Interaction of acoustic waves with flame front propagation

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Interaction of Acoustic Waves with Flame Front Propagation

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The mechanisms of laminar premixed flame propagation have been intensively studied over the last century. Numerous authors have highlighted intrinsic phenomena in flame propagation such as Darrieus-Landau instability and Rayleigh-Taylor instability. Rayleigh-Taylor instability is often linked to the interaction between the flame front and an acoustic wave.

To better characterize the interaction between a flame and aerodynamic conditions, we designed a special vertical closed tube apparatus. Our analysis focused on the behavior of a flame that propagates in a uniform stoichiometric mixture of H_2 *and* O_2 *diluted with nitrogen. The experimental investigation revealed that acoustic waves emitted as the flame formed near the ignition point could increase the flame front surface by a factor of 10. An acoustic node with an amplitude of 1.3 m was identified and seemed to be responsible for the disappearance of one of the acoustic modes and for a reduction in the average flame surface. This could explain why the flame trajectory had two distinct parts: one corresponding to propagation at a high speed in the lower part of the tube, and the other with a slower speed in the upper part of the tube. The flame surface seemed to depend primarily on the frequencies of vibration and marginally on the nature of the reactive components. Propagation velocities, obtained by multiplying these flame surfaces by the fundamental burning velocity, strongly depended on the mixture reactivity.*

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Keywords: Hydrogen, flame, Darrieus-Landau instability, Rayleigh-Taylor instability, acoustic waves

INTRODUCTION

The mechanisms of laminar premixed flame propagation have been intensively studied over the last century. Mallard and Le Chatelier [1] were the first to establish a theory that defined the laminar flame velocity. The mechanism of flame propagation control is by heat transfer in unburned gas layers. The flame consists of two zones (Figure 1). Zone 1 is the zone in which heat is transferred by conduction from the reactive zone. The unburned gases are heated until an ignition temperature, T_i, is reached. In the reactive zone, heat is produced. The flame propagation speed is constant if the heat transfer velocity in Zone 1 is equal to the heat production rate.

The expression describing laminar flame velocity is:

$$S_{\mathrm{lad}} \approx \left(\frac{\lambda}{\rho \cdot c_p} \cdot \mathrm{RR}\right)^{1/2} \quad (1)$$

where λ is the thermal conduction coefficient, c_p is the specific heat, and RR is the chemical reaction term. This approach was developed in the work of Zeldovitch, Frank-Kamenetskii, and Semenov [2].

The chemical reaction term is expressed by the classical Arrhenius law with different orders of reaction. With a Lewis number $Le \neq 1$ and an order of reaction not equal to 0, further developments led to the following expression for laminar flame velocity:

$$S_{\mathrm{lad}} = \left[\frac{2 \cdot \lambda \cdot Le \cdot Z' \cdot R \cdot T_f^2 \cdot \exp\left(-\frac{E_a}{R \cdot T_f}\right)}{\rho_0 \cdot E_a \cdot c_p \cdot (T_f - T_0)}\right]^{1/2} \quad (2)$$

where T_f is the burned gas temperature, T_0 is the unburned gas temperature, R is the ideal gas constant, Z' is the pre-exponential factor and E_a is the activation energy.

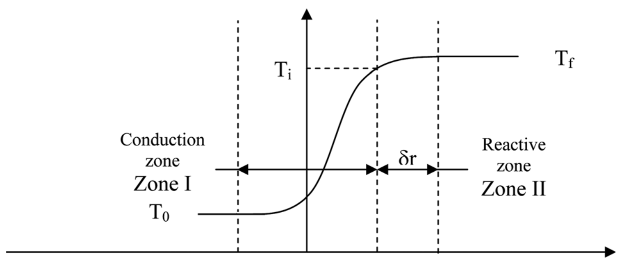

Figure 1. Combustion wave description.

This expression has been used for the last 30 years to study flame behavior under perturbations. Indeed, temperature variations have a large influence on laminar adiabatic flame velocity. This expression has also been used to take into account the effect of flow curvature on the flame velocity [3].

