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Experimental investigation of propane-air flame propagation in narrow circular ducts

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An experimental investigation was performed of propane-air flames propagating in narrow, horizontal, circular ducts with the purpose of establishing flame propagation phenomenology and comparing with recent theoretical findings that correlate propagation speed with heat release. Videos were taken at various axial locations to survey the entire development of the flame along the tube length. The phenomenology of the flame under various mixture compositions is discussed. Some of the features observed include stretching and undulation of the flame front, including inversion of the flame front at the leading edge – a phenomenon sometimes referred to as "tulip-shaped" flames. In addition, a sizeable increase in propagation speed and flame instability of fuel-rich and stoichiometric cases over lean cases was observed. These observations seem to undercut the traditional model of a stable flame shape with a uniform propagation speed. In addition, information regarding the propagation of the flame front over time was extracted via image processing. It was observed that the flame front accelerated as it traveled down the tube. The effects of factors such as stoichiometry, heat release, and tube length on the flame speed, travel time, and flame phenomenology were examined and compared with theoretical predictions.

1. Introduction

The propagation of laminar flames in ducts has been studied at least since Mallard and Le Chatelier (1883) [6]. The fundamental problem involves a long tube, which is filled with premixed gaseous reactants, and these are ignited at one end of the tube. One of the early motivations of such an experiment was the practical problem of transporting natural gas or coal-laden gases in pipes, where the hazards of ignition are paramount [7]. Mason and Wheeler (1920) [7] performed studies using methane-air mixtures in a relatively large tube (5 cm in diameter and 2-3 m in length), and established that the flame phenomenology observed, including shape, speed, acceleration, and undulation of the flame front, depended greatly upon the boundary conditions at the ends of the tube – whether either the ignition end or the distal end remained open to the atmosphere or closed, or both ends, or neither end. A more comprehensive series of studies was documented by Guénoche (1964) [4], in which he details phenomena such as the vibratory region of propagation, as well as different position vs. time profiles that are encountered under various tube boundary conditions and mixture compositions. The problem has also been studied by others [9, 10]. All of these studies were

performed in large-scale test tubes, with diameters of at least 2 cm in most cases. It is one of the goals of the current work to see to what extent these previous findings manifest themselves in smaller or meso-scale ducts.

The current investigation focuses in particular on recent analytical and computational studies by Kurdyumov and Matalon (2012) [5] which predict that, for long narrow channels open at both ends, the flame will undergo an acceleration that can be related to the heat released – or equivalently, to the adiabatic flame temperature – which is directly related to the mixture composition. It is further predicted that a Poiseuille flow develops in both the burned and unburned gases, traveling away from the propagating reaction zone. This flow away from the flame in the unburned gases in particular has not yet been observed experimentally, and Gamezo [2], who found similar computational results, has suggested that this acceleration of gases ahead of the flame front may have applications for producing thrust in novel types of propulsion systems, especially in a micro-gravity environment.

In the current investigation, the propagation of propane-air flames in meso-scale quartz tubes was studied using high-speed photography in order to characterize flame phenomenology and structure, as well as to extract quantitative position and speed data, and this is compared with the aforementioned computational results.

2. Experimental Methods

2.1 Experimental Setup

The experimental setup is depicted schematically in Fig. 1. It consisted of a quartz tube of inner diameter 1/4 inch (6.35 mm) and wall thickness 1/8 inch (3.2 mm), which was mounted horizontally. The reactants were fed into the tube via a thin plastic (Tygon R-3603) tubing through a small hole bored in the quartz, of diameter 1/8 inch (3.2 mm), which was recessed 1 inch (2.54 cm) from the end of the tube. Tube lengths of 23.25 inches (59.1 cm) and 41 inches (104 cm) were utilized. The ends of the tube could be opened or closed via a solenoid linear actuator placed at each end, with a dense felt material capping the tube and providing a seal sufficient for filling the tube with premixed reactants, but not so airtight as to cause any substantial pressure build-up. An aluminum wire mesh acting as a flame arrestor was placed in the tube between the test section and the inlet hole, to prevent flashback into the gas delivery system. In addition, a meter-long ruler was mounted just above the tube to provide a spatial reference for the high-speed videos.

