

Gas Flame Acceleration in Long Ducts

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Abstract

In many practical situations, a flame may propagate along a pipe, accelerate and perhaps transform into a devastating detonation. This phenomenology has been known, more or less qualitatively, for a long time and mitigation techniques were proposed to try and avoid this occurrence (flame arresters, vents,...). A number of parameters need to be known and in particular the “distance to detonation” and more generally the flame acceleration characteristic scales. Very often, the ratio between the run-up distance and the pipe diameter is used without any strong justification other than using a non-dimensional parameter (L/D). In this paper, novel experimental evidence is presented on the basis of relatively large scale experiments using 10 cm and 25 cm inner diameter duct with a length between 7 and 40 m. Homogeneous C_2H_4 -air, CH_4 -air, C_3H_8 -air and H_2 -air mixtures were used and different ignition sources. The interpretation suggests that the self-acceleration mechanism of the flame may be much better represented by flame instabilities than by turbulence build-up. One consequence would be that the maximum flame velocity and, following, the maximum explosion overpressure, would be rather linked with the run-up distance than with the L/D ratio.

Keywords: *gas explosions, DDT, flame acceleration, explosions in ducts*

1. Introduction

Most industrial processes are a network of vessels interconnected by pipeworks. Whenever an explosion is triggered somewhere inside, the flame propagates from vessel to vessels and accelerates all along its path especially in pipes. Detonations can produce (Hattwig, 2005) flame velocities amounting 2 km/s and local overpressures up to several tens of bars rendering the control of the escalation extremely difficult. Standard mitigation practice requires firstly isolating vessels from pipeworks to keep control upon the flame velocity. But the implementation of “isolation” techniques like flame arresters, safety valves,... is still a very difficult question because a number of questions pertaining to the physics of flame acceleration are still not correctly answered. In particular, the behaviour of the flame in a pipe is critical because in this configuration the flame is capable of self accelerating and the flame velocity may change by orders of magnitudes (from a slow deflagration to a detonation regime) over relatively short run up distances (Ginsburg and Buckley, 1963). Nearly twenty years ago, the present author reviewed (Proust, 1996) the potential flame acceleration mechanisms discussed in the scientific community at the turn of the century. The “academic” but challenging situation is that of a flame propagating in an explosive mixture confined in a

duct closed at the ignition end and open at the other end. The relative role of four mechanisms was discussed :

- The most widely accepted mechanism was 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. The Reynolds number is then assumed to play a key role in the process both encompassing the effect of turbulence generation (Hinze, 1975) and turbulent combustion (Bray, 1990). It might be a reason the pipe diameter is said to play a dominant role in the flame and pressure history inside a duct (NFPA 68, NFPA 69) ;
- It was shown on a theoretical basis (Deshaies and Joulin, 1989) that other mechanisms may also explain flame accelerating in pipes. In particular, 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 ;
- Less exotic would be the triggering of flame instabilities by the same pressure waves and their reflections on the extremities. These instabilities have been studied for a long time (Marsktein, 1954) but their exact role in the flame acceleration process down a pipe is still in debate.

In this paper a renewed discussion of the relative roles of these acceleration mechanisms is proposed in the first section in view of the most recent findings. In the second part the results of a large scale experimental programme are presented and interpreted using the conclusions of the first section. Practical implications are outlined in the conclusions.

2. Physical analysis

An excellent review of the state of the art was recently issued (Ciccarelli and Dorofeev; 2008). The configuration of interest is a flame propagating down a long tube closed at the ignition point. The tube is not obstructed but may be rough.

The analysis proposed by Ciccarelli supports the idea that the turbulence of the flow due to friction at the wall would be the leading flame acceleration mechanism all along the process leading to the transition to detonation. Details some relevant mathematical developments may be found elsewhere (Veser and al.; 2002, Dorofeev S.; 2007, Kuznetsov and al.; 2005, Silvestrini and al., 2008). Silvestrini for instance proposes the following correlation :

$$V_f = 6.5 \cdot \sigma \cdot S_l \cdot e^{0.0061 \cdot (\sigma - 1) \cdot \frac{X}{D}} \left(\frac{D}{0.15} \right)^{0.4} \quad [1]$$

Where S_{lad} is the laminar burning velocity, σ the expansion ratio of the burnt products, X the position of the flame, D the diameter of the duct and V_f the flame speed at X .

This correlation establishes a link between the flame velocity and X/D . However, it does not seem to hold for all experimental data, especially for those produced recently (Thomas and al.; 2010, Blanchard and al.; 2010). One reason may be that they result more from a fitting with existing experimental data than from a formal theoretical development. More fundamentally, some (unfortunately very limited) measurements of the turbulence generated in the flow ahead of the flame (Jones and Thomas, 1991) do not seem to exhibit a robust correlation between the flame speed and the turbulence intensity suggesting other mechanisms for flame acceleration may be at work.

Which alternative mechanism may be strong enough to fold the flame surface to such a large extent that a continuous acceleration may happen ?

Answers were given about ten years ago (Kerampran, 2000). Kerampran performed a detailed experimental analysis of premixed gaseous flames propagating down a straight pipe. Some of the data obtained can be used to discuss the physics of flames accelerating in ducts. One of the device (Figure 1) is a 4 m (varying from 50 cm to 4 m) long, 40 mm wide tube closed at the ignition end and open at the other end (in fact communicating with a very large expansion chamber). The cross section is square and the walls are transparent to allow excellent visualization conditions. Importantly the tube is perfectly smooth. The ignition source is a heated coil. Tests were performed using quiet and homogeneous propane, ethylene and acetylene-air mixtures. Kerampran also used a smaller setup (Plexiglas round 22 mm diameter tube, up to 1.72 m long).



