Study of the Mechanisms of Flame Acceleration in a Tube of Constant Cross Section

S.Kerampran, D.Desbordes, B.Veyssière

Laboratoire de Combustion et de Détonique (UPR 9028 CNRS)
Université de Poitiers - ENSMA
Téléport 2 - B.P. 109 - Chasseneuil du Poitou- 86960 FUTUROSCOPE Cédex - France
e-mail : kerampra@lcd.ensma.fr

Abstract

Flame propagation in a tube of constant cross section was studied experimentally, using propane-air and ethylene-air mixtures. The flame trajectory displays an oscillatory behaviour which can be correlated to pressure records. The overall phenomenon is highly dependent on the mixture composition and the tube length.

The current knowledge of the fundamental mechanisms of flame acceleration does not permit to predict accurately the velocity of a flame (and therefore the pressure effects it generates) in a given experimental or industrial setup. This is why the prevention of explosion hazards in industrial plants where gaseous reactive are processed, which is one of the major topics in the field of industrial safety, remains a difficult task. It is all the more tricky since reaching flame velocities high enough for an explosion to occur depends not only on the intrisic properties of the reactive mixture, but also on many other parameters, including the size and geometry of the confinement, the presence of obstacles and the characteristics of the ignition source.

In the present work, we investigate the problem of flame acceleration in elongated tubular vessels, in order to obtain data allowing the phenomenon to be modelized. The experimental setup consists in a transparent tube (made of Plexiglass) of constant circular (21mm) cross section and of variable length (from 0.22 to 2.72m), closed at one end and open at the other one. Ignition of the reactive mixture is achieved at the closed end with a very weak (heated wire) energy source, ensuring that a laminar flame propagates toward the opposite open end. The progress of the flame front is recorded continuously with a high framing rate video camera. Pressure is recorded at the closed end and along the tube by piezo-electric pressure gauges. The mixture is initially at amospheric pressure and ambiant temperature (293K). We have chosen to focus our study on two main parameters: the tube geometry (its length, in particular) and the mixture reactivity.

A first series of experiments have been done using stoichiometric and slightly rich propane-air mixtures. An example of the pictures provided by the high framing rate video camera is shown in Fig.1. The ignition occurs on the right side of the picture, where the heated wire appears as a bright spot.

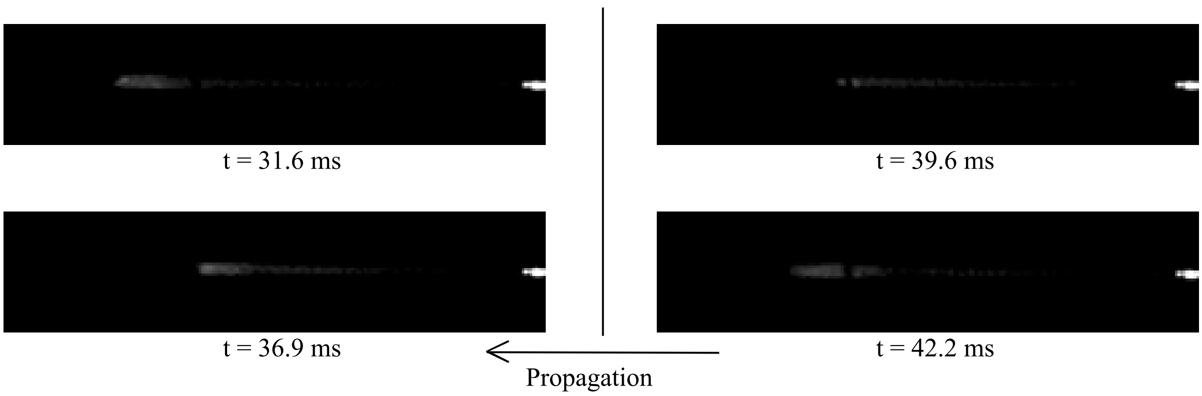

Fig.1. Flame propagation in a 1.22m-long tube.
Stoichiometric propane-air mixture

These pictures can be used to plot the flame positions versus time for a given tube length and a given mixture composition, as shown in Fig.2.