If a flame presents a positive curvature with regard to the flow, the heat flux towards the reactants have a tangential component. Thus, this phenomenon can be represented by a heat loss for the convex part of the flame. The effect of flow curvature is also amplified or decreased by "preferential diffusion" represented by $Le \neq 1$. Authors like Sivashinsky, Dold and Joulin, and Proust [4–6] used more precise models and more sophisticated resolution techniques to obtain expressions such as [6]:

$$S_u = S_{lad} \cdot \left(1 - L_{mk}\left(\frac{1}{R_{flame}} - \frac{1}{R_{flow}}\right)\right) \quad (3)$$

with L_{mk} the Markstein length

$$L_{mk} = \delta_f \cdot \left(1 + \frac{\beta}{2} \cdot \frac{Le - 1}{Le}\right) \quad (4)$$

where R_{flame} is the curvature radius of flame, R_{flow} is the curvature radius of flow and β is the Zeldovitch number.

This expression shows the impact of flow on flame velocity. By extension, it highlights the importance of interactions between flame and flow, commonly called flame instabilities.

Here, we focus our examination on two kinds of flame instabilities:

- Darrieus-Laudau instability
- Rayleigh-Taylor instability

In the case of an interface separating two media of different densities, the hydrodynamic instability results in the growth of a fortuitous disturbance (local curvature) in the gas flow in the vicinity of the flame front. Thus, the dynamics of the flame are superimposed on the dynamics of the flow in the global response and the evolution of the total quantity of burned gas per unit of time in the flame. The speed of fresh gases is increased in the concave part of the disturbance (towards the fresh gas) and decreased in the convex part. This observation led Darrieus [7] and Landau [8] to the conclusion that the flames of premixed gases can accelerate themselves by the mechanism of disturbance amplification. Thus, the flame can become turbulent even if the upstream flow is not. Without imposed hydrodynamics, an interface can become unstable and distort under the influence of an acceleration field, e.g., gravity. We are all familiar with the interface example of the separation of two liquids of different densities: in a gravity field, the interface is unstable if the heavier liquid is located above the light one; the interfaces between a fresh gas and a burned gas have the same properties. Consequently, the ascending propagation of a flame in a gravity field is unstable while the downward propagation is stable. This observation is still valid if the acceleration of gravity is replaced by an acceleration created by a pressure wave or a shock propagating through the gas, for example. In practice, the mechanisms of hydrodynamic and Taylor instabilities are simultaneous. The curved shape [9] is due to the thermal expansion of burned gas, which entails the growth of flame perturbations. Darrieus and Landau proposed a model that describes this instability. The flame is considered a surface separating burned and unburned gases. The flow is governed by classical fluid motion equations. Flame propagates normally to the surface with a constant velocity. The parameters on each side of the flame are linked by jump conditions that assure mass and momentum conservation. According to this model, the flame is unconditionally unstable and perturbations grow indefinitely. However, numerical and experimental observations show that the flame's curvature produces a flame growth stabilization.

As far as the flame modifies its shape, the unburned flow is disturbed and its perturbations (in tangential flow) stop flame deformation. Bychkov and Liberman [10] proposed, for an axisymmetric flame, an expression for flame velocity with respect to the unburned gas (Eq. 5):

$$U_{LD} = \left(1 + 4 \cdot \alpha \cdot \frac{(\alpha - 1)^2}{(\alpha^3 + \alpha^2 + 3 \cdot \alpha - 1)}\right) \cdot S_{lad} \quad (5)$$

Numerous experimental results have shown that there is a narrow relationship between flow disturbance and flame structure. If we consider a flame exited by an acceleration such as acoustic waves or gravitational acceleration (an instability commonly called Rayleigh-Taylor instability), the growth of the flame perturbation is stabilized. An example is flame propagation in a vertical tube excited by the acceleration of gravity. Under these conditions, the flame takes on the very curved shape of a bubble. The velocity of propagation is higher than S_{lad}. Bychkov [10] generalized the Rayleigh-Taylor model to obtain Eq. 6:

$$U_{RT} = 0.51 \cdot \sqrt{\frac{\alpha - 1}{\alpha} \cdot \gamma \cdot r} \quad (6)$$

where α is the expansion rate of burned gas, γ is the acceleration of the phenomenon, and r the radius