Figure 1: equipment used by Kerampran (2001), 4 m long tube, 40 mm wide, square cross section

A typical pressure signal is shown on Figure 2 together with some pictures showing the shape of the flame front for a flame propagating in an acetylene-air mixture (22 mm dia., 1.22 m long tube).

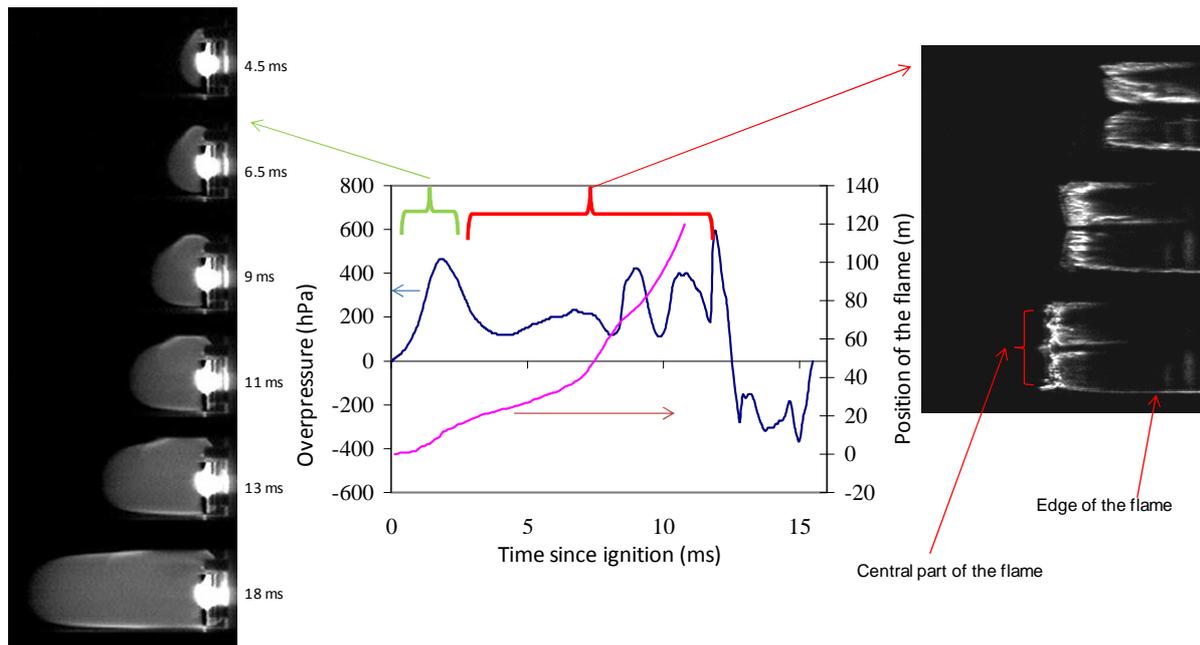


Figure 2: flame propagating in an acetylene-air mixture (1.22 m long tube, 22 mm diameter: the pictures were taken with the larger apparatus and are given to illustrate the aspect of the flame) from Kerampran 2001

A two stage propagation was clearly observed, the first one (0-3 ms) corresponding to the flame development around the ignition point producing an elongated parabolic flame. As soon as the sides of this parabola extinguish at the wall, the flame slows down (see the decrease of the slope of the flame trajectory around 2 ms). Soon after, the flame front becomes strongly corrugated. Keeping this structure, the flame accelerates more or less steadily, the variations of the slope of the trajectory being due to the collision with a pressure wave reflected from one extremity. It is very interesting to note that the corrugation of the flame is particularly marked near the axis of the tube while the front seems to remain smooth close to the walls. This observation seems in strong contradiction with the assumed flame acceleration by the turbulence of the flow since the later should be much larger at the wall. Small eddies appear in the trail of the flame but remain very limited. A similar observation was performed long ago by Leyer (1971, 1972) and the shape and structure of the corrugations led him to suggest the role of acoustic flame instabilities. These instabilities would be triggered by the pressure wave emitted during the partial extinction of the flame (at the wall) just after the initiation. In this case, the driving parameter for the appearance and development of the instabilities (Markstein; 1964, Bychkov and al., 2000) should be mostly be the expansion velocity of the flame ($\sigma.S_{lad}$: material velocity of the pressure wave). Other parameters might be of secondary importance.

Parametric experiments were performed to complete this investigation.

3. Experiments

a. Setup

Full scale experiments were performed using industrial tubes (Table 1 : 100 mm and 250 mm internal diameter). The results obtained by Kerampran are included since being part of this investigation. The tubes are closed near the ignition end and open at the other end.

Table 2: experimental setups and conditions (*Kérampran, 2000)

Diameter (mm)	Length (m)	Mixtures	Ignition	Rugosity
22*	0.62	C ₃ H ₈ -air (stoich.)	Hot coil	≈0 mm
	1.22	C ₂ H ₄ -air (stoich.)		
	1.72	C ₂ H ₂ -air (stoich.)		
40*	2	C ₃ H ₈ -air (stoich.)	Hot coil	≈0 mm
	4	C ₂ H ₄ -air (stoich.)		
	8	C ₂ H ₂ -air (stoich.)		
100	7	CH ₄ -air (7-11% v/v)	Hot coil	0.2 mm
	14	C ₃ H ₈ -air (4% v/v)		
	19	C ₂ H ₄ -air (6-9% v/v)		
	26	H ₂ -air (14-31% v/v)		
250	10	CH ₄ -air (5-14% v/v)	Hot coil	0.2 mm
	20	C ₃ H ₈ -air (2-6% v/v)		
	30	C ₂ H ₄ -air (6.5% v/v)		
		H ₂ -air (10-20% v/v)		

In laboratory equipments (22 and 40 mm tubes), the mixture is prepared using the partial pressure method in a separate reservoir, the tube is evacuated and the mixture is introduced until the atmospheric pressure is reached. With larger tubes (100 and 250 mm), the gases (air and combustible gas) are injected via the same line in a port located in the “ignition flange”. The composition is controlled using oxygen meters at two locations inside the pipe (near both ends). The expected accuracy may amount about $\pm 0.3\%$ of the combustible gas absolute concentration.

