Effect of tube length on flame acceleration and DDT in tubes of constant cross section

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Introduction

Elucidating the mechanisms of flame acceleration in a horizontal tube of constant cross section is a problem of great importance for fundamental reasons as well as for practical applications. Indeed, a quantitative model able to predict the acceleration of a flame in the basic configuration of a constant cross section smooth wall tube does not exist yet now. In the same time, there is an important need to improve safety of industrial plants, where more and more often complicated networks of vessels and channels are present. But methods available for designing plants so that to prevent accidental explosions and their effects remain largely empirical.

The case of a flame ignited at the closed end of a tube and propagating toward the open end is of particular interest as it is the most favourable for flame acceleration: at the same time, the flame is pushed from the back side by burnt products which are confined by the closed part of the tube, and propagates in the fresh mixture which is moving in the same direction as the flame front, toward the open end. Thus, in such a situation, DDT can be expected to occur.

In preceding works /1/, /2/, /3/, it was shown that acoustic effects could play a determining role at the initial stage of flame propagation. Under certain circumstances, interaction of the longitudinal oscillations of the column of gases in the tube with the flamefront may prevent flame acceleration, and the average flame speed inside the tube remains smaller than the sound speed. It was demonstrated /3/ that the initial value of the laminar flame speed V = α .S_u (α is the expansion ratio and S_u the laminar burning velocity) was one governing parameter of the phenomenon.

Better understanding of the flame acceleration mechanisms requires further investigation of the role played by the tube length. First results are exposed in the present paper.

Experimental conditions

Experimental results discussed hereafter have been obtained in three different setups, the main characteristics of which are the following:

A - 21mm diameter, circular cross section tube, with a length varying from 0.72 m to 2.72m by sections of 0.5 m. The tube is transparent (plexiglass).

B - 40 mm x 40 mm, square cross section tube, with a length varying from 0.6 m to 8.1m by sections of 0.5 m. This tube is steel made (can support 40 bar static pressure) and equipped with lateral glass windows which permit to follow flame propagation along a 4m distance.

C - 100 mm diameter, circular cross section tube, with a fixed length of 26 m. This tube is steel made over the whole length and is equipped with photocells for flame detection.

In all cases, ignition is achieved at the closed end by a heated wire; thus, a laminar flame is generated. One pressure gauge is disposed at the closed end and other ones at different locations along the tubes. Details of the experimental setups and procedure can be found in /1/, /2/, /4/.

The tested gaseous mixtures are stoichiometric mixtures of air with propane (P1), ethylene (E1) or acetylene (A1).

Experimental results.

Experiments performed in the large tube (C) have displayed two different flame behaviours.



With mixture P1, the flame speed progressively increases up to about 50m/s (see Fig.1). Beyond a 10-12 m propagation distance, the flame slows down and, in some cases, photodetectors fail to record flame propagation, which let think that it could be extinguished. On the opposite, with mixture E1, flame speed rapidly increases to reach values of the order of magnitude of a few hundred meters per second at 5 m (see Fig.2). At that moment, the flame accelerates strongly until it goes out of the tube. At the exit, velocities of the order of magnitude of 2000m/s are recorded, which let suppose that DDT occurred. Pressure gauges located at the closed end reveal that pressure evolution present common characteristics: a first pressure maximum P_{max1} (~200-400 mbar) occurs early after ignition, followed by a pressure decrease. Then, it increases again toward a second maximum P_{max2}. However, place of occurrence and amplitude of this second maximum are completely different in the two cases. With mixture P1, the second maximum occurs before the flame reaches the tube exit and its value is about 400 mbar. On the opposite, with mixture E1, P_{max2} is observed at the moment the flame leaves the tube and its value is at least 10 times higher (5-10 bar). The first stage of pressure evolution (increase of pressure to P_{max1} followed by pressure decrease) was shown to be independent on the tube length /1/, /2/ and to depend on the gaseous mixture /1/, /4/. It corresponds to the period during which a spherical flame expands after ignition and enters in contact with the tube walls: during this period, increase of flame speed is proportional to augmentation of flame area; then, competition between increase of burning rate and heat losses to the walls results in a finger shaped flame propagating with a quasi-constant velocity. At the subsequent stage, flame accelerates, which results in a re-increase of pressure. Differences observed in pressure evolution at the closed end of the tube between the different mixtures can be interpreted by means of a simple analysis. In the initial stage of propagation, the laminar flame may be modeled as a semipermeable piston with an initial speed V = α S_u (S_u is the laminar burning velocity, α is the expansion ratio $\rho_{\rm f}/\rho_{\rm b}$). At the moment of ignition, it emits a compression wave propagating in the fresh gases toward the open end of the tube, where it reflects into a rarefaction wave propagating toward the flame front. This interaction plays a determining role on the further evolution of the flame. Indeed, it can be seen in Fig.1 (mixture P1, V = 3 m/s) that this first rarefaction wave interacts with the flame front at about 7 m from the closed end and is responsible for the decrease of the pressure beyond P_{max2} . On the opposite, Fig.2 (mixture E1, V = 5.3 m/s) reveals that the flame has left the tube even before the reflection of the first compression wave. This means that the flame front has not been attenuated by the first rarefaction wave and was able to accelerate by its own dynamics and to transit to detonation.

