Methane/Hydrogen/Air Flame Oscillations in Open Ended Tubes

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1 Introduction

The propagation of premixed flames in tubes date to 1883 with the experiments of Mallard and Le Chatelier [1]. They identified a region where the flame stabilised and obtained a burning speed at that point. Subsequently, different researchers [1-7] have examined combustion in tubes in an attempt to obtain burning velocities.

Flames can spontaneously produce acoustic oscillations in tubes or any other confined space[7]. The oscillations are thought to occur due to a feedback process where the acoustic wave modulates the heat release. According to the Rayleigh's criterion [8], the acoustic wave will be amplified if the fluctuations in the heat release and the acoustic pressure are in phase. Many researchers since 1883 have examined this. Two of the more recent studies were by Searby[9] who experimentally observed that fast flames produce stronger acoustic waves and lead to violent turbulent burning in the remaining half of the tube. Akkerman et al. [10] showed that flame interaction with the walls leads to an oscillation regime of burning which causes variation of the flame shape and flame velocity. They concluded oscillation period and frequency depends on the tube width, which controls the Reynolds number of the flow. In narrower tubes, the oscillations are weaker, while in wider tubes, they become stronger with well pronounced nonlinear effects, the oscillation period increases for wider tubes and decreases for narrower tubes while the average surface area of the flame front and the burning rate slightly depend on the tube width.

Although, numerical simulations have been carried out on open-ended tubes, there is little experimental analysis to support these studies. In this work, the propagation of premixed methane-air flames has been observed in an open-ended tube. At both leanest and richest values of the equivalence ratio, ϕ, the flame propagates steadily, however from $1.1 < \phi < 1.4$ the flame is subjected to acoustic oscillations in the central part of the tube. A fixed equivalence ratio of 1.2 was used as this has been found to result in the maximum oscillation for methane/air flames enriched with hydrogen. Hydrogen was added to the fuel, with its concentration increased in the interval of $R_H = 0.1$ up to 0.5 to observe the sensitivity of the laminar burn rate to the onset and the magnitude of the oscillations.

2 Experimental Set-up and Methods

The experimental rig consisted of a tube of inner diameter of 20 mm and length 1200 mm with the central 700mm length of the tube quartz, providing optical access. The required volume of methane and hydrogen at each equivalence ratio was measured and injected into the rig using a syringe and two fans attached to the rig were used to create a homogeneous mixture. The propagating flame was recorded using a Phantom V210 high-speed camera at a framing rate of 3000 fps. Ignition was performed using a pilot flame. This was achieved by opening a port at one end of the tube and directing a flame from a gas lighter into the tube. The propagation of flames in tubes has been found to vary considerably with the ignition source. Spark ignition has been shown to enhance the onset of flame oscillations with a resulting increase in the flame speed so was not used in the study[11]. The methane, hydrogen and air volumes used were determined using the equations derived in Wu et al.[12].

$$\phi_F = \frac{C_F/[C_A - (C_H/(C_H/C_A)_{st})]}{(C_F/C_A)_{st}} \tag{1}$$

$$R_H = \frac{C_H + (C_H/(C_H/C_A)_{st})}{C_F + [C_A - (C_H/(C_H/C_A)_{st})]} \tag{2}$$

Where the subscript *st* represent the mole concentration of the mixture at stoichiometric condition, ϕ_F represent the effective equivalence ratio of the main fuel and R_H represent the amount of hydrogen addition, i.e., the ratio of the total mole concentration of the hydrogen-air mixture to the total mole concentration of the main fuel-air mixture.

3 Experimental Results

The propagation of methane-air flames with R_H = 0.1 and 0.5, ignited at one end of an open-ended tube are shown in Figs. 1 and 2. The photographs illustrate the shape variations of the travelling flames. Shown in Fig. 1(a) is the early stage of the flame propagation immediately after ignition for R_H = 0.1. The flame front is convex towards the unburnt gas mixture and tipped forward. The convex shape has been attributed to the non-slip condition at the walls acting on the burnt gases and heat transfer from the reaction zone to the wall. The tipping is thought to occur due to the hot and less dense combustion gases behind the flame rising relative to the cooler unburnt gases[11]. In Fig. 1(b) captured in the central length of the tube, the flame constantly changed shape and area forming a wave pattern. Fig. 1(c) shows the final stage of the flame propagation before extinction. The flame regained its stability and appeared similar to its propagation in the early stages. However, the flame tipping can be seen to have reversed with the top of the flame longer than the bottom. Thus, alternative (non-gravitational) mechanisms may have imposed the non-symmetrical behaviour on the flame. These three stages were also observed for all the other methane/hydrogen flames at ϕ =1.2. Shown in Fig. 2(a,b,c) are methane/hydrogen flames with R_H = 0.5. Despite the high burn rate resulting from the increased hydrogen concentration, the flame immediately following ignition is strongly tipped with a long tail following the flame at the bottom of the tube. In the central length of the tube, the flame was again subjected to oscillations resulting in an alternate lengthening and shortening of the flame. Following the oscillatory period in the central length of the tube, the flame again stabilised becoming convex towards the unburned mixture and propagating steadily down the tube.