In the laboratory equipments, the flame history is recorded using high speed imaging. In the larger tubes and in the gallery, photodiodes are used (regular spacing along the length of the pipe). About 20 points in the 100 and 250 mm. The static pressure (piezoresistive transducers : accuracy $\pm 0.1\%$ full scale) is measured closed to the ignition sources in all cases but additional measurements are available (in first half of the pipe).

The ignition time is not known accurately and a pretrigger delay was set on the first photodiode so that time zero on the graph is only qualitative.

The burning properties of the different fuels are recalled in table 2.

Table 2: burning properties of the various fuels-air mixtures used (stoichiometry)

Fuel	S_{lad} (m/s)	σ	$\sigma \cdot S_{lad}$ (m/s)
methane	0.38	7.6	2.8
Propane	0.42	8	3.4
Ethylene	0.7	8.2	5.7
Hydrogen	2.3	7	16.1

b. Results

A typical experimental dataset is presented in figure 3 for a flame propagating in a 26 m long-100 mm inner diameter tube filled with a 6.5% v/v C_2H_4 in air (hot coil). The trajectory of the flame is shown together with the overpressure measured on the ignition flange. Systematically two characteristic pressures peaks are detected: P1 is observed just after an exponential growth of the pressure and is sometimes followed by a decrease of the pressure and P2 is the maximum overpressure. The flame trajectory is divided into two periods : before about 35 ms the average flame velocity is about 150 m/s and, after, is constant and equal to 2000 m/s (figure 4) suggesting a detonation regime occurred at this time, 6-7 m from the ignition point. Note a transient overdriven detonation appears with a velocity pointing at 2500 m/s much larger than the expected Chapman-Jouguet velocity. This transient is also visible on the pressure trace at 35-40 ms. After this, and all along the rest of the propagation, the pressure is maintained at about 6 bar corresponding to 1/3 of the detonation overpressure (Chapman-Jouguet conditions) as expected. Note the transition to the detonation is very fast, happens when the flame velocity exceeds 500 m/s and takes place in typically two meters.

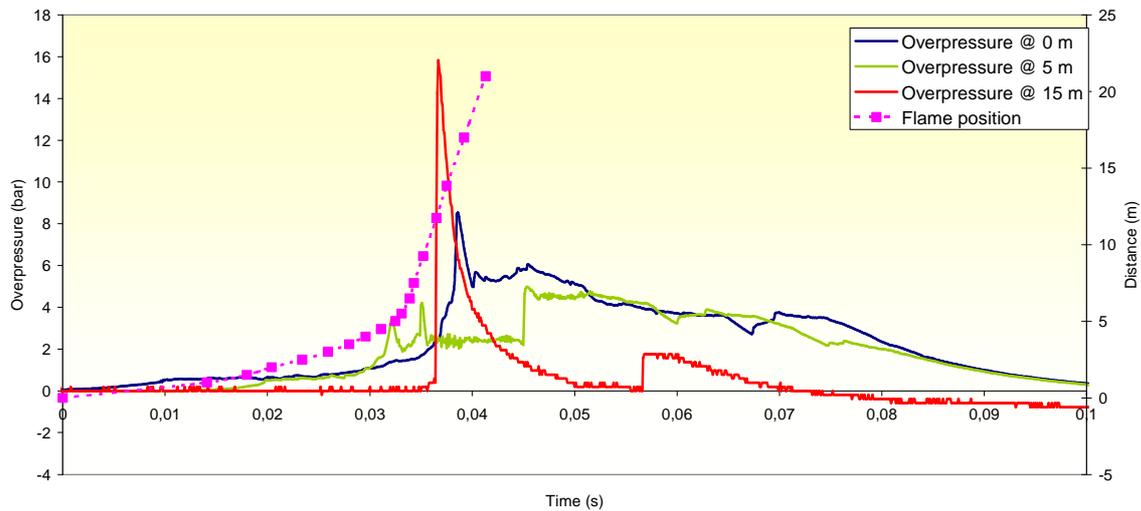


Figure 3 : Explosion overpressure (measured at the ignition point, 5 and 15 m downstream) and flame trajectory (100 mm diameter and 26 m long pipe, 6.5% v/v C_2H_4 -air)