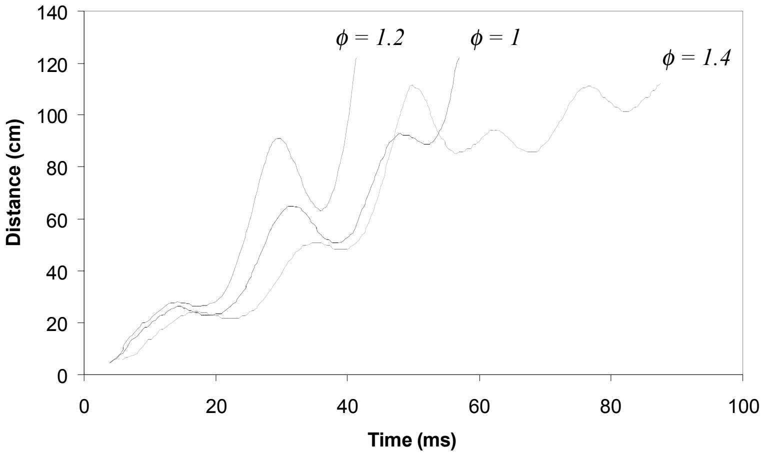

Fig.2. Flame position as a function of time for three propane-air mixtures.
Tube length 1.22m

It is observed that for tubes longer than 0.22m, the flame does not accelerate monotonically: after a certain propagation distance, the flame stops or even travels backwards before going on propagating forwards. This phenomenon may occur one or several times, depending on the tube length and the mixture composition, and seems to be of the same nature as that observed by Guénoche [1]. It appears that the measured flame velocity during the initial acceleration phase (up to the first stop of the flame) does not depend on the tube length, but only on the mixture composition, and has a mean value of $25ms^{-1}$, which is much higher than the spatial velocity predicted for a laminar flame propagating in the considered mixtures (about $3.2ms^{-1}$ for a stoichiometric propane-air mixture). The flame always has a higher velocity when it resumes its propagation toward the open end of the tube than before it stopped. The position of the first stop of the flame slightly depends on the tube length and the mixture composition.

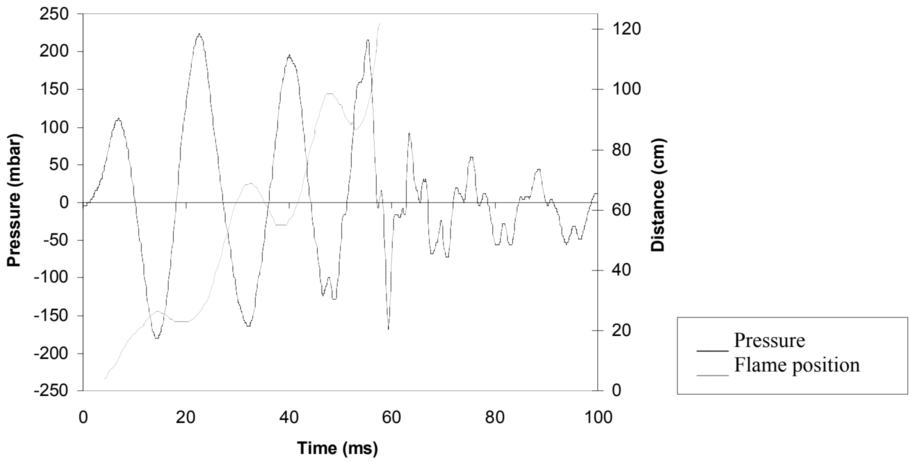

Fig.3. Pressure measurement in a 1.22m-long tube. Stoichiometric propane-air mixture.
Pressure gauge located at the closed end of the tube.

Pressure records diplay an oscillatory variation of the pressure in the tube, as shown in Fig.3. These records can be split up in two consecutive phases. While the flame propagates in the tube, several high magnitude pressure peaks are observed. After the flame exits the tube, the pressure oscillations are of a lesser magnitude and eventually decay. Their frequency decreases as well, because of the cooling of the burnt gases which results in a lower sound velocity. The frequencies recorded, both during and after the flame propagation, depend only on the tube length and can be correlated to the acoustic vibration modes of the tube. The agreement with the frequency of the fundamental mode in the fresh gases is satisfying before the flame exits the tube, as shown in Table 1. After the flame exits the tube, the agreement with the frequency of the fundamental mode in the burnt gases (calculated assuming adiabatic flame temperature) is not as good, because of heat losses at the tube walls.