Shown in Fig. 3 are plots of maximum flame position with time for increasing H_2 concentration. Pure methane flames were observed to propagate steadily along the entire length of the tube with a slight increase in velocity as they progressed. One of these flames was subjected to small oscillations, but no changes in the flame shape were seen. For mixtures of R_H = 0.1 to 0.3, strong oscillations were observed, and these flames are grouped together on the plot. As the hydrogen concentration was increased to R_H = 0.4 and 0.5, the initial flame propagation was noticeably higher than for the flames with small values of R_H as evidenced by the distance achieved by these flames at 0.05s. When the oscillation occurred in the central length of the tube, the flame slowed and then started to accelerate once the flame had passed through the acoustic field. To summarise, three types of behaviour were observed for premixed flames passing down open-ended tubes: I, the flame propagated down the tube steadily (R_H = 0); II, the flame propagated down the tube steadily and was then subjected to violent acoustic oscillations resulting in an increase in the burn rate (R_H = 0.1 to 0.3); and III, the flame propagated down the tube steadily and was then subjected to acoustic oscillations that resulted in a decrease in the burn rate (R_H = 0.4 to 0.5).

Further analysis has been performed on the flame front images and this is shown in Fig. 4 for two flames at R_H = 0.1 and 0.5. The flame position plotted against time is shown in Fig. 4i. A low pass FFT filter was applied to the flame position and the result subtracted from the original data giving Fig. 4ii, the amplitude of the high-frequency oscillations of the flame front, *a*. In both cases, the oscillations appear part way along the tube. The frequency of the oscillations was found to be approximately 240 Hz (237 Hz for R_H = 0.1 and 246 Hz for R_H = 0.5), and this is thought to be a characteristic of the tube. The maximum amplitude fluctuation in the flame front position of the R_H = 0.1 flame is ±10 mm compared to ±4.6 mm for the R_H = 0.5 flame. In both cases, the reacting flame front is being dragged back towards the burned mixture some of the time, although this seems to be more so for the R_H = 0.1 flame. Yang et al. [11] have measured CH^*/C_2^* emission from propane-air flames subjected to acoustic oscillations in the same rig and demonstrated significant variation of this ratio as the flame oscillates. This might be a result of changes in the flame front chemical mechanism as the flame traverse the acoustic field. The underlying burn speed derived from the low pass FFT filtered flame position, u_{fft}, is shown in Fig. 4iii where the different behaviour of the two flames is evident. In the case of the R_H = 0.1 flame, it initially slightly slowed as it reached the acoustic field but then rapidly accelerated reaching a maximum speed of 4.70 m/s (approximately 10 times the laminar burning velocity). The maximum underlying flame speed occurs with the maximum amplitude of the oscillations. For the R_H = 0.5 flame, it slows as it passes through the acoustic field and has a speed of 2.81 m/s (approximately 4 times the laminar burning velocity) which is lower than the peak velocity seen for the R_H = 0.1 flame.

In order to obtain an approximate flame area, the numbers of illuminated (white/grey) pixels, n_f, were counted in each image. These are shown in Fig. 4iv. Similarly, with Fig 4ii and 4iii different behaviour can be seen for the two flames. In the case of the R_H = 0.1, n_f, was seen reach much higher values when subjected to acoustic oscillations while the flame area at R_H = 0.5 decreased. These results compliment the measurements of flame speed, u_{fft}. There does appear to be a correlation of n_f with u_{fft}, both when the flame is subjected to acoustic oscillation and when it is not. For example, for the R_H = 0.1 both the flame speed and n_f can be seen to increase between 0.2 and 0.25s. Akkerman et al. [10] investigated the propagation of flames in infinitely long open ended tubes and demonstrated that pulsations could be set up in the tube, driven by the expansion of the burned gases. Their flame shape was observed to evolve from a series of cusps to a single large cusp at the tube axis in the burned gases. A similar evolution in flame shape was observed here, especially for the methane flames with R_H = 0.1 (Fig. 1b). However, here the oscillations are acoustically driven (the oscillation can be damped by placing an acoustic impedance (orifice plate) at the tube ends). Nevertheless, it appears the flame response to pulsations or oscillations is similar despite different forcing mechanisms.