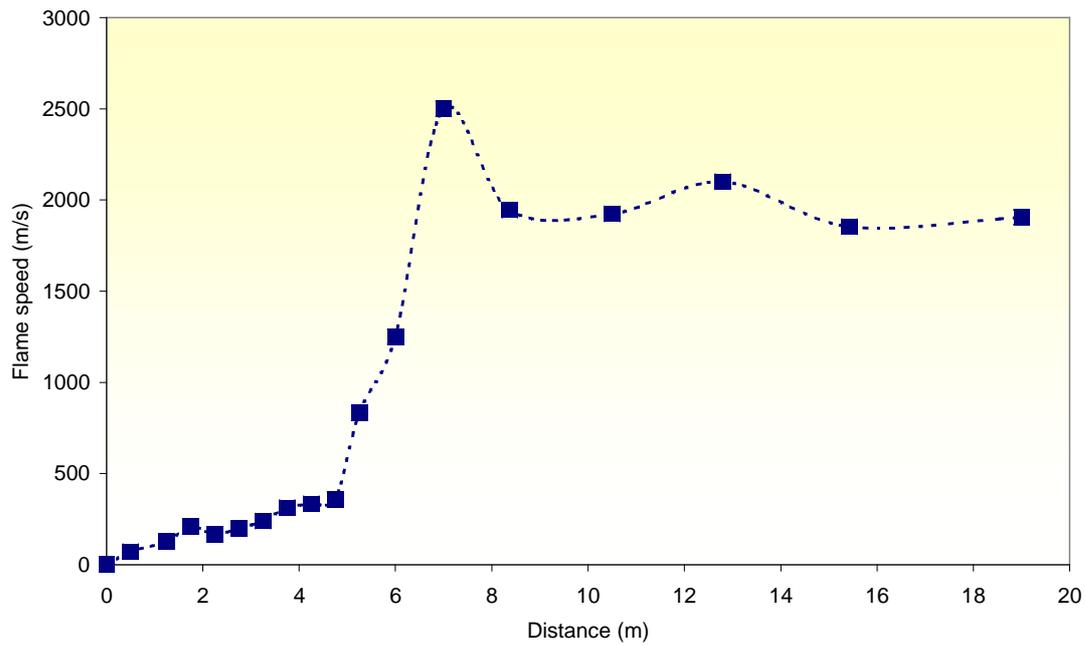


Figure 4: Flame velocity along the pipe (100 mm diameter and 26 m long pipe, 6.5% v/v C_2H_4 -air)

Other typical results are presented in the following figures showing the incidence of the length of the duct (figure 5), of the diameter of the duct (figure 6), of the composition of the mixture (figure 7) and of the nature of the gaseous fuel (figure 8).

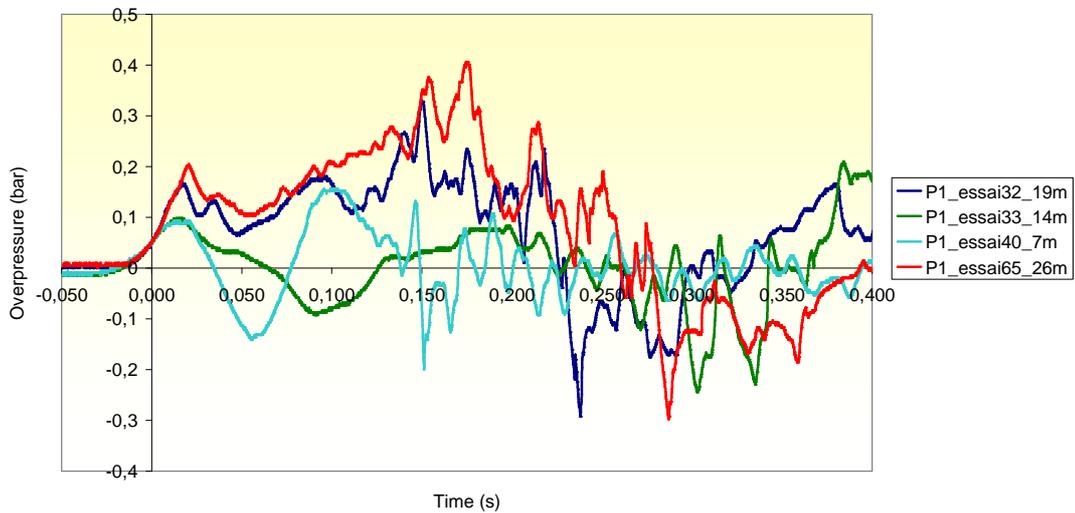


Figure 5: Pressure at the ignition end : 100 mm ID pipe, various lengths ($9.5 \pm 0.3\%CH_4$ -air)

