Propagation of a Flame from the Closed End of a Smooth Horizontal Tube of Variable Length

S.Kerampran, D.Desbordes, B.Veyssière

Laboratoire de Combustion et de Détonique (UPR 9028 CNRS)
Université de Poitiers – ENSMA
veyssiere@lcd.ensma.fr

Introduction

It is well known that flames propagating in tubes can accelerate (because of intrinsic properties or external aerodynamic perturbations) and eventually undergo deflagration to detonation transition (DDT), which is a major concern as far as industrial safety is concerned. In a previous paper [1], we have studied flame propagation in circular Plexiglas tubes, with an inner diameter of 21 mm and a length L varying from 0.22 m to 2.72 m, closed at the ignition end and open at the other, for mixtures of propane, ethylene and acetylene with air. For flames with a low laminar flame velocity $V = \alpha.S_u$ (α denoting the isobaric expansion ratio and S_u the laminar burning velocity), oscillatory propagation has been observed, due to the acoustic oscillations of the column of gas in the tube. Further analysis of the experimental data collected has shown that:

- in the case of oscillatory flame propagation, the average flame velocity V_m (defined as the ratio of the tube length to the time at which the flame reaches the open end of the tube) does not depend on the tube length for a given reactive mixture.
- the early stage of propagation does not depend on the tube length, but only on the laminar flame velocity V.

Experiments were not performed for tube lengths greater than 2.72 m because of the important hazard of DDT occurrence, which the experimental set-up was not able to sustain.

This paper presents the first results obtained in a new experimental set-up specifically designed to further study the influence of the tube length on flame propagation. Given the high number of experiments required to fully investigate this phenomenon, the present study has mainly been restricted to propane-air mixtures so far, i.e. mixtures for which oscillatory propagation has previously been observed (the flame laminar velocity V is approximately 3.0 ms^{-1} for this mixture).

Experimental set-up

The experimental set-up is made of a stainless steel tube equipped with windows, in order to visualize flame propagation. This tube has a square cross-section (40 mm x 40 mm) and its length can be varied from 0.6 m to 8.1 m. It is composed of 0.5 m-long modular elements, which makes it fairly easy to change the tube length. The tube is connected to a large tank, in order to collect the unburnt gases ejected during flame propagation. Ignition is achieved at the closed end, with a heated wire. Flame propagation is recorded with a high framing rate video camera (these records are used to derive flame front trajectories), and pressure is recorded with piezoelectric transducers located at the closed end and at some point along the tube.

Experimental results

Figure 1 shows flame trajectories and pressure records for two tube lengths, in the case of a stoichiometric propane-air mixture. Experiments have shown good reproducibility. Flame propagation in tubes shorter than 3.6 m was similar to that observed in the previous set-up [1]. For a tube length L of 3.6 m, flame propagation can be divided in two parts :

- $t \leq 60$ ms : the flame undergoes several small-amplitude oscillations. The associated pressure record shows two large amplitude (150 mbar) oscillations, with a frequency of the same order of

- magnitude as the frequency of the fundamental vibratory mode of the column of gas in the tube (calculated for the unburnt gases).
- $t > 60$ ms : flame movement becomes jerky (although this is hardly apparent on Fig. 1, because the plot has been scaled down) and a large amplitude oscillation is recorded just before the flame exits the tube (at $t_s = 132$ ms). The pressure record exhibits several pressure oscillations with a higher frequency than those observed during the first step of propagation.

In the case of a longer tube (L = 7.1 m), it can be seen that flame behaviour is the same until, at some stage (t = 150 ms), the flame starts oscillating around a mean position (x = 5.5 m) and eventually extinguishes without reaching the open end of the tube. The associated part of the pressure record consists in several high frequency oscillations. The overall behaviour of the flame in this experimental set-up seems consistent with our previous observations.