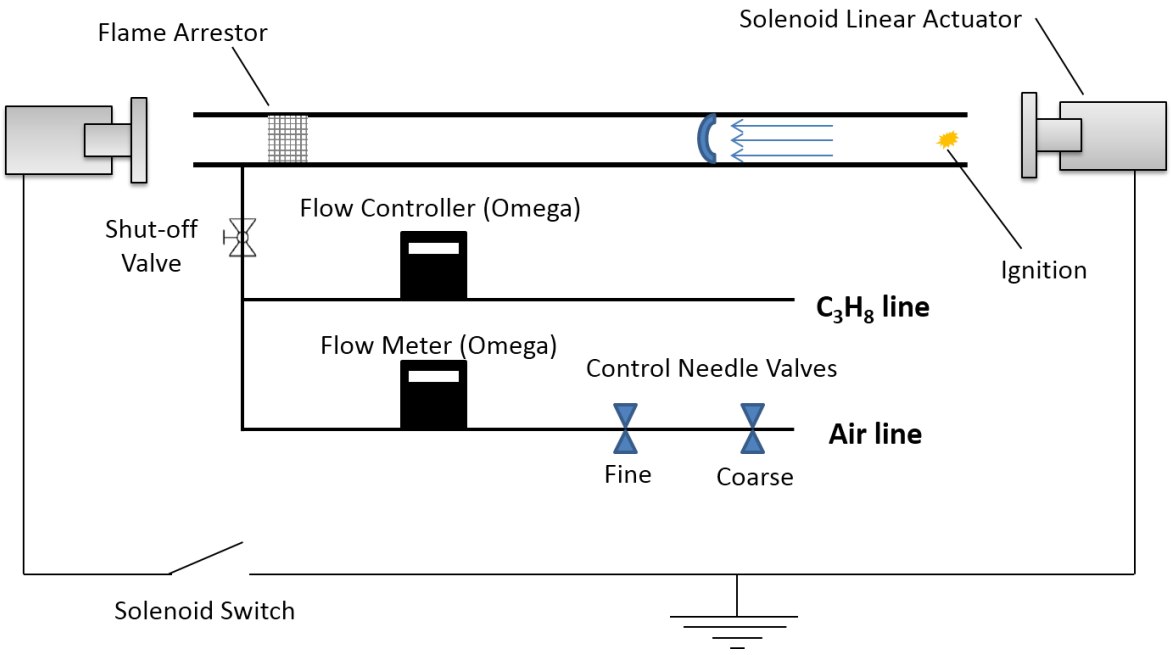

Fig. 1 – Schematic of experimental setup

The reactants were C_3H_8 gas and air (79% N_2 and 21% O_2 according to the vendor specifications), which were metered out of high-pressure cylinders into the test section. The mixture composition was controlled by equating the volumetric flow rates (given at standard conditions) with molar flow rates using an Omega FMA5400/5500 mass flow controller for the propane, and an Omega FMA-1600A flow meter with a system of control valves for the air, as shown in Fig. 1. This method assumes the gaseous mixture to be ideal.

2.2 Experimental Conditions

Typical values for flow rates were 225 mL/min for air and 9.45 mL/min for propane, which would yield a stoichiometric mixture. The global reaction equation for premixed propane-air combustion is given by:

$$C_3H_8 + 5(O_2 + 3.76N_2) \rightarrow 3CO_2 + 4H_2O + 18.8N_2 \quad (1)$$

The fuel-air equivalence ratio ϕ was varied from 0.8 to 1.4, by varying the fuel content while keeping the air flow rate constant. Once a mixture composition was chosen, the gases were metered into the test section with the tube end nearest to the inlet closed for 2-3 min, allowing the mixture to completely fill the tube. Next, the tube at the ignition end was closed and the inflow shut off for 2-3 seconds, allowing the mixture to stagnate. Finally, both ends were opened and the mixture was ignited using a standard butane lighter held to the open end of the tube.

High-speed videos were recorded using a Phantom v7.0 camera capable of up to 4800 fps and a maximum resolution of 800x600. The lenses utilized included a Nikkor 50mm f/1.8 and Nikkor 105mm f/2.8, the former being preferred for wide-angle views encompassing a large section of the test tube, and the latter for closer views showing more detailed flame structure.

2.3 Image Processing

Images were processed to extract qualitative information on the flame structure, as well as quantitative position vs. time data. The latter analysis was performed using MATLAB, using thresholding and object tracking algorithms found in the Computer Vision System toolbox, as well as custom-designed MATLAB codes.