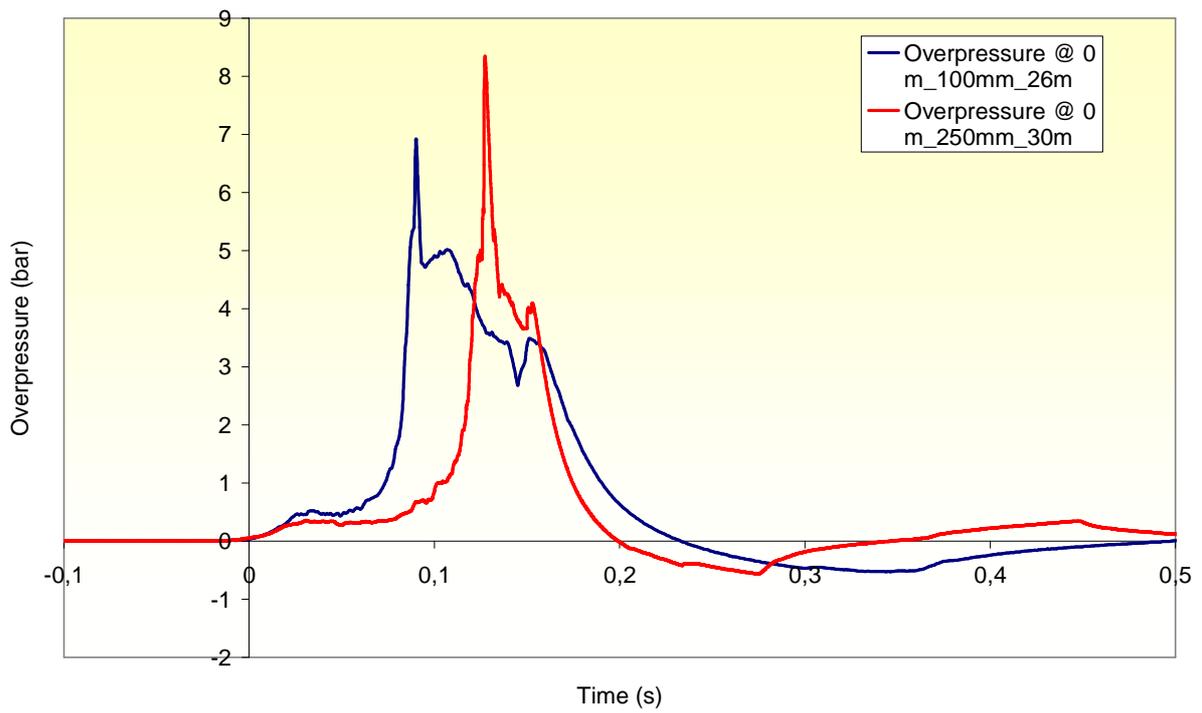
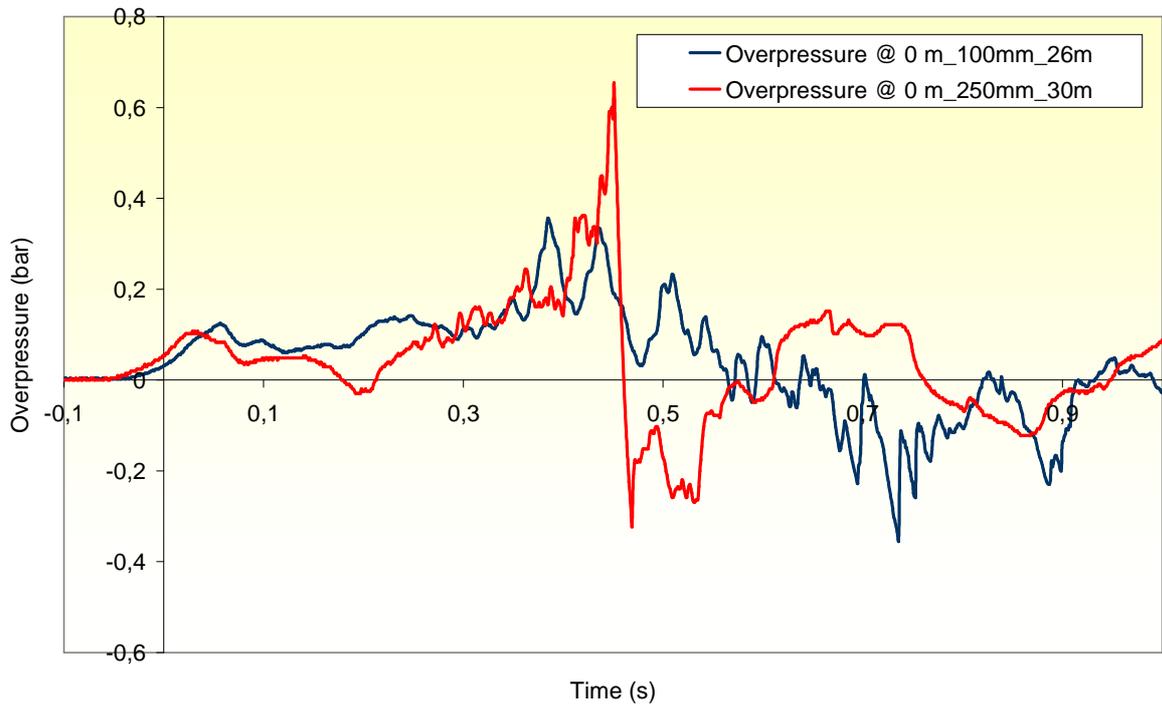


Figure 6 : Overpressure at the ignition end : 100 and 250 mm ID pipe, 26 and 30 m
($10 \pm 0.3\% \text{CH}_4$ -air top; $7.5 \pm 0.3\% \text{C}_2\text{H}_4$ -air bottom)

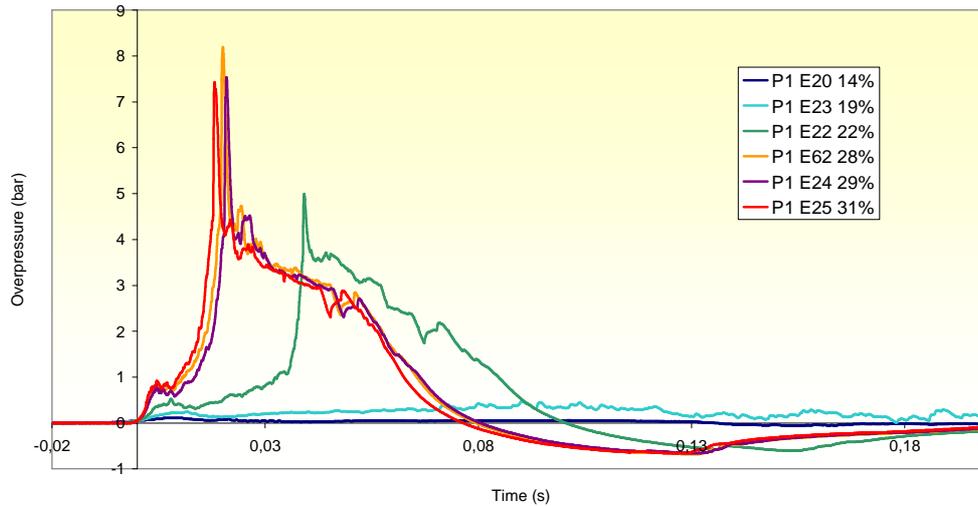


Figure 7 : Overpressure at the ignition end : 100 mm ID pipe, 26 m
(H₂-air various compositions)