Experiments performed in the small tube (A) with mixture A1 lead to similar conclusions. As observed in Fig.3, pressure evolution recorded at the closed end is very similar to that of Fig.1. However, here, the tube length is only 1.72 m, but the initial flame speed V is 11.8 m/s for mixture A1, instead of V = 3 m/s for mixture P1. Again, the value of P_{max2} is obtained as the result of the attenuation of pressure increase by the counterflow rarefaction wave. This is confirmed when comparing the pressure evolutions recorded in the same conditions for different tube lengths: as seen in Fig.4, the pressure signals are perfectly superposed at the beginning, until the interaction of the flame with the first returning rarefaction wave. When diminishing the tube length, the interaction occurs too early for the pressure to re-increase under the effect of flame acceleration. Note that the phenomenon is globally the same as for flame propagation with mixture P1 in setup (C), but characteristic times of typical events are divided by more than 10.



Fig.3 – Flame trajectory and pressure recorded at the closed end of the tube - Setup *A* - mixture A1



Fig.4 – Pressure recorded at the closed end of the tube for different lengths - Setup *A* - mixture A1

In the case of Fig.3, flame velocity at tube exit is greater than 500 m/s. It is likely that with a slightly longer tube, DDT could be reached. But it was not possible to observed it with this setup (A) because for longer distances, the plexiglass tube is not sufficiently resistant and would burst.

Above conclusions are confirmed by experiments conducted in setup (*B*) with mixture P1. Fig.5 (tube length = 6.1 m) corresponds approximately to the situation displayed in Fig.3, but the interaction between the flame front and the rarefaction wave takes place farther from



Fig.5 – Flame trajectory and pressure recorded at the closed end of the tube - Setup B -L = 6.1m - mixture P1

Fig.6 – Flame trajectory and pressure recorded at the closed end of the tube - Setup B -L = 3.6m - mixture P1

the open end of the tube than in Fig.3. As a result, pressure oscillations are recorded during the subsequent stage of flame propagation with frequencies evolving from the fundamental mode of vibration of the column of gases in the tube, up to higher modes as revealed by Fourier transform analysis (see /2/). In Fig.6 (tube length = 3.6 m), interaction occurred earlier, during the stage of pressure decrease after P_{max1} , thus the fundamental mode of vibration becomes more accentuated.



Fig.7 – Flame trajectory and pressure recorded at the closed end of the tube - Setup B - L = 2.6 m - mixture P1

In the case of Fig.7 (tube length = 2.6 m), interaction occurred even before the first pressure maximum P_{max1} has been reached. In this situation, the fundamental mode of vibration becomes predominant, and flame propagation is strongly governed by acoustic oscillations of the column of gases inside the tube, which prevent flame acceleration.

Concluding remarks

From the preceding results, it appears that after ignition at the closed end of the tube, the first stage of flame development has a determining influence on the possibility for DDT to occur at a subsequent stage of flame propagation. As long as the flame has not been perturbed by the first rarefaction wave returning from the opposite open end, it can accelerate under the effect of its own dynamics. Thus, it is confirmed that for a horizontal tube of constant cross section, longitudinal acoustic effects may play an important role for delaying flame acceleration. This effect is a function of tube length, which is a geometric parameter depending on the confinement, and of the initial flame speed V, which is an intrinsic parameter of the reactive mixture (depending on the laminar burning velocity and the expansion ratio). To prevent flame acceleration, mixtures with a high value of V (such as mixture A1) require much shorter tubes than mixtures having lower values of V. The required value of tube length moderately depends on its cross section size, which confirms that the phenomenon is dominated by the longitudinal vibration modes. Our first experiments seem to indicate that the critical tube length could roughly vary as the inverse of the square of V. In other respects, it is not possible to decide, in the state of our knowledge, if augmentation of tube length beyond 26 m would permit to observe DDT in mixture P1. Hence, further studies are needed before giving reliable conclusions which could permit to propose quantitative rules for designing plants where DDT could be avoided in case of undesired ignition of a reactive mixture.

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