3. Results and Discussion

3.1 Flame Propagation Phenomenology

A general picture of the flame propagation behavior observed throughout the various cases is as follows. The flame began by assuming a coherent, parabolic shape almost immediately (within 1 or 2 tube diameters after ignition), with a nearly uniform propagation speed that varied from about 40 to 100 cm/s, with the highest speeds occurring in stoichiometric and slightly rich mixtures. Flame luminosity also increased with higher equivalence ratios. After this period of smooth propagation, which comprised, generally, between one-eighth and one-half of the total tube length, the flame entered a less stable region characterized by axial undulation of the flame front. This region was called the "vibratory" region by Mallard [6] and was also studied by Mason [7] and Guénoche [4]. This transition is visible in Fig. 2, which shows a stoichiometric flame propagating in the 104 cm tube. The view encompasses 22.9 cm or about one-quarter of the test section. As seen in Fig. 2, the transition to the vibratory region occurs at about 13.5 cm (note here that x is the axial coordinate, and the origin is about 3 cm from the end of tube where ignition takes place).

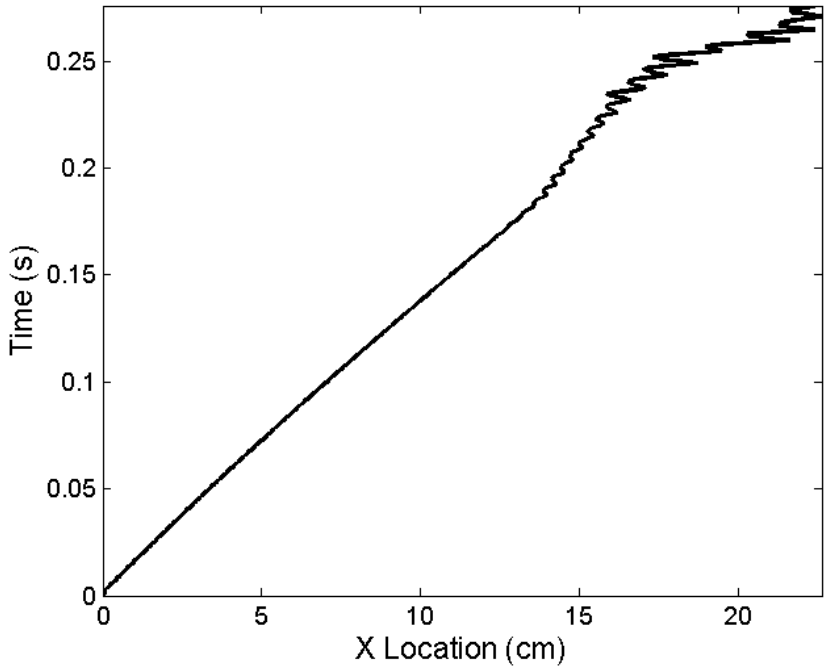

Fig. 2 – Time history of the flame front propagation in a 104-cm-long tube filled with a stoichiometric mixture.