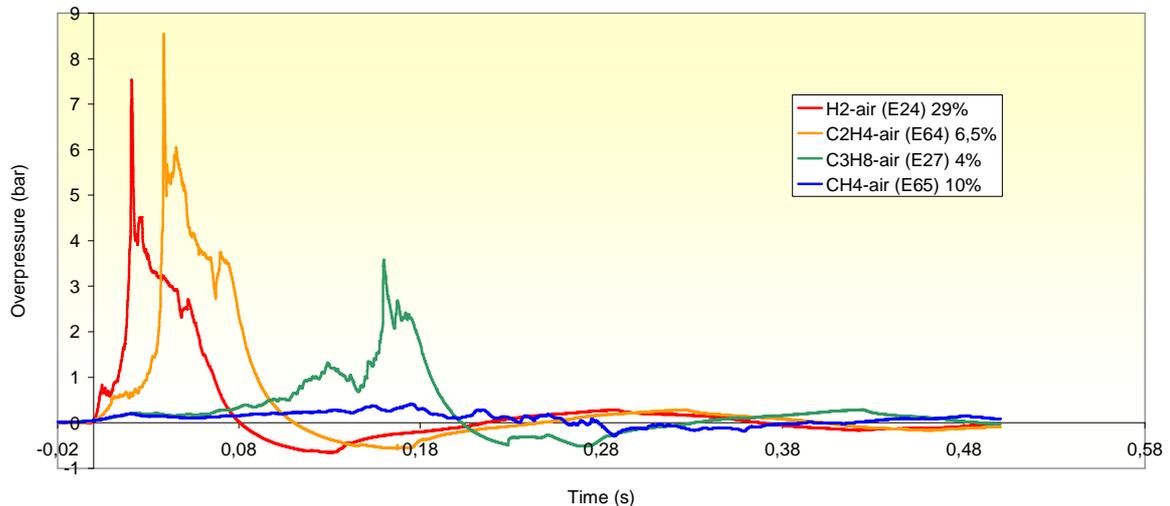


Figure 8 : Overpressure at the ignition end : 100 mm ID pipe, 26 m
(various fuels-air stoichiometric conditions)

4. Discussion

Obviously the reactivity of the mixture (nature, composition) is the leading parameter: the more reactive, the fastest the flame and the strongest the explosion effects. Then comes the length of the pipe but, apparently, it is difficult to clearly identify the incidence of the diameter. Kerampran came to the same conclusion.

It is possible to analyse further the pressure traces. Nearly systematically, the pressure signal is the superposition of a first nearly sinusoidal pressure pulse (see for instance at time 20 ms, 30 ms and 5-10 ms on figure 5, 7 and 8 respectively) followed by an exponential pressure growth until either DDT or flame exit. The amplitude of the first pressure pulse seems closely linked with the burning properties of the mixture. In sufficiently large pipes, it does not seem to depend significantly on the geometry of the pipe (table 3). As recalled above, direct

visualization of the flame development around the ignition point reveals that the flame grows as a “finger” until the sides extinguish when in contact with the outer walls. The pressure increase is closely linked with the expansion of the burned gases producing the measured pressure wave (piston effect). This phenomenon was modeled theoretically (Bychkov and al., 2007). In small tubes, the wall effects might be more pronounced. The typical duration of this phase is typically 50 ms for methane and 5 ms for hydrogen, roughly in proportion with the expansion velocities. Note that the one dimensional material velocity in the pipe produced during this expansion (ratio between the pressure and the specific mass of the reactants times the sound velocity) is about for methane 30 m/s and 150 m/s for hydrogen. This is about 10 times the expansion velocity suggesting an increase of the flame area amounting 10 times the cross section of the pipe. This is in full agreement with the existing data. Obviously, the mode of ignition should influence this phase (see below).

Table 3: Amplitude of the first pressure pulse in bar (stoichiometry only)

Fuel	$\sigma \cdot S_{lad}$ (m/s)	Pipe 100mm- 26m	Pipe 100mm- 14m	Pipe 250mm- 30m	Pipe 22mm- 1.2m	Pipe 40mm- 6m
methane	2.8	0.12	0.12	0.12	N.D.	N.D.
Propane	3.4	0.25	0.2	0.2	N.D.	0.15
Ethylene	5.7	0.50	0.35*	0.35*	0.25	N.D.
Hydrogen	16.1	0.75	0.7*	0.7*	N.D.	N.D.

*leaner than stoichiometry

This initial phase is also visible on figure 9 and 10 giving the evolution of the flame trajectories as function of the time. A flame speed “plateau” is visible especially for methane and propane for which the initial flame development is slower. Note the values of the flame speed are in good agreement with the above estimations. A detonation regime was clearly triggered for hydrogen and ethylene. The transition happens when the flame speed is on the order of 500 m/s and lasts about 2 m. For propane-air mixtures the DDT seems to occur close to the exit. The description of this phase is still a matter of debate (Oran and Gamezo, 2007). For our purpose, it is sufficient to realize that whenever the flame can accelerate above 500 m/s, DDT will spontaneously occur (Table 4).

Table 4: Transition to detonation (stoichiometric conditions), L_{DD} is the run up distance at which DDT occurs and V_{DDT} is the last deflagration speed measured before DDT

Tube	ID 100 mm		ID 250 mm	
	L_{DDT} (m)	V_{DDT} (m/s)	L_{DDT} (m)	V_{DDT} (m/s)
methane	N.O.	N.O.	N.O.	N.O.
Propane	18	>350	18	650
Ethylene	6	550	18*	600*
Hydrogen	5	550	9*	600*

*leaner than stoichiometry

It is thus of importance to focus of the acceleration phase from the initial flame development (“finger”) to this threshold velocity (figure 9 and 10). To a reasonable degree of certainty, during this phase, the flame is uniformly accelerated since the flame velocity seems to increase linearly with time. Note there is a transient phenomenon for methane around time 0.15 s. Considering the pressure traces (figure 5 test 65), it appears that after time 0.15 s, a set of pressure oscillations is triggered. 0.15 s is exactly the time required for a pressure wave to travel way and back inside the pipe¹. This pressure wave is certainly produced by the initial flame development. It can be verified that its amplitude is about 100-200 mbar and, following, the corresponding material velocity should be about 50 m/s². This value is in line with the observed velocity fluctuations on figure 10. It can be further noted that, in many cases, the duration of the explosion is smaller than 0.15 s so that the flame trajectory is not influenced by the resonance of the pipe. For shorter pipes, the pressure oscillations superpose with the acceleration process (Kerampran, 2000).