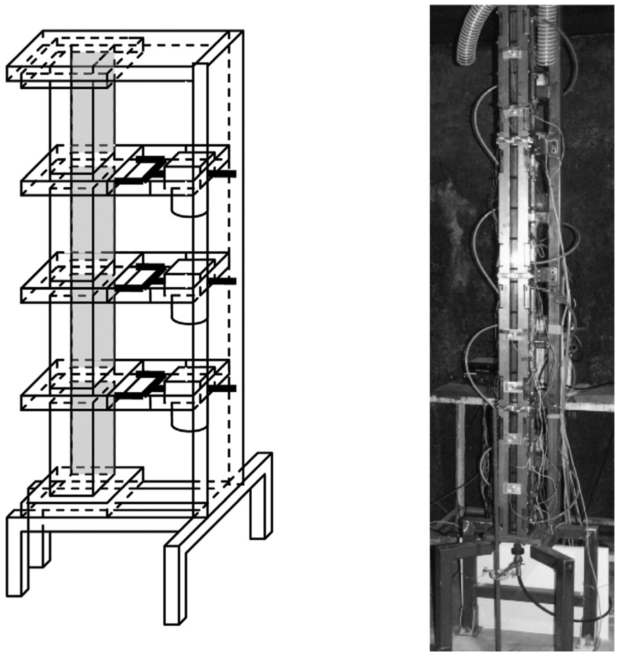

Figure 2. Global view of experimental set-up. [Color figure can be viewed in the online issue, which is available at **www.interscience.wiley.com.**]

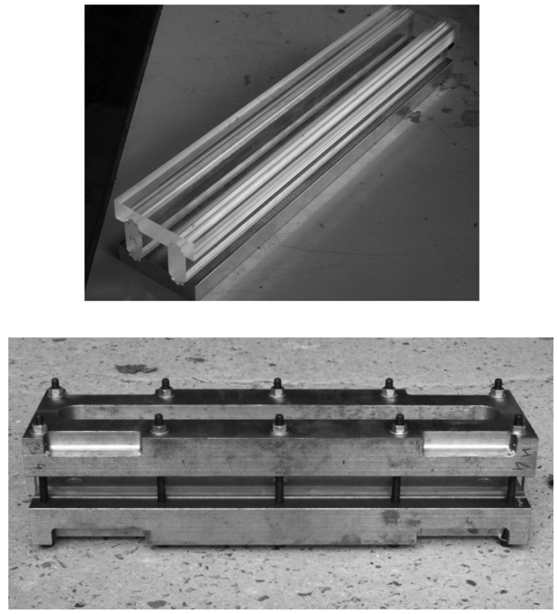

Figure 3. One part of the tube and its metallic skeleton. [Color figure can be viewed in the online issue, which is available at **www.interscience.wiley.com.**]

of curvature of the disturbance. For Byckov, the combustion velocity resulting from the Darrieus-Landau and Rayleigh-Taylor instabilities can be estimated by Eq. 7:

$$U_{\mathrm{Comp}} = \sqrt{U_{\mathrm{RT}}^2 + U_{\mathrm{LD}}^2} \qquad (7)$$

EXPERIMENTAL SET-UP

To characterize the interaction between a flame and aerodynamic conditions, we designed a special set-up. The experimental configuration was a vertical closed tube, as a closed tube is favorable for the appearance of flame instabilities. Using the basic principles of conservation, this configuration allows for a good analysis of flame behavior by a crosscheck between flame trajectory and pressure signal. The test set-up was a 2 m long tube with a diameter of 0.03 m (Figure 2). Specifically, the set-up was a transparent chamber that was resistant to high pressure explosions (~150 bar). The tube was composed of four equal parts, allowing for the creation of concentration gradients. Each part was composed of three PMMA walls and one aluminum wall set in a metallic skeleton (Figure 3). This skeleton provided all of the mechanical support; silicone putty was applied as necessary to ensure gas-tight fittings.

Special effort was made to develop the instrumentation necessary to conveniently interpret the tests, specifically consisting of an opacimeter system consisting of a laser diode and a photovoltaic cell fixed on two aluminum supports magnetically mounted on the metallic skeleton (Figure 4). Eight opacimeters were distributed along the tube. These allowed for the detection of flame via modifications in a luminous laser signal detected by the photovoltaic cell, allowing us to obtain the flame speed and trajectory. A second optical technique was developed to capture the flame area. It consisted of illuminating a thin slab of the tube with an Argon Ion laser via a rotating mirror. Ammonium chloride particles, which diffuse green light, were added to the tube during combustion. During propagation, the flame dissociates the ammonium chloride particles without modifying the combustion. Thus, the flame area can be detected via high speed video as the threshold between high and low contrast regions. Pressure was measured using a classical piezoresistive gauge.

