Flammability and Gravity Effect of Horizontal and Vertical Propagating Flames in Tube: A Comparative Studies

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Abstract—In the current research, experimental work is investigated for vertically and horizontally downward propagating flames in an open-ended tube. The objective was to study and compare the influence of flammability limits, gravity, and the flame speed in the different tube configuration for two different fuels. The experimental facility included a 20 mm inner diameter tube, 1200 mm in length and an optical access quartz tube made centrally of 700 mm in length. Methane-air and propane-air fuel were compared for both vertically and horizontally downward propagating flames. The flame speed at each equivalence ratios for both fuels was lower for the flame that propagates downward compared to the flame that propagates horizontally. For both fuels, the flammability limits tend to rise for the vertically downward flame. The influence of gravity was seen as the flames become leaner and richer in methane-air and propane-air flames that propagate vertically downwards, causing a transformation in the contour of the flame from a steady curved flame to a vibrating corrugated flame.

Index Terms—Equivalence Ratio, Flame Speed, Flame Tube, Flammability Limit.

I. INTRODUCTION

Experiments have shown that the ratio of fuel and oxygen which can support a flame varies with each combustible gas or vapour and determines the propagation of the flame. A flammable mixture could be rendered non-flammable by dilution with one of its constituents (either the fuel or oxygen) or with another gas. The limit of dilution such that the flame remains flammable is called the flammability limit. The minimum amount of fuel required to support the formation of a flame in air is the Lower Flammability limits (LFL). Similarly, the maximum amount of fuel required to support the formation of a flame in air is the Upper Flammability limits (UFL), and above this amount, the mixture is considered too rich to burn. In between the LFL and the UFL is known as the flammable region for the fuel. Flammability limits are characterised using a percentage by volume of the amount of fuel contained in air or by the fuel-air mixture equivalence ratio. Flammability limits are determined in tubes, where the criterion is the ability of a combustion wave to traverse a long tube from one end to the other, and it varies in the direction the flame propagates in the tube [1], [2]. For a tube mounted vertically with the mixture ignited at the lower end (upward propagation), it is possible to go richer or leaner than when the mixture is ignited at the upper end (downward propagation) and for a tube mounted horizontally, the limits are usually between the limits for downward and upward propagation [2].

Strebelow et al. [3] have shown that for a vertical tube, the flammability limit at fuel lean is higher for downward propagation than that for upward propagation. Jarosinski [1] has also shown that as the deviation from stoichiometric mixture increases, the differences between the downward and upward flammability limits increase. He opined that this difference arose from the difference in the time taken for the flame extinction. Therefore, since the downward and upward propagating flame has different flame extinguishment process/time, then the difference in flammability limit is inevitable. Burning at LFL is advantageous in the application of the lean combustion technology. Since at the LFL, the combustible mixtures are burnt in abundant air which allows for complete combustion, thus reducing toxic emission such as NOx into the atmosphere. Also burning at the LFL decreases the temperature of the burned gas, therefore, increasing the specific heat ratio.

II. EXPERIMENTAL RIG AND METHODOLOGY

The test rig consisted of 20 mm bore copper tubes formed in a rectangular shape used for pre-mixing the fuel/air before being ignited. The central 700 mm length of one side of the tube is quartz to provide optical access, with two standard 50 mm computer cooling fans on adjacent sides of the rig for homogeneous mixing of the mixture. The pressure indicator fitted to the rig is a PDCR 810 Druck digital pressure indicator and can read a maximum pressure of up to 1 bar, sufficient enough for checking the rig’s pressure. The test rig is equipped with two three-way valves and a two-way valve, primarily used for letting air in or releasing air from the rig. Schematic of the experimental rig is shown in Fig. 1.
The required volume of the fuel at each equivalence ratio was calculated using Equation 1, measured and injected into the rig using a syringe and two fans attached to the rig were used to create a homogeneous mixture.

\[
V_f = \left( \frac{\bar{V}_T}{\left( \frac{M_f(A/F)_{stoic}}{\bar{M}} \right)^{\phi} + 1} \right)
\]

(1)

Where \( V_T \) is the total volume of the rig, \( \bar{M}_a \) molecular weight of air, \( \bar{M}_f \) is the molecular weight of the fuel, \( \phi \) is equivalence ratio, and \((A/F)_{stoic}\) is the stoichiometric air-fuel ratio.

The propagating flame was recorded using a coloured Casio EX-FH100 high-speed digital camera, with 224 x 168 pixels resolution operated at 420 fps. Ignition was performed using a pilot flame from a gas lighter by opening a port at one end of the tube. 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 [4]. The images of the propagating flames filmed were processed using a code written in Python programming language and the data generated was then saved as an Excel file for further processing using Excel, SciDavis, Origin and MATLAB.

III. RESULTS AND DISCUSSIONS

This chapter presents results and discussions from the experimental work conducted in an open-ended tube with orifice plates at both ends. Propane and methane flames were tested propagating both horizontally and vertically downwards. Firstly, the flame shapes are presented, followed by the flame position with respect to time, then the flame speed versus equivalence ratio flammable limits. Previous research has shown that with orifice plates at both ends of the tube produced relatively steady flame propagation in the entire length of the tube over a large range of equivalence ratio. Mossa [5] had reported the best orifice plate size for the rig was 5mm after doing a comparison using different orifice plates.