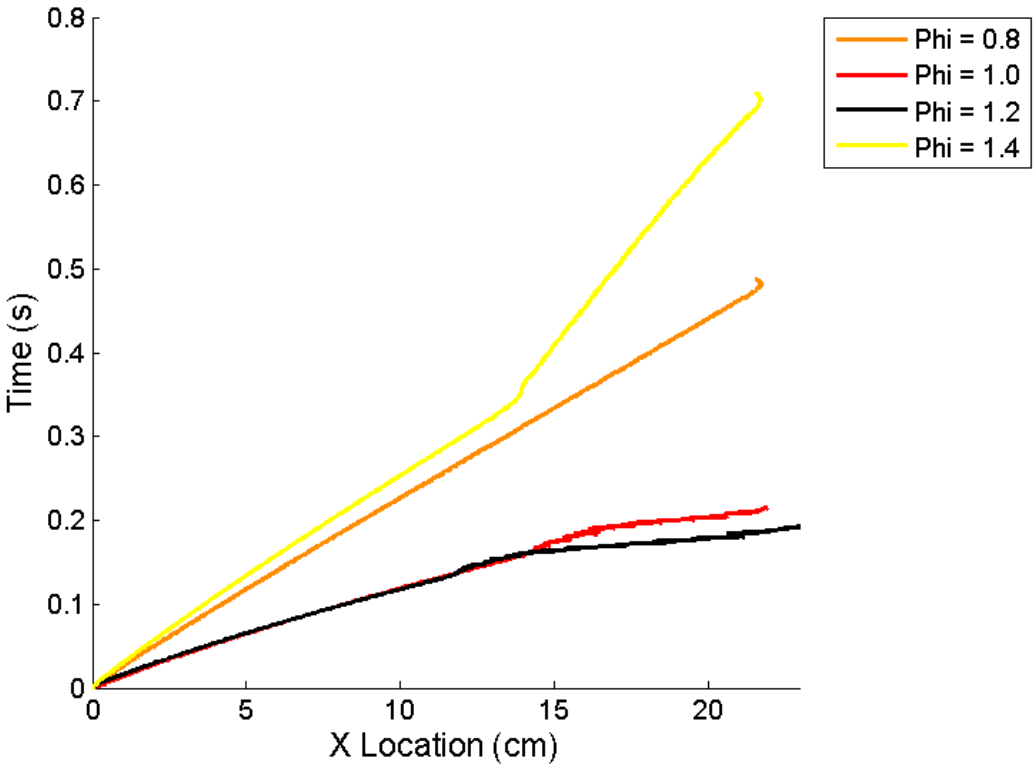

Fig. 3(a) – Time history of the flame front propagation in a 59.1-cm-long tube with four mixture compositions, equivalence ratios 0.8, 1.0, 1.2, 1.4 (1st half)

Figures 3(a) and (b) depict the flame front propagation in the tube 59.1 cm in length, at equivalence ratios of 0.8, 1.0, 1.2, and 1.4. Fig. 3(a) depicts approximately the first half of the tube: the region encompassing about 3 cm from the ignition end to 24 cm downstream of that end. Fig. 3(b) shows the second half: from 24 cm to 54 cm downstream of the ignition end, the latter being approximately the location of the flame arrestor. It is to be noted that the videos for these two locations were taken separately, so there is not a direct correspondence between any curve in Fig. 3(a) and a curve in Fig. 3(b). The general behavior, however, is similar for each mixture composition.

It can be observed in Fig. 3(a) that each case begins with a region of relatively smooth propagation at nearly constant speed. The transition to the vibratory region is heralded by a distinct change in behavior, during which the flame accelerates forward abruptly for a short distance (usually about 1 cm or less), and then slows down, sometimes even backtracking its position, before repeating this process. The general trend is that the onset of this transition to the vibratory region occurs earlier the greater the equivalence ratio. For the fuel-lean case, ϕ = 0.8, the transition does not seem to occur at all. A definite increase in overall propagation speed can be seen in raising the equivalence ratio from lean to stoichiometric, whereas increasing from stoichiometric to rich (ϕ = 1.2) shows only a minor increase. It is postulated that this is due to the greater heat release accompanied by the change from lean to stoichiometric; further increasing the fuel mole fraction from stoichiometric to rich will not affect heat release in a premixed flame, since the same amount of fuel is burned. The most fuel-rich case, ϕ = 1.4, is observed to have a speed even slower than the