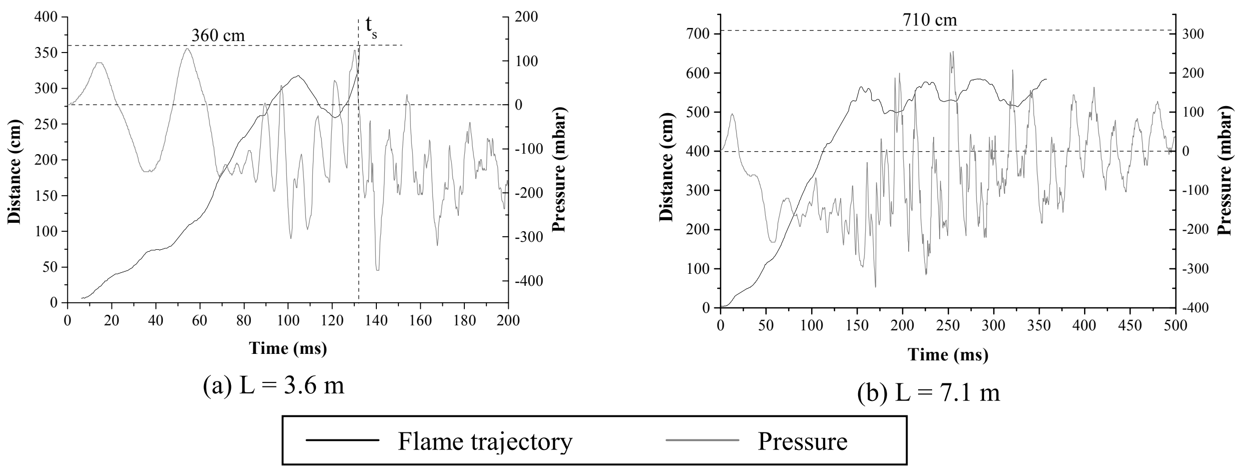

Fig. 1 Flame front trajectory and pressure record
(gauge located at the closed end of the tube) - C_3H_8/air ($\phi = 1$)

The influence of the tube length on flame propagation can readily be seen by considering the evolution of the average flame velocity V_m and the flame velocity V_s at the open end of the tube when the tube length is increased (fig. 2). Contrarily to observations in the first experimental set-up [1], V_m is dependent on the tube length. Increasing the tube length does not necessarily result in higher values of V_m. Although V_s varies approximately in the same way as V_m, it is in fact highly dependent on whether the flame undergoes a large-amplitude oscillation right before exiting the tube (such as in fig. 1) or not.

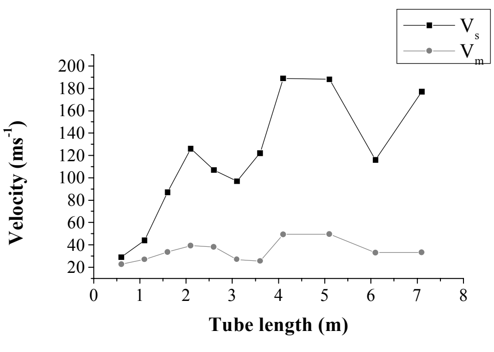

Fig. 2 Dependence of the average flame velocity V_m and the flame velocity at the open end of the tube V_s on the tube length L - C_3H_8/air ($\phi = 1$)

Role of acoustics

In order to ascertain the acoustic origin of the flame oscillations, experiments were performed with a stoichiometric propane-air mixture diluted with helium. The sound velocity in this mixture is about 600 ms^{-1} and the laminar flame velocity slightly larger than that of the stoichiometric propane-air mixture (it was estimated at 5.6 ms^{-1}). The results obtained in a 2.1m-long tube for both mixtures are compared in figure 3. Oscillations of the flame front are more numerous during the propagation in the helium-diluted mixture (which was expected as the consequence of an increase of the sound velocity) and the flame does not reach the open end of the tube. The acoustic oscillations of the column of gas in the tube and the high diffusivity of helium in air are likely to be responsible for a mixture composition below the lower flammability limit at the open end of the tube.

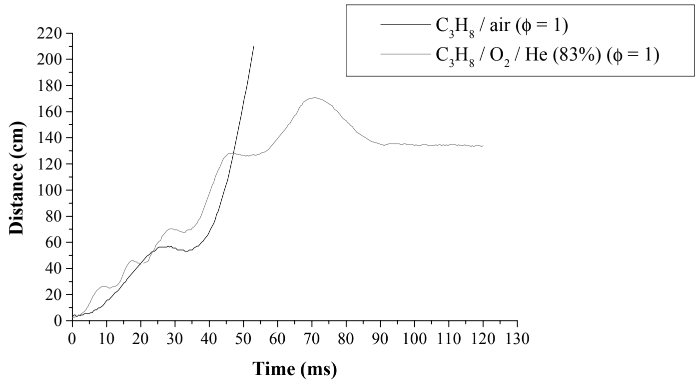

Fig. 3 Comparison of flame trajectories for two reactive mixtures with different sound velocities - L = 2.1 m