It is not possible to decouple the behaviour of the flame from the acoustic field at present. The reduced amplitude of the oscillations of the R_H = 0.5 flame compared to the R_H = 0.1 flame might be the result of the changes in the acoustic field or the higher burn rate of the hydrogen rich flames traversing the acoustic field with relative ease.

4 Conclusion

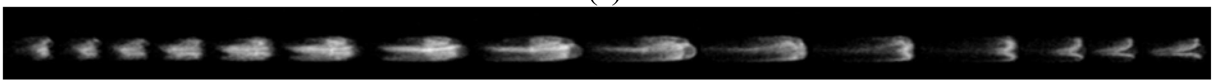
Experimental investigation to determine the laminar flame speed of methane-air mixture and methane hydrogen-air mixtures has been carried out using a 20 mm internal diameter quartz tube opened at both ends. The flame was ignited using flame ignition and the flame propagation captured. The following observations/findings were drawn from the experimental measurements:

1. Three types of behaviour were observed: I, the flame propagated down the tube steadily (R_H = 0); II, the flame propagates down the tube steadily and is then subjected to violent acoustic oscillations resulting in an increase in the burn rate (R_H = 0.1 to 0.3); III, the flame propagates

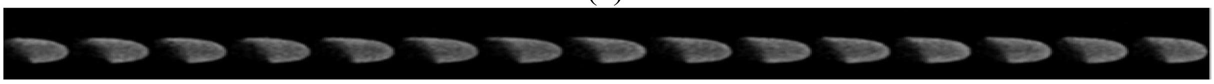
down the tube steadily and is then subjected to acoustic oscillations that result in a decrease in the burn rate (R_H = 0.4 to 0.5).

2. The frequency of the acoustic oscillations was similar for all flames (~ 240 Hz) and is thought to be a characteristic of the tube.
3. The flame area (here approximated by the number of grey/white pixels) appeared to have some influence on the underlying flame speed. The larger area flames were observed tended to travel faster.

(a)

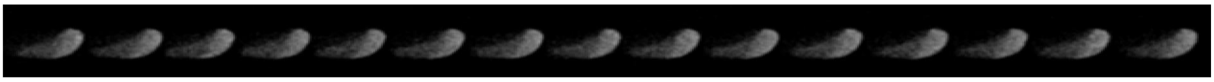


(b)

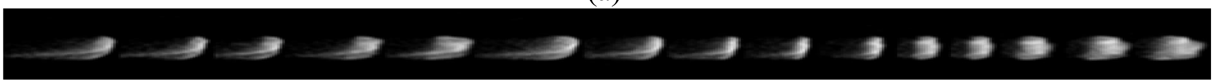


(c)

Figure 1. Methane hydrogen-air flame at ϕ =1.2 and R_H=0.1 (a) early stage (b) Intermediate stage (c) final stage: tube diameter - 20mm



(a)



(b)

(c)

Figure 2. Methane hydrogen-air flame at ϕ =1.2 and R_H=0.5 (a) early stage (b) Intermediate stage (c) final stage: tube diameter - 20mm

