008).

5.2 Influence of pipe material

The influence of pipe material is studied by comparing the pressure signals obtained with the 250 mm plastic transparent tube and with the 250 mm steel tube (Figure 16) still for stoichiometric methane-air mixture. The transparent plastic pipe is considered as a perfectly smooth pipe. The roughness of metallic pipe is due to the oxidation of the wall. It can be estimated that the roughness is 100 µm.



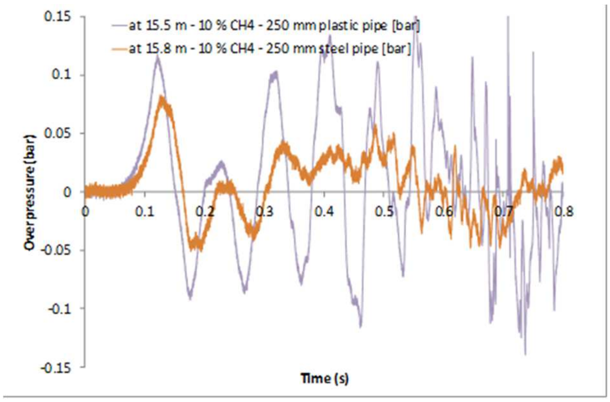


Figure 16 : Comparison between the pressure signals in 250 mm plastic transparent tube and 250 mm steel tube near the ignition, at 10 m and 15 m to the ignition source– stoichiometric methane/air mixture.

The global trend of the pressure signal is conserved. The frequencies of the oscillations are similar but their amplitudes differ. It is twice larger in the plastic pipe (signals at 15 m). Up to know there is no clear explanation to these differences.

5.3 Influence if the initial conditions

The impact of the initial conditions was experimentally investigated studied in the 24 m long metallic tube with diameter of 150 mm for stoichiometric methane/air mixture (Figure 17). The flammable mixture is ignited with an electrical spark (energy : 100 mJ) and a pyrotechnical match (energy : 60 J). The spark ignition is punctual whereas the ignition with a pyrotechnical match is more diffuse since several hot particles are emitted

In contradiction with the usual opinion that a more powerful ignition source would lead to a more severe explosion, the contrary is obtained. A possible explanation would be that multiple ignitions, like with the pyrotechnical match, would inhibit the first flame elongation phase from which the subsequent flowfield in the pipe depends on. The flame reaches earlier the edge than in punctual ignition.

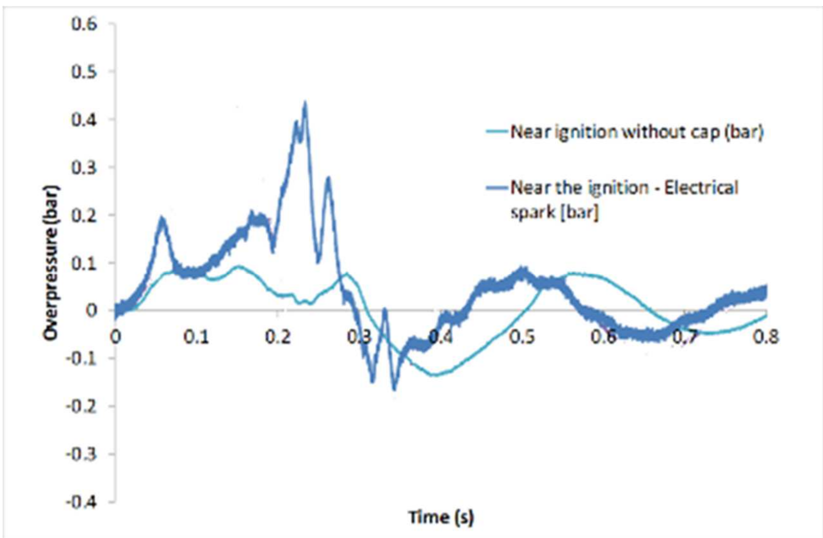


Figure 17 : Pressure signals near the ignition source for stoichiometric methane/air mixture ignited with spark and pyrotechnical match – 24 m long 150 mm steel pipe

A further illustration of the potential influence of the first phase of the explosion (first pressure pulse) is provide in Figure 18 showing the pressure signals for stiochiometric CH4/air mixtures burning in 150 mm plastic and steel pipes (Figure 18). The slope and timing of the first pressure pulse is the same in both situations but P1 is higher in the steel pipe. This higher value could be explained by the influence of sensor ports located about 1 m from the ignition source (Figure 2). It is believed that he explosion of the small gas pockets trapped into the sensor ports could destabilize the flame, increasing its area and thus the first peak value.