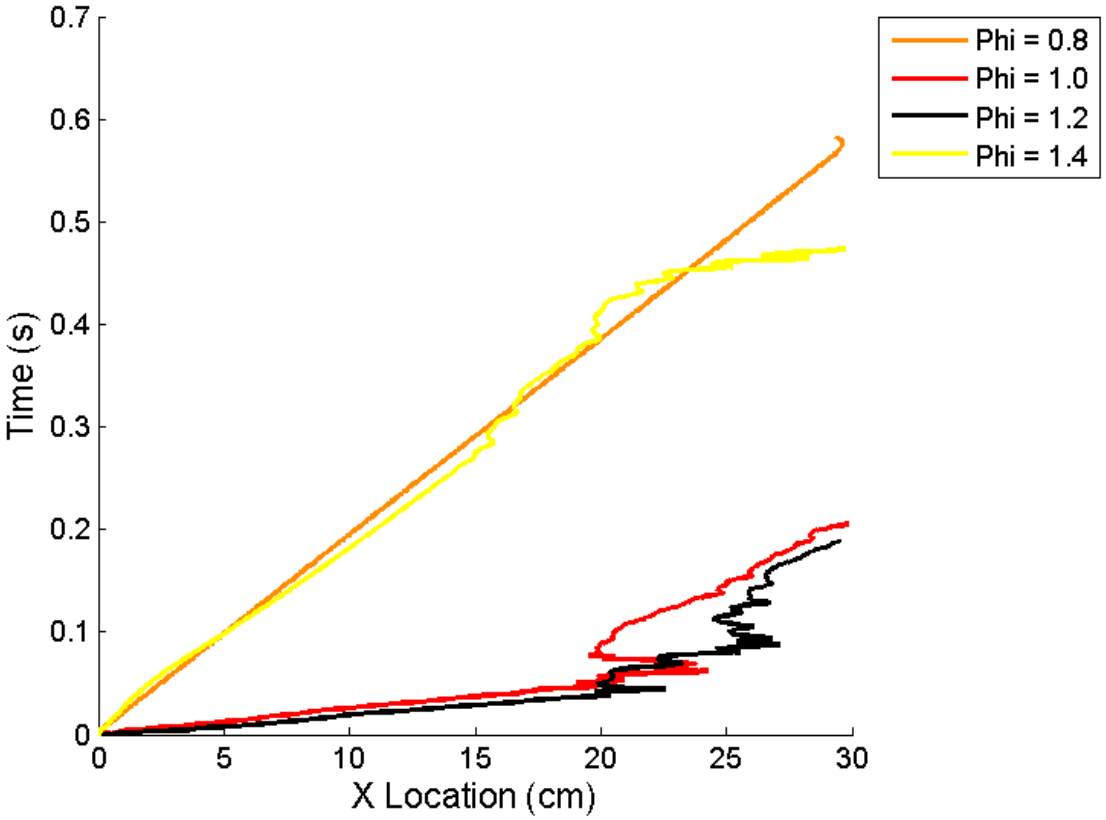

Fig. 3(b) – Time history of the flame front propagation in a 59.1-cm-long tube with four mixture compositions, equivalence ratios 0.8, 1.0, 1.2, 1.4 (2^{nd} half)

lean case, and this may be evidence that, near the flammability limits, the flame cannot propagate as quickly. Another feature of the ϕ = 1.4 case is that the vibratory region is characterized by a flattened flame front undergoing very small, rapid oscillations (a few millimeters in amplitude), which leads to an overall decrease in propagation speed along the tube. This points to one of the key assertions made in previous studies [4, 5, 8], that flame acceleration is directly correlated to an increase in flame surface area. This agrees with the observations of this study, that the luminous flame region assumed a "stretched" shape, with a 2-D profile about 2-3 cm in length during the fastest regions of propagation, and conversely, a very flattened profile of 5 mm length or less during the slowest regions, such as the ϕ = 1.4 case in the latter part of Fig. 3(a).

Figure 3(b) details the second half of the test section. It is seen that the speed and behavior are relatively contiguous with the first half, before coming to a further transition. This last phase is characterized, in the stoichiometric and rich cases, by oscillations of much greater amplitude than before, resulting in high fluctuations in velocity. In the lean case, the propagation is relatively uniform throughout, with only minor fluctuations just before extinguishing.