We focused our work on the analysis of a flame propagating in a uniform stoichiometric mixture of H_2/O_2 diluted with nitrogen in a closed volume. We used the stoichiometric mixture 25% H_2 + 12.5% O_2 + 62.5% N_2.

PRESSURE SIGNAL ANALYSIS

Global Description

Following ignition, the pressure signals obtained in each part are reported in Figure 5. A fitting of each curve shows clearly that the pressure was homogeneous in the tube. However, Figure 5 also indicates that a high-frequency signal of low amplitude (100 mbar at few hundred Hz), corresponding to the local overpressure peaks, F_I, was superimposed on a signal of low-frequency and amplitude (typically 3 bar at 10 Hz, between 0 and F). The dominant frequency was 100 Hz up to the inflection point I, and beyond this the main frequency was 350 Hz. A magnification of the signal is presented in Figure 6. One notes a first

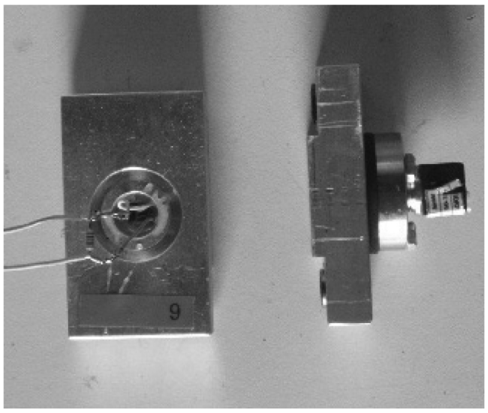

Figure 4. Opacimeters. [Color figure can be viewed in the online issue, which is available at **www.interscience.wiley.com.**]

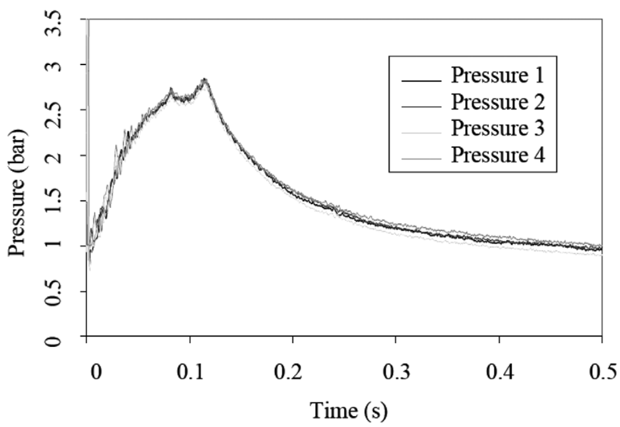

Figure 5. Pressure signals in each section of the tube.

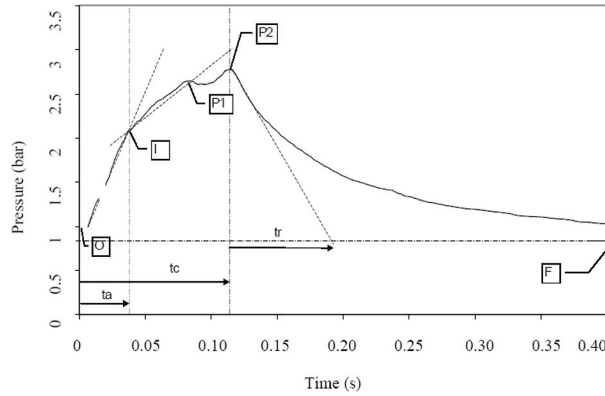

Figure 6. Zoom of the first period of the pressure signals.

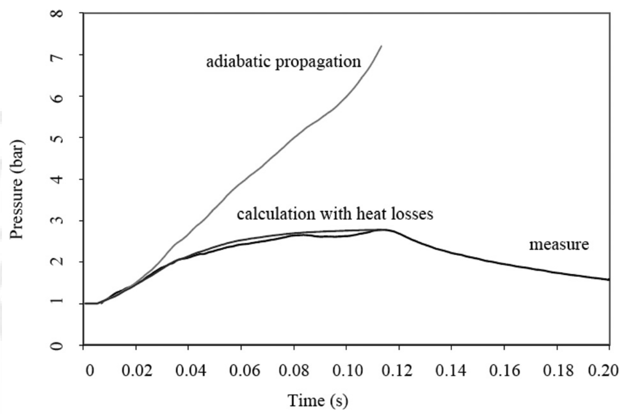

Figure 7. Pressure versus time.

phase of duration 0.043 s where the increase in the pressure is almost linear up to inflection point *I*, marking a rupture in the slope. Beyond this point, the increase in pressure clearly inflects and presents irregularities such as a secondary maximum P1 that precedes the maximum of the signal, P2 (2.77 bar). Beyond this point, corresponding to 0.115 s, the pressure decreases exponentially with a characteristic duration t_r (0.076 s), up to an end-point pressure value systematically less than atmospheric pressure, typically about 0.7 bar.