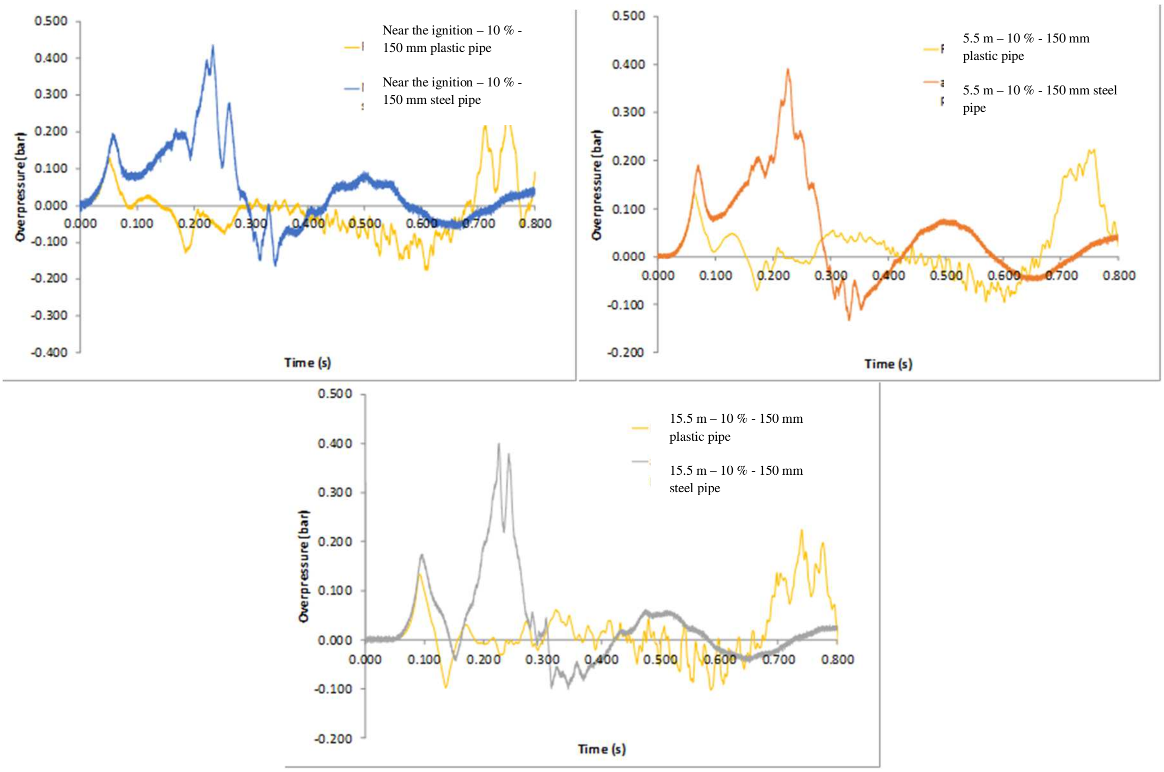


Figure 18 : Comparison between the pressure signals in 150 mm plastic transparent tube and 150 mm steel tube near the ignition, at 10 m and 15 m to the ignition source – 10% methane/air mixture

6. Discussion

The present results and the parametric investigations confirm the previous findings (Proust, 2015). If the mechanisms explaining the flame propagation regimes still need to be clarified, it seems nevertheless that the first pressure pulse plays a significant role. The latter is clearly produced by the initial flame ball development and subsequent elongation. The subsequent flame propagation, after this initial elongation phase, is a constantly accelerating flame resembling a piston in terms of pressure generation. Over this general trend pressure oscillation are superposed due the acoustic resonance of the pipe.

The first elongation last from the spark ignition time to when the flame reaches the pipe lateral walls. As suggested earlier (Proust, 2015; Kerampran, 2000), and confirmed by the present measurements, the magnitude of the overpressure is proportional to the material velocity of the flow, the latter parameter being very close to the flame velocity. The maximum flame velocity is proportional to the expansion velocity of the burnt gases represented by the parameter E.Slad. The coefficient of proportionality is simply the maximum elongation of the flame Af/A (or "aspect ratio"). The maximum flame elongation is about 10, which is close to the value measured on videos by Kerampran.

After the first peak, a self-accelerated motion of flame occurs despite the oscillation. A reasonable correlation between the expansion velocity of the burnt gases represented by the parameter E.Slad and some value of flame acceleration can be found (Proust, 2015). This analysis of flow velocity in explosion tests in plastic and metallic pipes shows that the flow created in front of the flame seems to be not turbulent and quite flat. The flow in front of the flame may be considered as a pressure zone (pressure plug) whose length depends on the first flame development and which propagates in the pipe.
The self-accelerated motion can be estimated using Vf = af.t where Vf is the flame velocity, af is the flame acceleration and t is the time. For stiochiometric methane/air mixture, this value is about 130 m/s2.

The last point deals with the acoustic oscillations after the first overpressure peak. It's possible to estimate the resonance frequencies of constant section pipe although it contains gases of different nature (Kerampran, 2000). The tube with length L, closed at one end and open at the other, contains burnt gases up to the xf position. In this region, the acoustic waves propagate at ab velocity. In the other part of the tube, it contains unburned gases where acoustic waves propagates at au. The period T and the frequencies f of third harmonics oscillations are given by:

$$T = \frac{4 \cdot x_f}{3.a_b} + \frac{4 \cdot (L - x_f)}{3.a_u} \qquad f = 3.\frac{a_b \cdot a_u}{4 \cdot [(L - x_f) \cdot a_b + x_f \cdot a_u]}$$

Figure 19 presents a comparison between the estimated frequencies and the frequencies deduced from the flame velocity.