The coefficient of acceleration of the flame between this initial phase and the onset of the detonation regime were calculated plotting a linear regression curve in the graph time-flame velocity. The values are listed in table 5 for the experimental situations under concern. On the basis of the accuracy of the experiments, the acceleration coefficient seems to be mainly mixture dependent. Although some geometrical effects may intervene for the smallest experimental setups, they might remain of second order.

¹ Two times the length of the pipe (2 x 26 m) divided by the sound velocity of the mixture (340 m/s).

² The material velocity induced by the wave is the ratio between the overpressure (15000 to 20000 Pa) and the product of the specific mass (1.1 kg/m³) and sound velocity of the mixture (340 m/s)

Table 5: Flame acceleration coefficient for the various fuels-air mixtures used and various geometries (stoichiometry only)

Fuel	$\sigma \cdot S_{lad}$ (m/s)	Acc (m/s ²)				
		ID=100 mm	ID=100 mm	ID=250 mm	ID=22 mm	ID=40 mm
		L = 26 m	L = 14 m	L = 30 m	L = 1.7 m	L = 6 m
methane	2.8	1000	N.D	1500	N.D.	N.D.
Propane	3.4	4300	5000	3500	1000	2000
Ethylene	5.7	16000	18000	7000*	6000	N.D.
Hydrogen	16.1	45000	50000	20000*	N.D.	N.D.

*leaner than stoichiometry

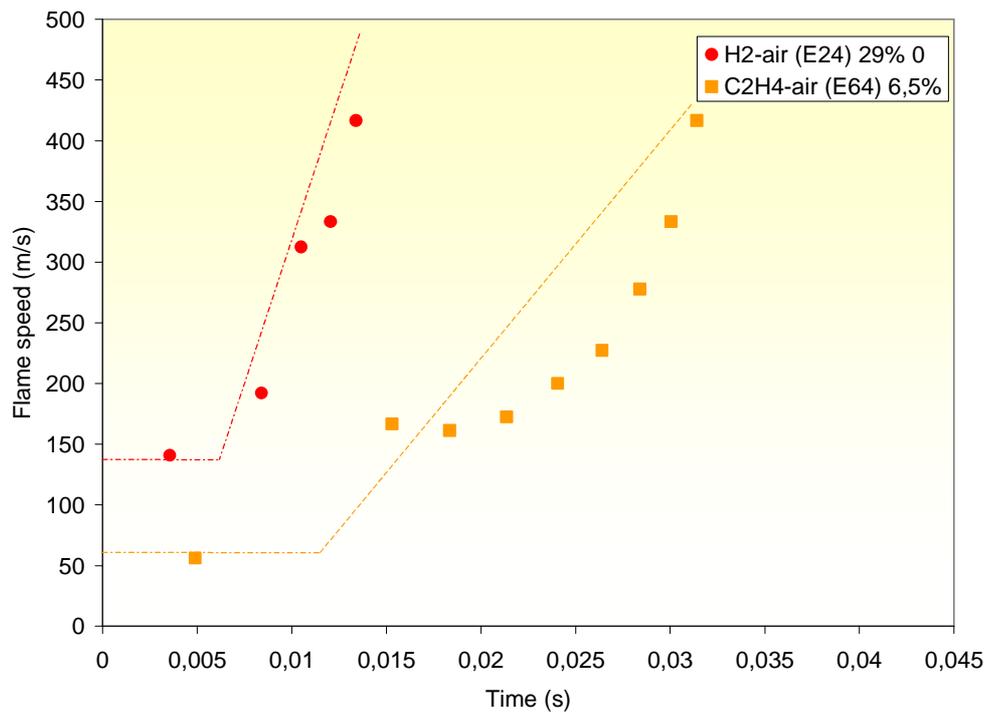


Figure 9 : Acceleration phase of the flame trajectory in the 100 mm ID pipe, 26 m (H₂-air and C₂H₄-air stoichiometric mixtures)