For the downwardly propagating flames, the images are presented horizontally with images presented from left to the right direction, represents flame propagation from top to bottom.

A. Horizontal propagating methane/air mixture

Fig. 2 shows images of the propagating flame approximately halfway down the tube for the different equivalence ratios. These images were captured using the coloured Casio EX-FH100 high-speed digital camera at a framing rate of 420 fps. The flame, shaped like a hemisphere, propagated steadily down the tube at all equivalence ratios. Though as the flame become richer, the shape tended to slightly tip towards the unburned mixture. The tipping of the flame has been attributed to the influence of gravity on the hot gases causing the flame to tilt forward at the upper part of the tube [6]. The hemispherical shape is the result of the effect of viscous force near the wall of the tube and heat transfer from the flame to the tube.

![Fig 2: Horizontal propagating methane flame shape at different equivalence ratio](image)

Generally, the overall shape of the flame is highly influenced by the no-slip condition at the walls and the heat transfer from the reaction zone to the wall. Three repeat experiments were carried out for each equivalence ratio to check for the repeatability of the experiment and the representative result of the flame position against time for the range of equivalence ratio possible are shown in Fig. 3.

![Fig 3: Flame front position against time for horizontally propagating metha flame](image)

At lean and rich equivalence ratios, self-induced turbulence of the flame was observed to sets in, making it difficult to accurately process the flame front. Similar observations were made by Hamins et al. [7]; where they reported the presence of self-induced turbulence in the flame as a consequence of hydrodynamic instability.

The speed of the flame was calculated by taking the gradients of the position-time plot and the burning speed was also computed using the method described [8], and the results are shown in Fig. 4. The flame and burning speed peaked at 1.1 equivalence ratio with a flame speed of 0.76 m/s and burning speed was 0.58 m/s.
The values of the burning speed are higher than the values of the laminar burning velocity obtained from spherically expanding flames of Yu et al. [9]. The main error was the calculation of the flame surface area which if not correctly calculated, influences the result of the laminar burning speed. Another source was also the wall quenching effect which retards the flame movement and because of the variability in the mixture formation as slight changes in the mixture formation can change the equivalence ratio and in turn changes the flame speed. A solution to this would be to use a complete premix mixture (i.e. premixing chamber).

B. Horizontal propagating propane/air mixture

Images from a horizontal propagating propane/air flame are shown in Fig. 5. The flame propagated with a hemispherical shape for all equivalence ratios within the flammable limits as was the case for methane flames. Fig. 6 shows the flame front position as a function of time at each equivalence ratio.

The flame speed was determined by finding the gradients of each line; this was plotted against the equivalence ratio ($\phi$) as shown in Fig. 7. There was a considerable variation in these data, though the flame speed tended to peak between $\phi = 1.1$ and $\phi = 1.3$ as against $\phi = 1.1$ for methane-air flame.

This behaviour is very different from that of the measured laminar burning velocity also shown in Fig. 7. This would seem to indicate that the flame stretch or the thermo-diffusion effects are more significant in these flames.

C. Downward Propagating methane/air mixture

The flame images of downward propagating methane/air flame are shown in Fig. 8. There was a continuous change in the shape of the flame, though mostly hemispherical, at the different equivalent ratio within the flammable region. The flame front position at different equivalence ratio is plotted against time shown in Fig. 9.

The flame speed and the burning speed are also plotted as functions of the equivalence ratios as shown in Fig. 10. The flame speed peaked at $\phi = 1.1$ and decreased at richer and leaner $\phi$ up to the flammable limit, though with a very strong variation at $\phi = 1.5$, hence was not processed.
There was strong variability in the burning speed calculated for $1.0 \geq \phi \geq 1.5$, which are higher than the flame speed at some equivalence ratios; this can be attributed to the uncertainty in the mixture composition as a slight change could change the equivalence ration, hence, the flame speed. The flame speed peaked at $\phi = 1.1$ with a speed of 0.63 m/s, however the burning speed, peaked about $\phi = 1.0$ at a speed of 0.64 m/s.

Comparing the flame speed results for few equivalence ratios with results from Coward and Hartwell [10], Hamins et al. [7], and Strehlow and Reuss [11], there was a general satisfactory agreement as shown in Fig. 11. It is worthy to note that their results are in tubes of larger diameter compared to the tube used for the current research.

D. Downward propagating propane/air mixture

Photos of the shape of a propane-air flame, propagating downwards in the tube with 5mm orifice plates placed at both ends are shown in Fig. 12. The flames of 0.8 to 1.5 equivalence ratios propagated steadily with a hemispherical shape, however, for $\phi > 1.5$, the flames initially propagated steadily with hemispherical shape until approximately 0.4 m from the point of ignition, before they became corrugated.

The flame front position against time at the different equivalence ratio within the flammable region is shown in Fig. 13. The flame speed and the burning speed are also plotted as functions of the equivalence ratios in Fig. 14. The flame speed peaked at $\phi = 1.1$.