Pressure records have been systematically analysed using Fast Fourier transform (FFT) and low-pass filters. Energy spectra derived by this analysis always show a first maximum at a frequency close to the frequency of the fundamental vibratory mode of the column of gas in the tube, as can be seen in figure 4. Depending on the tube length, several other maxima can be observed, at frequencies corresponding approximately to the frequencies of the first to fourth harmonic modes of the column of gas.

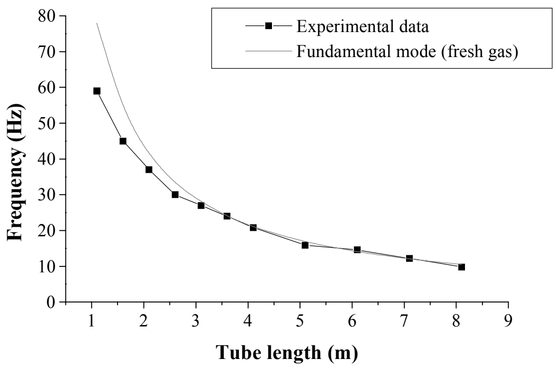

Fig. 4 Frequency of the first maximum observed on energy spectra as a function of tube length L C_3H_8/air (ϕ = 1)

Initial stage of flame propagation

Particular attention has been paid to the beginning of propagation. Figures 5 and 6 show the flame trajectory and pressure evolution corresponding to this stage of propagation, for increasing tube lengths. The flame trajectory is independent of the tube length, whereas the amplitude of the first overpressure increases when the tube length is increased, up to a limit value ΔP_a reached for a critical tube length L_a. L_a is the minimal tube length for which the rarefaction waves reflected at the open end of the tube do not have time to reach the closed end and interfere with the initial pressure build-up. This again is in good agreement with our former observations.

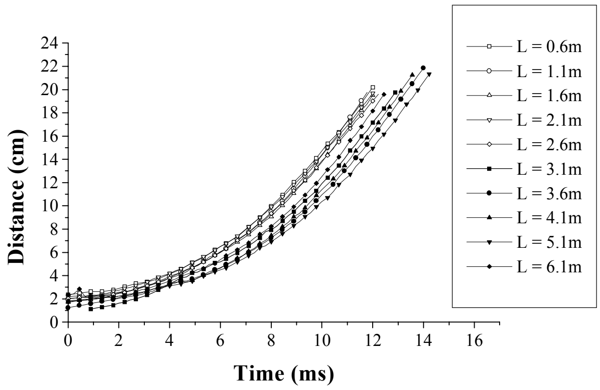

Fig. 5 Initial stage of flame propagation as a function of tube length - C_3H_8/air ($\phi = 1$)

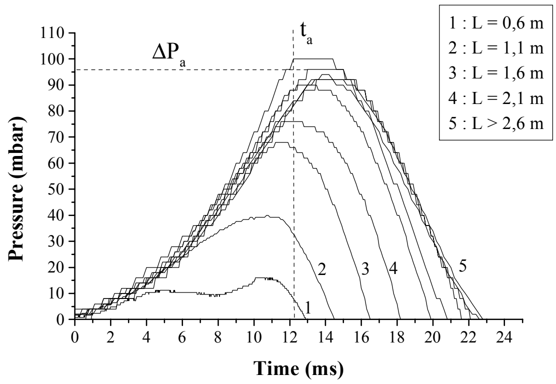

Fig. 6 Amplitude of the first overpressure as a function of tube length - C_3H_8/air ($\phi = 1$)

Making the assumption that the flame is axisymetric, its surface can be estimated from photographic records provided by the high framing rate video camera, as shown on figure 7. S_{F1} denotes the surface of a paraboloid and S_{F2} that of a cylinder connected to a hemisphere, both adjusted to fit the flame front. The respective ratios σ_1 and σ_2 of surfaces S_{F1} and S_{F2} to the tube cross section are compared to the ratio V_F/V of the flame velocity V_F to the laminar flame velocity V (= $\alpha.S_u$) in figure 8, in the case of a tube length L of 1.6 m. The good agreement between σ_2 and V_F/V indicates that the initial flame acceleration is only due to the increase of flame surface during this stage of propagation. This matches the observations of Clanet and Searby [2].