Low-Frequency of Pressure Signal

The final pressure of combustion resulting from the experiments was approximately two times smaller than the predicted value. Two possibilities must be taken into account to explain these variations: leaks to the outside of the apparatus and an intense cooling of burned gases during the propagation. The gas-tightness of the tube was controlled very meticulously and so is not called into question. To explore the second possibility, a traditional model of combustion by sections was used and adapted to our study by including heat losses to the walls by conduction and condensation. These result in a thermal loss and volume contraction of the gases responsible for the reduction of the pressure effects. Thus, cooling is carried out in two stages. The first stage is the cooling of the burned gas column, section by section, via turbulent non-stationary thermal conduction. The second stage consists of the contraction of the gas column by turbulent non-stationary condensation, section by section, of the steam towards the cold walls, where it condenses completely. The corrected model of combustion by sections, by introducing the trajectory of flame from experiment to model, allows us to define the level of stretching of the flame. It is noted that the method of combustion by sections (under the assumption of a non-adiabatic propagation of the flame) makes it possible to reproduce with precision the pressure signals from the experiments (Figure 7).

It can be seen from this model that the shape of the pressure signal results directly from the evolution of the average burning rate of the flame. Furthermore, the good agreement between the experiments and the simulation of non-adiabatic propagation justify the assumption according to which the contraction of the

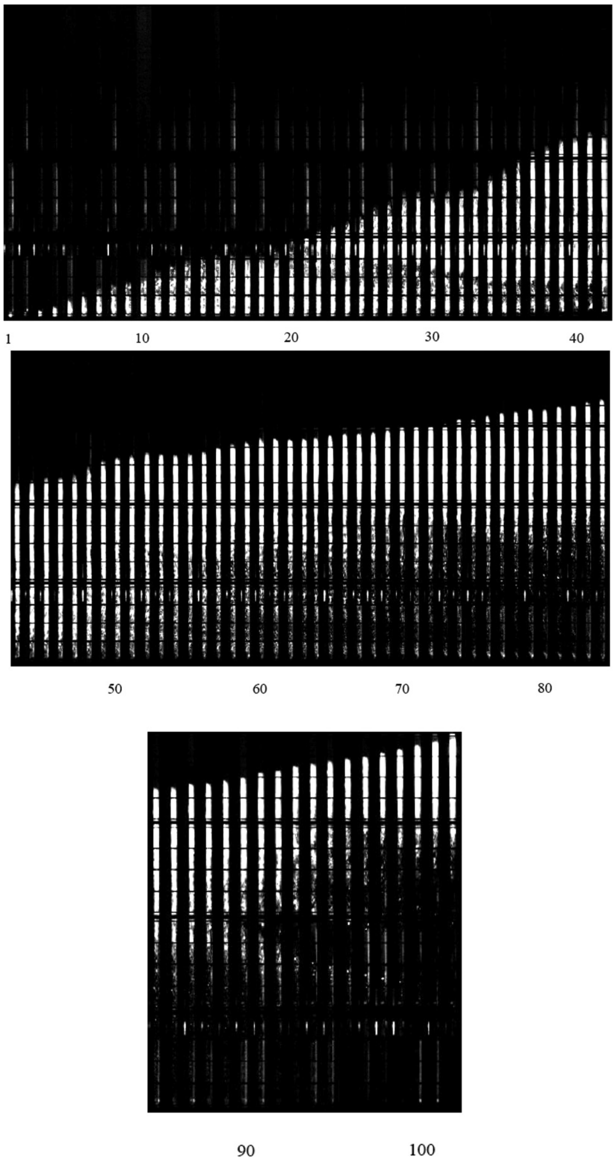

Figure 8. Flame propagation—Frames 1 to 88: 1/1500 s; Frames 89 to 95: 2/1500 s; Frames 96 to 102: 4/1500 s.

burned gas column under the effect of thermal losses is responsible of the difference between the maximum explosion pressure measured and that resulting from an adiabatic calculation of combustion.