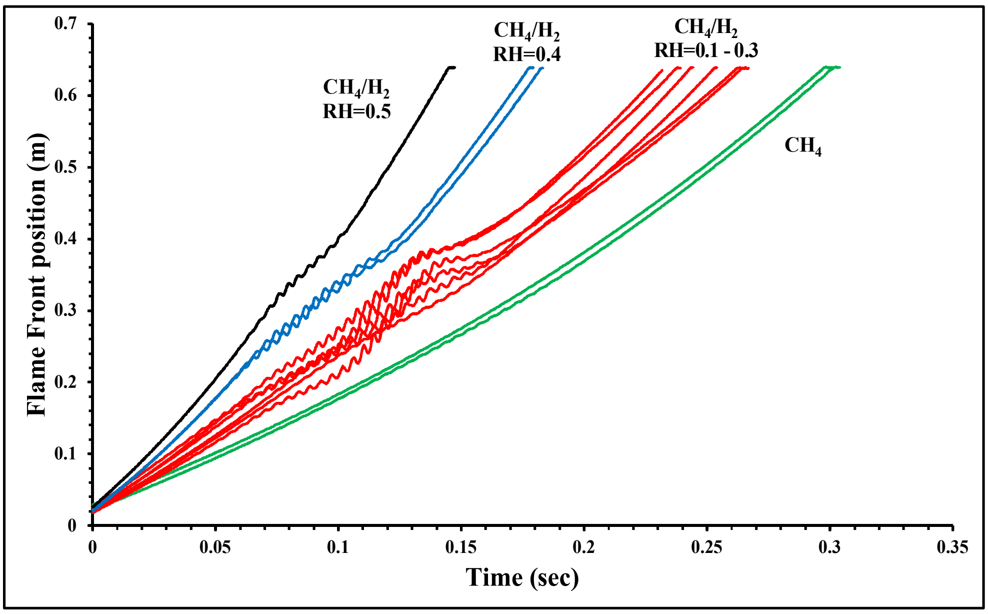
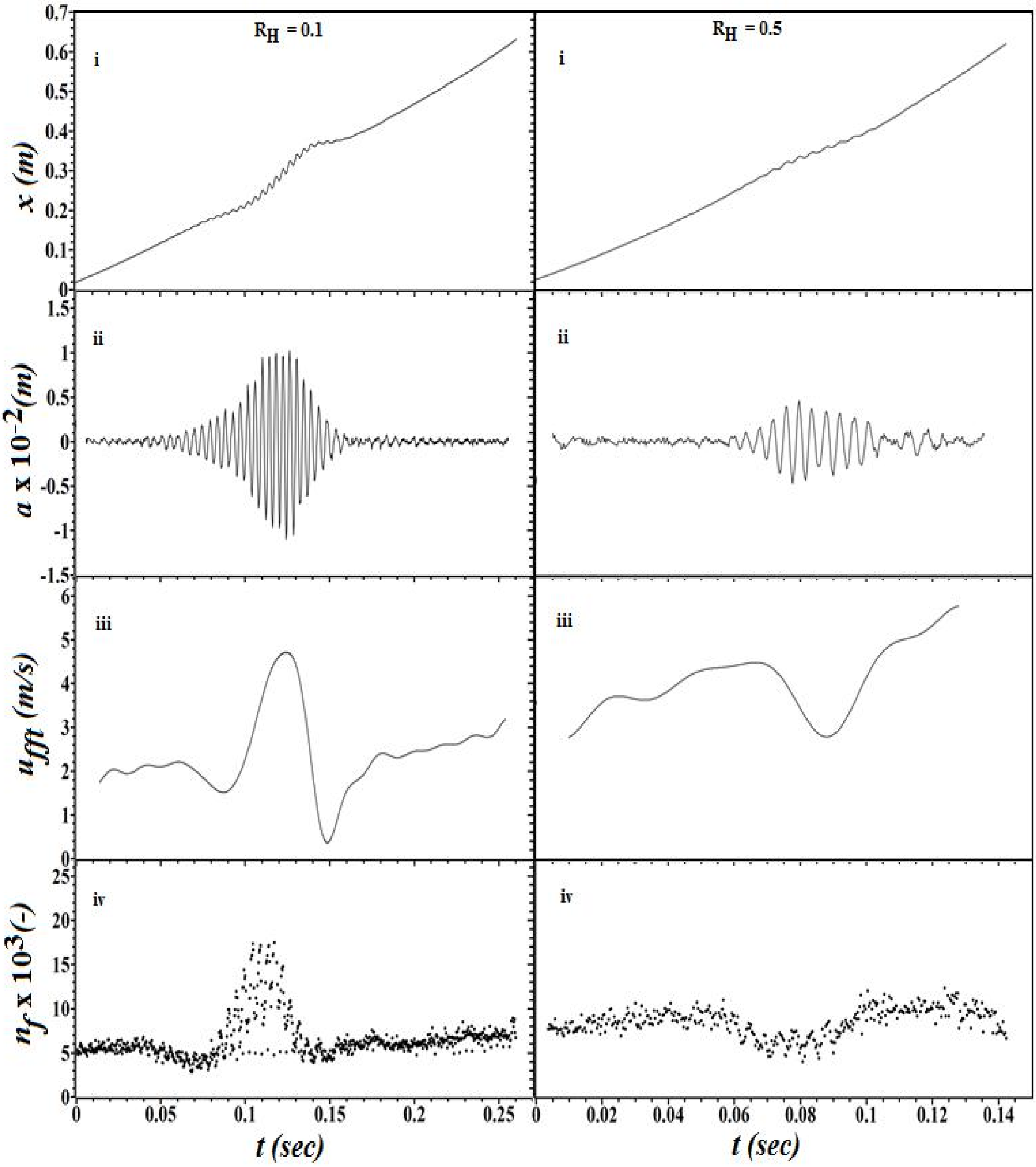


Figure 3. Methane/Hydrogen/air flame propagation at ϕ =1.2



(a) (b)

Figure 4. Methane hydrogen-air flame at ϕ =1.2 (a) R_H=0.1 (b) R_H=0.5 **:** ***x*** in the flame front position, ***a*** is the amplitude, $\boldsymbol{u_{fft}}$ is the FFT filtered flame speed and $\boldsymbol{n_f}$ is the flame size.

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