When the flame position is correlated with the pressure records, it can be observed that the pressure is at its lowest when the flame stops and at its highest when the flame resumes its propagation toward the open end of the tube. This indicates that the origin of the behaviour of the flame is likely to be linked to the interactions between the flame and the pressure waves it generates during its propagation.

Tube length (cm)	22	72	122	172
Oscillation frequency of the fundamental mode in the fresh gases (Hz)	386	118	70	49
Oscillation frequency before the flame exits the tube (Hz)	/	93	63	47
Oscillation frequency of the fundamental mode in the burnt gases (Hz)	993	304	179	127
Oscillation frequency after the flame exits the tube (Hz)	833	156	81	53

Table 1. Measured oscillation frequencies compared with the frequency of the fundamental mode of the tube as a function of tube length

Further experiments have been made with ethylene-air mixtures. In spite of the increase in the burning velocity ($0.7 ms^{-1}$ for a stoichiometric ethylene-air mixture), the overall behaviour of the flame is the same as the one observed for propane-air mixtures. In particular, the flame velocity during the early acceleration phase seems to be still independent of the tube length. A few differences may be pointed out, nonetheless. The flame does not travel backwards after it has stopped for tubes longer than 0.72m. Furthermore, the pressure records related to this case display oscillations of lesser magnitude around a higher mean value after a certain propagation time, as shown in Fig.4. The pressure minima and maxima still seem to be linked to the stops of the flame and the ensuing accelerations. The fact that the pressure records are not as regular as those obtained for stoichiometric propane-air mixtures appears to be intimately linked to the fact that the flame does not move backwards in the present case.

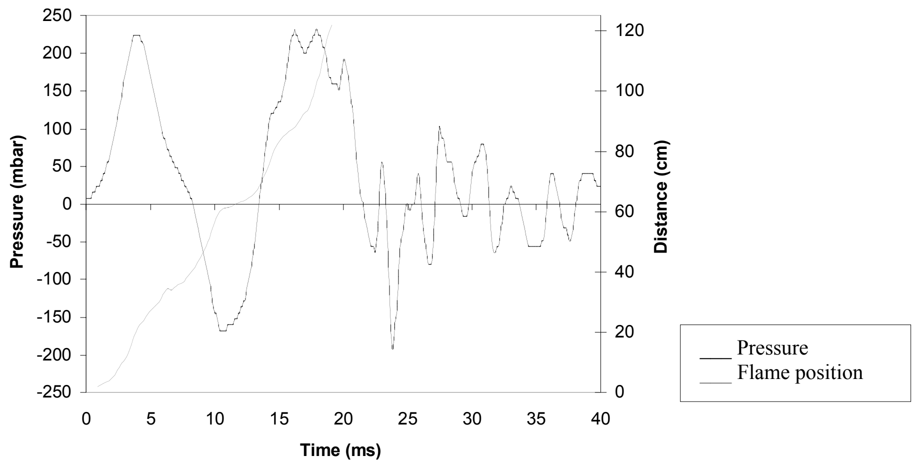

Fig.4. Pressure measurement in a 1.22m-long tube. Stoichiometric ethylene-air mixture. Pressure gauge located at the closed end of the tube.

In conclusion, it seems that the oscillatory behaviour of the flame is closely linked to the pressure waves it generates during its propagation. The fact that the oscillation frequency of the pressure can be related to that of the fundamental mode of the tube would suggest that the pressure field in the tube is governed by the early motion of the flame. The flame then interacts with this pressure field during its propagation, which makes it possible to correlate the flame front position with the pressure records. The experiments made with ethylene-air mixtures show that the phenomenon is highly dependent on the burning velocity of the mixture.

References

[1] H. Guénoche, *Non-steady flame propagation (G.H. Markstein, Ed)*, Pergamon, Berlin, pp 107 - 181, 1964.

Acknowledgements

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