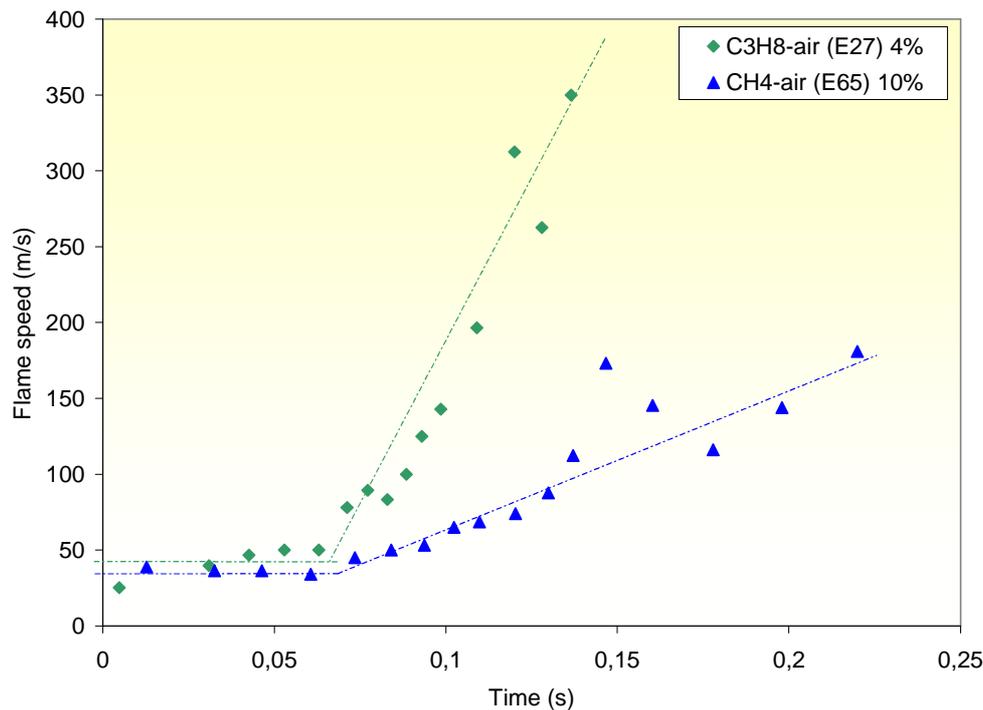


Figure 10 : Acceleration phase of the flame trajectory in the 100 mm ID pipe, 26 m (C_3H_8 -air and CH_4 -air stoichiometric mixtures)

To conclude, the present experimental data suggest that the flame acceleration process leading eventually to a DDT, may not depend strongly on the geometry of the pipe but, to a considerable extent on the nature and composition of the fuel. This finding, if confirmed, might suggest that other parameters than the turbulence of the flow might intervene.

References

- Blanchard R., Arndt D., Grätz R., Poli M., Scheider S. (2010), Explosions in closed pipes containing baffles and 90 degree bends, *Journal of Loss Prevention in the Process Industries*, 23: 253–259
- Borghini R. (1988), Turbulent combustion modelling, *Progress in Energy Combustion Science*, 14
- Bray K. (1990), Studies of turbulent burning velocities, *Proceedings of the Royal Society of London*, A431: 315-325
- Byvchov V.V., Liberman M.A. (2000), Dynamics and stability of premixed flames, *Physics Reports*, 325: 115-237
- Byvchov V.V., Akkerman V., Fru G., Petchenko A., Eriksson L. (2007), Flame acceleration in the early stages of burning in tubes, *Combustion and Flame*, 150: 263-276
- Cicarelli G., Dorofeev S. (2008), Flame acceleration and transition to detonation in ducts, *Progress in Energy Combustion Science*, 34: 499-550
- Clarke J.F. (1989), Fast flames, *Progress in Energy Combustion Science*, 15
- Deshaies B., Joulin G. (1989), Flame-speed sensitivity to temperature changes and the deflagration to detonation transition, *Combustion and Flame*, 77: 201-212

- Dorofeev S. (2007), Hydrogen flames in tubes : critical run-up distances, *Proceedings of the International Colloquium on Hydrogen Safety*, San Sebastian, Spain, sept. 2007
- Ginsburg I., Buckley W.L. (1963), Hydrocarbon-air detonations...industrial aspects, *Chemical Engineering Progress*, 59: 82-86
- Hattwig M., Steen H. (2008), *Handbook of Explosion Prevention and Protection*, SBN 978-3-527-61247-5, Wiley
- Hinze J.O. (1975), *Turbulence*, 2nd edition, Mc Graw-Hill company, New-York, ISBN 0-07-029037-7
- Jones S.A.S, Thomas G.O. (1991), Pressure hot-wire and laser doppler anemometer studies of flame acceleration in long tubes, *Combustion and Flame*, 87
- Kerampran S. (2000), *Etude des mécanismes d'accélération des flammes se propageant depuis l'extrémité fermée vers l'extrémité ouverte de tubes horizontaux de longueur variable*, PhD thesis, Univ. Of Poitiers, France
- Kuznetsov M., Alekseev V., Matsukov I., Dorofeev S. (2005), DDT in a smooth tube filled with a hydrogen–oxygen mixture, *Shock Waves*, 14: 205–215
- Leyer J.C., Manson N. (1971), Development of vibratory flame propagation in short closed tubes and vessels, proceedings of the 13th Symposium (International) on Combustion, 551-557
- Leyer J.C. (1972), Importance des effets dynamiques liés au développement de la flamme lors de la combustion à volume constant des mélanges propane-oxygène-azote, *Revue de l'Institut Français du Pétrole*, 27: 229-316
- Lindstedt R., Michels H. (1989), Deflagration to Detonation Transitions and Strong Deflagrations in Alkane and Alkene Air Mixtures, *Combustion and Flame*, 76: 169-181
- Markstein G.H. (1964), *Non-steady flame propagation*, Pergamon Press, Oxford, U.K.
- NFPA 68: *Standard on Explosion Protection by Deflagration Venting*
- NFPA 69: *Standard on Explosion Prevention Systems*
- Oran E., Gamezo V. (2007), Origins of the deflagration-to-detonation transition in gas phase combustion, *Combustion and Flame*, 148: 4-47
- Proust Ch. (1996), Dust explosions in pipes : a review , *Journal of Loss Prevention in the Process Industries*, 9
- Silvestrini M. Genova B., Parisi G., Leon Trujillo F. (2008), «Flame acceleration and DDT run-up distance for smooth and obstacles filled tubes, *Journal of Loss Prevention in the Process Industries*, 21: 555-562
- Thomas G., Oakley G., Bambrey R. (2010), An experimental study of flame acceleration and deflagration to detonation transition in representative process piping, *Process Safety and Environmental Protection*, 88: 75–90
- Veser A., Breitung W., Dorofeev S. (2002), Run-up distances to supersonic flames in obstacle laden tubes, IV ISHPMIE, *Journal of Physics IV*, 12: 333-340.