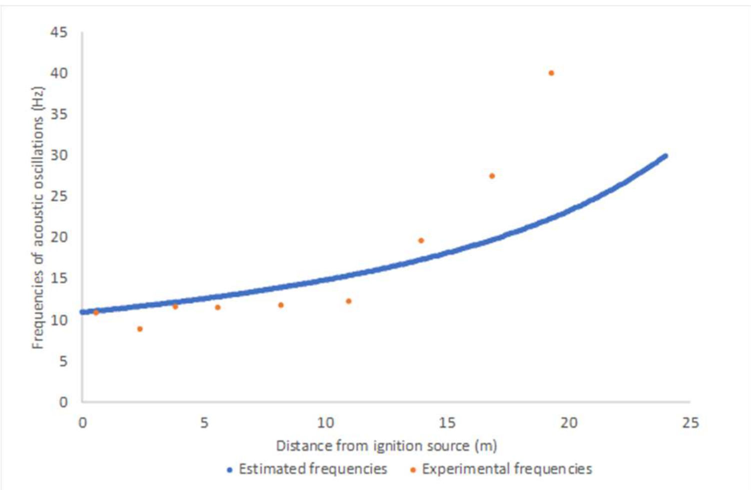


Figure 19 : Comparison between the estimated frequencies and the frequencies deduced from the flame velocity

Since the flow behind the flame seems at rest, the flame acts as a piston. From the start of its propagation, the flame sends a pressure wave. It propagates behind the flame and reflects at the opposite extremity. After, the pressure wave interacts with the flame. It's possible to represent that by a simple equation $\Delta p(t) = \rho.c.U_{flame}(t)$ (Gilles, 2000).

Figure 20 presents a comparison with experimental and estimated flame velocity. The first phase of flame development is completely characterized. The second phase is the coupling of the self-accelerated motion of flame whose value of acceleration is defined by $E.S_{lad}$ and the acoustic oscillations of pipe. The value of acceleration for stoichiometric methane/air mixture is 130 m/s^2.

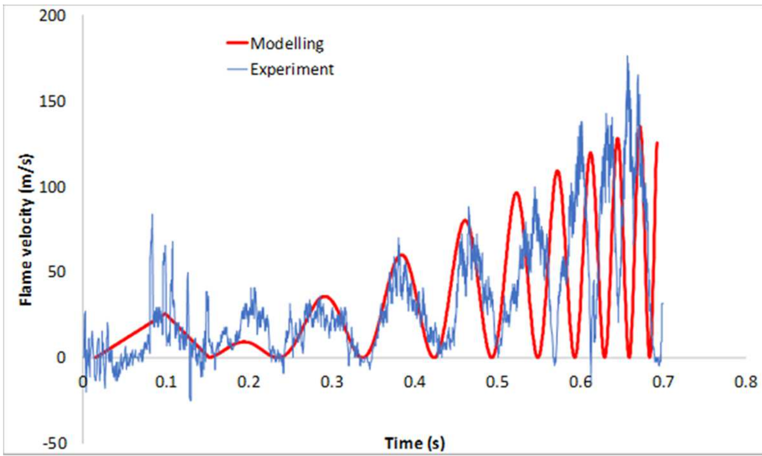


Figure 20 : Comparison with experimental and estimated flame velocity

The estimation of overpressure thanks to the flame velocity is presented in Figure 21. The model gives a reasonable agreement for the first acoustic oscillations, but overestimated the value of pressure. The mechanism of pressure production must be different with acoustic oscillations.

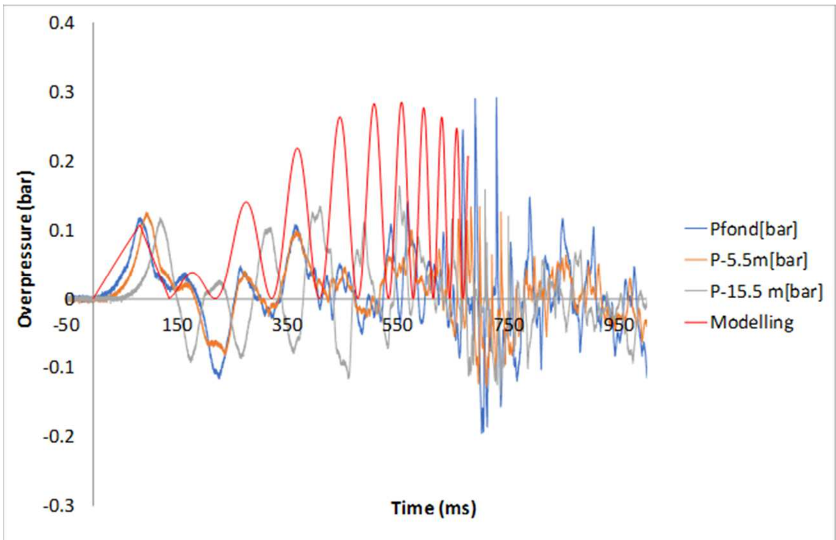


Figure 21 : Estimation of overpressure thanks to the flame velocity

Acknowledgements

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