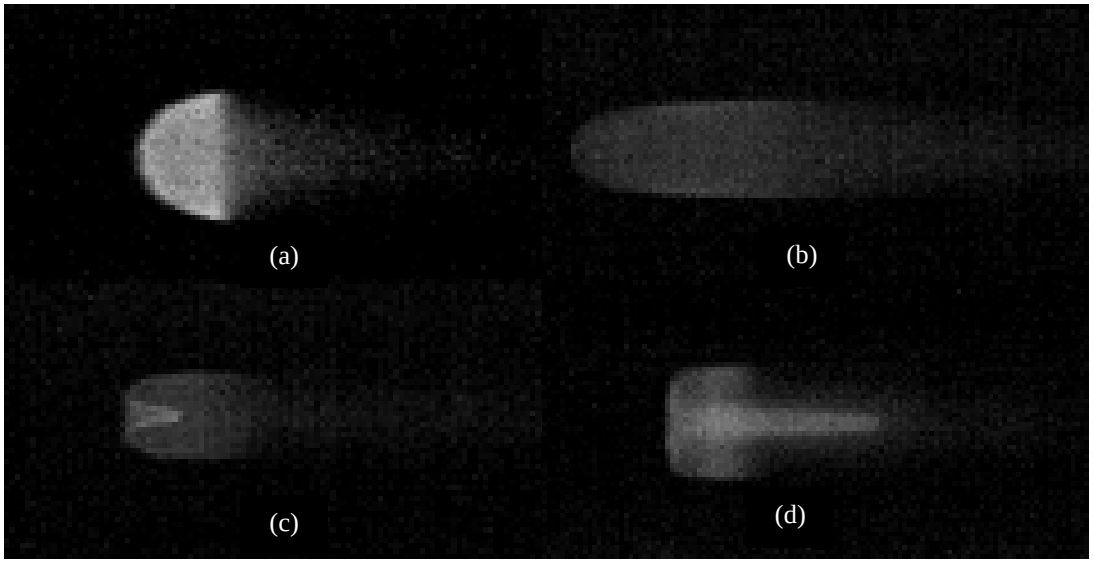

Fig. 4 – Selected flame images, all cases stoichiometric
(a) Typical uniform propagation shape (b) Stretched during undulation
(c) Tulip inversion (d) Extensively inverted

In the current study, the vibratory region was characterized not only by oscillation of the entire luminous region back and forth axially, but also by stretching, shrinking, and often complete inversion of the luminous region. Fig. 4 displays some characteristic flame morphologies. The most common shape during uniform propagation was quasi-parabolic, as in Fig. 4(a). During the vibratory stage, the flame would accelerate, first assuming a stretched shape as in Fig. 4(b), and then shrinking again while decelerating. This would sometimes result in what has been termed a "tulip-shaped" flame [1, 8], shown in Fig. 4(c), and occasionally the oscillation would be so extreme as to produce an almost completely inverted flame front, similar to Fig. 4(d).

3.2 Quantitative Comparisons

Kurdyumov and Matalon [5] define a heat release parameter γ given by:

$$\gamma = (T_{AFT} - T_u)/T_u \tag{2}$$

where T_{AFT} is the adiabatic flame temperature of the mixture (at constant pressure), and T_u is the unburned mixture temperature. One of the main results of the theoretical study [5] is that the total travel time t through a long narrow tube is given by:

$$t \approx \frac{\ln(1+\gamma)}{\gamma}\frac{L}{S_L} \tag{3}$$

where L is the total tube length, and S_L the laminar flame speed. In order to compare with this study's experimental results, for the four cases plotted above in Fig. 3, the actual travel time was compared with one calculated using equation (3). For this purpose, the test section length L was 53.9 cm, and tabulated values of laminar flame speed S_L for propane were taken from Glassman [3]. The heat release parameter γ was computed for the mixture compositions in these experiments using the equilibrium solver GasEQ, with T_u taken to be equal to ambient, measured at 289 K. The results are listed in Table 1. It can be seen than there is very good agreement for the cases ϕ = 1.0, and 1.2,

particularly the latter. The lean and very rich cases also agree to within an order of magnitude, and this is striking considering that the methodologies used by Kurdyumov and Matalon [5] do not account for the drastic change in flame propagation behavior manifested in the vibratory region seen experimentally, but rather, predict a smoothly accelerating propagation curve.

Table 1 – Comparison of theoretical travel time [5] with experimental data

Equivalence Ratio ϕ	T_{AFT} (K)	γ	Laminar Flame Speed [3] S_L (cm/s)	Theoretical Travel Time [5] (s)	Experimental Travel Time (s)
0.8	2036	6.0	32.0	0.554	1.071
1.0	2263	6.8	44.0	0.369	0.421
1.2	2195	6.6	43.5	0.381	0.381
1.4	2041	6.1	28.0	0.621	1.183

4. Conclusions

In summary, the flame propagation observed in these experiments can be characterized by an initial regime of smooth propagation exhibiting a very stable flame shape – see Fig. 4(a) – and nearly uniform propagation velocity. Thereafter, the flame transitions to a vibratory regime characterized by axial oscillations of the flame front and large undulations in flame shape, depicted in Fig. 4(b-d), often involving complete inversion in concavity of the flame front from its usual shape. This vibratory regime varies widely in terms of the amplitude of the oscillations and the duration of the regime. However, some conclusions can be drawn, such as that the onset of the vibratory transition is generally earlier the more fuel-rich the mixture is, and that during the oscillations themselves, a direct correspondence can be seen between instantaneous propagation speed and flame surface area. Finally, a quantitative comparison with theoretical results relating total travel time to heat release was surprisingly accurate given the assumptions involved in the theoretical model.

Acknowledgements

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