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Gas flame acceleration in long ducts

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A B S T R A C T

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 detonation run-up distance and the pipe diameter is used without any strong justification other that 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.

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 and Steen, 2008) 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

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Fig. 1. Equipment used by Kerampran (2000), 4 m long tube, 40 mm wide, square cross section.

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 et al., 2002, Dorofeev, 2007, Kuznetzov et al., 2005, Silvestrini et al., 2008). Silvestrini for instance proposes the following correlation:

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

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 Vf 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 et al., 2010, Blanchard et 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

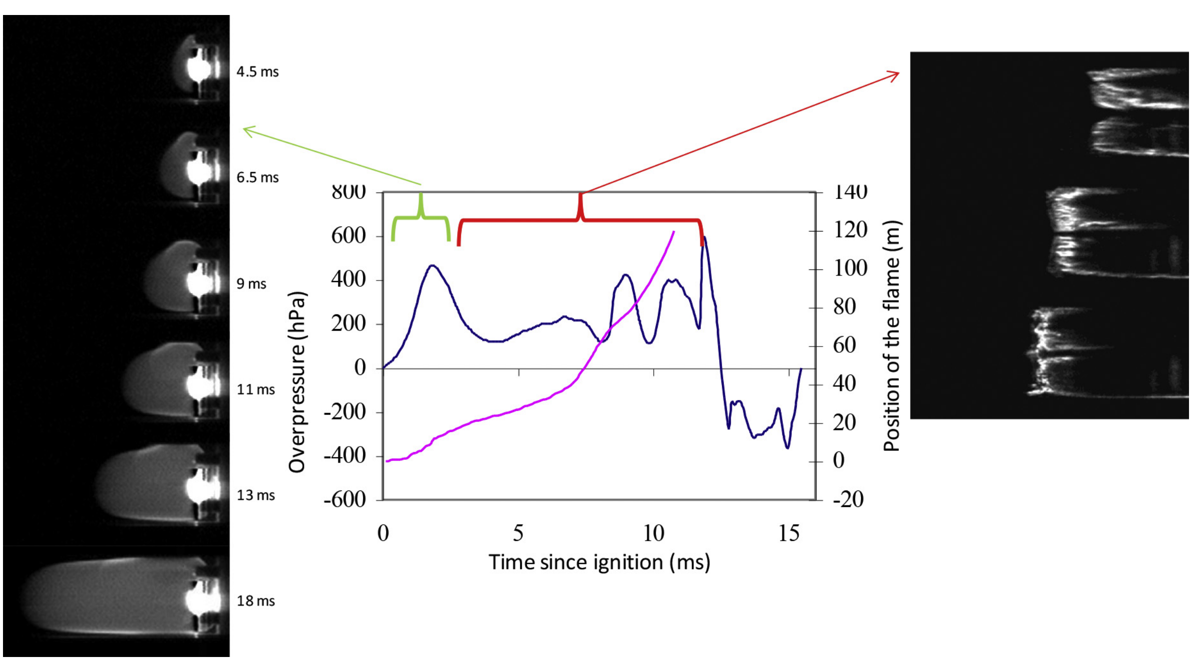

Fig. 2. Flame propagating in an acetylene-air mixture (1.22 m long tube, 22 mm diameter from Kerampran, 2000: the picture were taken with the larger apparatus and are given to illustrate the aspect of the flame).

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