High-Frequency Pressure Signal

The analysis of the high-frequency part of the pressure highlights the coexistence of two distinct bands during the propagation. The pressure signal measurements between the bottom and the top of the tube are in opposition of phase, suggesting that the gas column vibrates. The frequencies of resonance of a constant section tube can be calculated by considering that the tube of length *L*, closed at the two extremities, contains burned gases from 0 to x_f (in which the acoustic waves are propagated at the sonic speed, a_b) and in the other part the unburned gases (in which the acoustic waves are propagated at the sonic speed a_u). If it is supposed that this column vibrates, then a fluid particle that sees a passing disturbance at a given time sees it again in the same direction and with a time delay *T* such that:

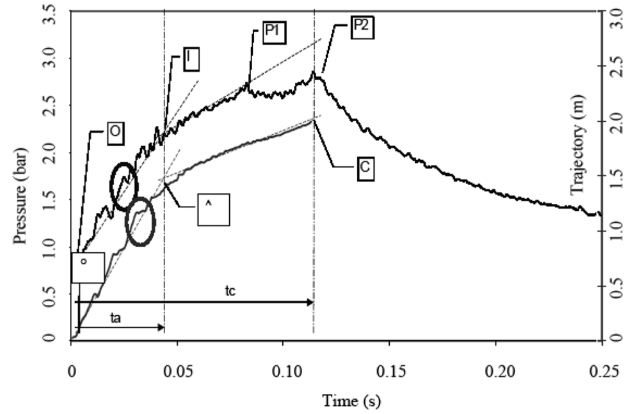

Figure 9. Pressure signal and flame trajectory.

$$T = \frac{2 \cdot x_f}{a_b} + \frac{2 \cdot (L - x_f)}{a_u} \quad (8)$$

The associated frequency is:

$$f = \frac{a_b \cdot a_u}{2 \cdot [(L - x_f) \cdot a_b + x_f \cdot a_u]} \quad (9)$$

which corresponds to the fundamental mode of vibration of the gas column.

This makes it possible to distinguish a singular point in the tube corresponding to the equality of passage times of the waves in the flame through the burned gases on the one hand and through the reactive gas on the other hand. This point corresponds to the position in the flame, x_{fs}, such that:

$$\frac{2 \cdot x_{fs}}{a_b} = \frac{2 \cdot (L - x_{fs})}{a_u} \quad (10)$$

x_{fs} is very close to 1.4 m (under the assumption of an adiabatic combustion). However, it is observed that one of the wavebands disappears at a height of 1.3 m for the tests carried out. One can propose following interpretation: when the surface of the flame is disturbed, a wave of the same pressure amplitude is emitted towards the gases and towards the fresh gases. If their passage times are strictly identical, then the considered waves arrive at the flame front at the same time and hence are mutually destroyed. It is thus possible that this position of flame plays the part of a filter.

CHARACTERISTICS OF THE FLAME

Flame Trajectory

The study of the propagation of the flame is mainly undertaken through the use of film images. An example is proposed in Figure 8 of a broad plan F8

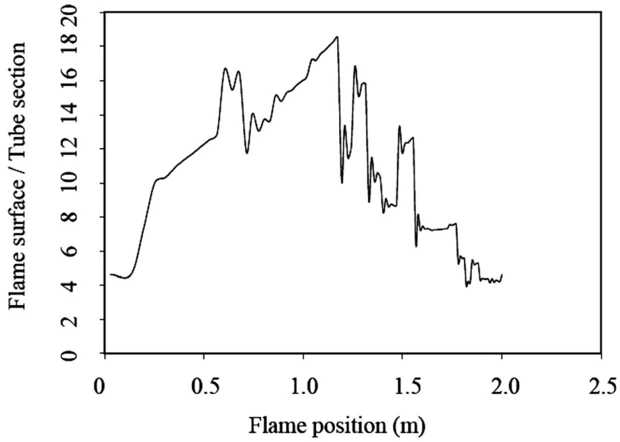

Figure 10. Flame surface over tube section versus flame position.

making it possible to extract the trajectory, the flame, and its speed. It is noted visually that the propagation of the flame is pulsed, and sometimes the front even moves back (frames 15–19).