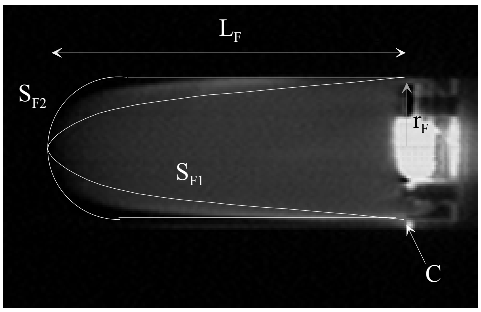

Fig. 7 Estimation of flame surface

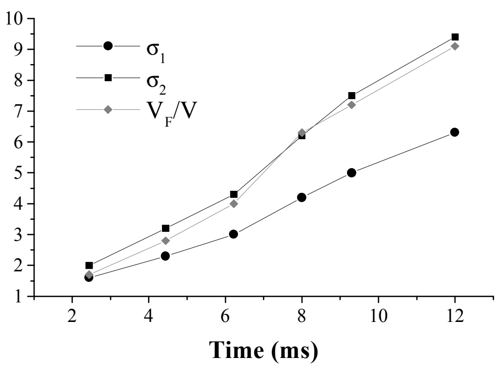

Fig. 8 Comparison of flame surface growth and flame velocity – L = 1.6 m - C_3H_8/air ($\phi = 1$)

Chu has shown that a slight variation of flame velocity δV_F generates pressure waves at the flame front, which propagate both in the fresh and burnt gases [3] The associated pressure variation δP can be expressed as follows:

$$\frac{\delta P}{P} = \frac{\gamma_f(\lambda-1)}{\sqrt{\lambda\frac{\gamma_f}{\gamma_b}+1}}\frac{\delta V_F}{c_f}$$

subscripts f and b refer respectively to the fresh and burnt gases, and λ denotes the ratio of the stagnation temperatures on both sides of the flame. We have used this relation to calculate a theoretical evolution of the pressure (ΔP_{th}) during the initial flame acceleration. The results obtained in the case of a 1.6 m-long tube are compared to the corresponding evolution of the experimental pressure ΔP_{exp} in figure 9. The good agreement between both series of values shows that, during the first stage of propagation, the pressure increases as a result of flame motion. The flame initially behaves as a "piston" on the fresh gases ahead of it and sets them into motion, thus generating the acoustic oscillations of the column of gas in the tube.

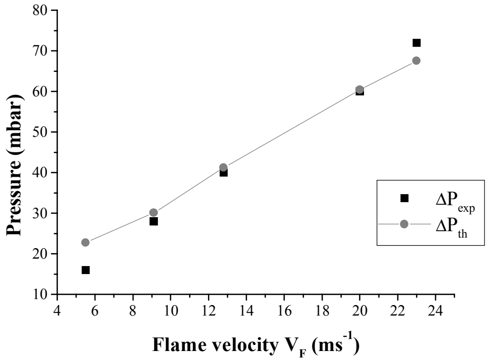

Fig. 9 Comparison of theoretical and experimental values of the overpressure during the initial stage of propagation – L = 1.6 m - C_3H_8/air (ϕ = 1)

Concluding remarks

In the case of a flame having a moderate laminar velocity (here 3.0 ms^{-1}), the propagation can be split in two consecutive stages:

- the initial flame development, during which the flame sets the fresh gases in motion, acting as a piston, and accelerates because of its surface growth,
- the acoustic stage, during which the flame propagates in the oscillatory flow of gas in the tube and undergoes several oscillations, since its velocity with respect to the unburnt gases is smaller than the acoustic velocity of the gas in the tube.

The results presented here are in good agreement both with observations previously made in a smaller scale experimental set-up and with the predictions of a one-dimensional acoustic model [4]. Analysis of the second stage of propagation, and in particular of the evolution of the flame front during the interactions with the oscillatory flow of gas, will be addressed in a forthcoming paper.

References

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