F9 The trajectory of the flame with time (Figure 9) is given by regarding the position of the most advanced part of the front. However, the flame is not planar. If, for the final part of the propagation, the idea of considering a planar flame is reasonable, it becomes more questionable in the first moments of the flame because the flame can be stretched over a length of 5 cm. The point P2 of the pressure signal corresponds to the X-coordinate at 2 m of the flame (point C), which means that combustion is completed at this point. It is also noted that, as for the pressure signal, an oscillation of the trajectory is superimposed on the average propagation, whose shape and frequency are similar to the pressure oscillations; these oscillations are strongly attenuated beyond this point.

By examining the overall tendencies, one notes two distinct modes of propagation between OA and AC. Each one can be characterized by a mean flame velocity: $v_{0A} = 31.7$ m/s and $v_{AC} = 9.0$ m/s^{-1}. Finally, the point A corresponds strictly to the point I on the pressure signal, and beyond that, a similar structure of the curves of pressure and trajectory appears, which suggests a relation between the two. Note that despite the difference for the extrema, P1 and P2, whose peaks are corresponding, do not have parallels on the curve of the flame trajectory. The fluctuations of the trajectory of the flame have an identical base frequency to the pressure oscillations.

Flame Structure

The strong deformation of the flame, highlighted in the analysis of the ratio of the flame surface at the section of the tube (Figure 10), encourages us to seek the effect of the pressure waves that are propagated in the tube. F10

These are then compared to sinusoidal waves, and the induced acceleration is approximated as: $\gamma = 2\pi U_a f$, where U_a is the rate of acoustic velocity associated with the amplitude of the pressure wave ($\Delta P = \rho a U_a$). Knowing that the amplitude of the pressure wave is about 100 mbar, U_a is ~25 m/s while f lies between 100 and 500 Hz, so γ varies from 15,000 to 80,000 m/s^2.

To a first approximation, the generalized model of the Rayleigh-Taylor instability (Eq. 2) is used to evaluate the effect of this type of acceleration:

$$U_{RT} = 0.51 \cdot \sqrt{\frac{\alpha - 1}{\alpha} \cdot \gamma \cdot r} \qquad (11)$$

where α is the expansion rate of burned gas, γ is the acceleration of the phenomenon and r the radius of curvature of the disturbance. This makes it possible to find a ratio of flame surface to tube section, A_f/A_t, which ranges from six to 13, indicating a coherent order of magnitude with respect to the experimental observations.

Flame Velocity

The propagation velocity of the flame can be evaluated theoretically in each part of the tube. In the zone OA, the velocity is given by considering:

- the ratio of the flame surface of the tube section,
- the compression of the gas column, proportional to $(P_0/P_{I1})^{1/\gamma}$ (where P_{I1} is the pressure corresponding to the point A)
- the contraction of the burned gas column under the effect of heat losses and proportional to $(P_f/P_{expl})^{1/\gamma}$ (P_{expl} is the theoretical pressure of constant-volume combustion)

Hence, the flame velocity between OA is expressed by:

$$V_{OA} = \left(\frac{A_f}{A_t} \cdot S_{lad} \cdot \alpha\right) \cdot \left(\frac{P_0}{P_{I_1}}\right)^{1/\gamma} \cdot \left(\frac{P_f}{P_{expl}}\right)^{1/\gamma} \qquad (12)$$

In the reactive zone (AC), the velocity is simply determined by:

$$V_{AC} = \frac{A_f}{A_t} \cdot S_{lad} \qquad (13)$$

Hence, the flame velocities $V_{OA} = 40$ m/s and $V_{AC} = 13$ m/s are in good agreement with observed velocities of 32 m/s and 9 m/s, respectively.

CONCLUSIONS

In this article, the interaction of acoustic waves emitted near the ignition point during flame formation with the flame propagation is highlighted. The acoustic waves could increase the flame front surface by a factor of 10. An acoustic node appears to exist at a height of 1.3 m that is responsible for the disappearance of one of the acoustic modes and of a reduction in the average flame surface. This disappearance of an acoustic mode could explain why one observes a flame trajectory in two distinct parts: one corresponding to propagation with a high speed in the lower part of the tube, and the other with a slower speed in the upper part of the tube. It was noted that the flame surface depends mainly on the frequencies of vibration and marginally on the nature of the reactive components. On the other hand, propagation velocities, obtained by multiplying these flame surfaces by the fundamental burning velocity (or the expansion speed of the burned gases), strongly depend on the mixture reactivity.

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AQ1: Please provide the location for the Refs. 2, 6, and 7.

AQ2: Kindly provide the volume number for Reference 10.