The burning speed data is scattered with the majority of the data within the error band and peaks at $\phi = 1.2$. The flame speed also have majority of its data within the error band and has a peak value at $\phi = 1.1$, of 0.84m/s whereas the maximum value of the burning speed is at $\phi = 1.0$ with a value of 0.65m/s.
For the downwardly propagating flame, the flame speed of methane/air and propane/air peaked at $\phi = 1.1$, decreasing on the right and left of the peak forming a bell shape. The flames also tend to change shape and extinguished when propagating in the downward configuration at some equivalence ratio, especially at the rich conditions of $\phi \geq 1.4$.

For methane/air flame, flame extinguishing was observed at $\phi \leq 0.9$ and $\phi \geq 1.3$ and for propane/air flame, the flame extinguishing was observed at $\phi \leq 0.9$ and $\phi \geq 1.5$. Therefore, the flame speed of the flames at $\phi \leq 0.9$ and $\phi \geq 1.4$ where processed using only the visible flames before it extinguish. For the downward propagating propane/air flame, the presence of cellular flames with rotating characteristics was first observe at $\phi \leq 1.7$.

The flame speed at each equivalence ratio for both fuel tested, tended to be lower for the downwardly propagating flame when compared to the horizontally propagating flame because of the influence of gravity which reduces the surface area of the flame, hence reducing the speed of the flame. This result is in agreement with Strehlow et al. [3], as they showed that flames propagating in the downward direction give lower flame speed when compared to flames propagating with zero gravity and flames propagating in the upward direction.

The effect of gravity was only observed as the flames get leaner and richer for the vertically downwardly propagating flames on both methane-air and propane-air. The effect resulted in a decrease in the propagating flame speed for the vertically downwardly propagating flames compared to the horizontally propagating flames for both fuels tested. There was also a change in the shape of the flame which can be attributed to the gravity effect.

From the flammability limits results of the current experiment, as expected, it was observed that the flammability limits increased in the lean regime as well as the rich regime for both fuels when propagating downwards in the vertical configuration. The flammability range for methane/air and propane/air for the two configurations studied are shown in Table 1 and Table 2 respectively. These results have been compared to results in [12] and show reasonable agreement. The difference in the values can

E. Flame comparison, flammability limits and gravity effect

The compared flame speeds of methane/air and propane/air flame in the horizontal and vertically downward propagation are shown in Fig. 15 and 16. Though from literature, the maximum laminar burning velocity for both methane and propane lies around $\phi = 1.0$ and $\phi = 1.1$, but our result shows a shift in the peak flame speed into the rich region for horizontally propagating propane/air flame.

The reason for the shift in the peak of the propane/air can be attributed to the variability in the mixture composition which changes the equivalence ratio, hence, the flame speed.
be attributed to the different apparatus used for the experiments as it has been shown in [13] that flammability limits of gases depend on the apparatus used for the experiment.

### TABLE I: Flammability Limit Data for Downwardly Propagating Methane Flame

|          | Horizontal Propagation | Downward Propagation | Flammability Limit from [13] |
|----------|------------------------|----------------------|-----------------------------|
| Methane  |                        |                      |                             |
| Lean Flammability Limit | 0.8                   | 0.7                  | 0.6                         |
| Rich Flammability Limit  | 1.4                   | 1.5                  | 1.35                        |
| Max. Flame Speed          | 0.76 m/s @ \( \phi = 1.1 \) | 0.63 m/s @ \( \phi = 1.1 \) |                             |

### TABLE II: Flammability Limit Data for Downwardly Propagating Propane Flame

|          | Horizontal Propagation | Downward Propagation | Flammability Limit from [13] |
|----------|------------------------|----------------------|-----------------------------|
| Propane  |                        |                      |                             |
| Lean Flammability Limit | 0.9                   | 0.6                  | 0.8                         |
| Rich Flammability Limit  | 1.4                   | 1.8                  | 1.8                         |
| Max. Flame Speed          | 1.05 m/s @ \( \phi = 1.2 \) | 0.84 m/s @ \( \phi = 1.1 \) |                             |

IV. CONCLUSION

The effect of gravity, flammability limits and laminar burning speed for a propagating flame was studied with orifice plate placed at the tube ends. Methane and propane-air mixtures were tested for horizontal and downward propagating flame with a 5mm orifice plate on both ends and the results are compared. For the horizontal propagation, the flame propagated steadily with a relatively constant hemispherical or semi-ellipsoidal shape at all equivalence ratios studied. Methane gives a flame speed graph comparable to data in the literature. The laminar flame speed of methane peaked at equivalence ratio of 1.1 and fell off for both rich and lean mixtures while that for propane shifted from the literature value of \( \phi = 1.1 \) to \( \phi = 1.3 \). For the downward propagation, there was a variation in the flame shape for the different equivalence ratios studied. There was a change in shape for methane-air flames at \( \phi < 0.9 \) and \( \phi > 1.3 \), accompanied by flame quenching. For propane, similar behaviour as that of methane-air flame except for \( \phi > 1.5 \), where there was a continuous change in the shape of the flame throughout the propagation was observed. The flammability limits of both fuels tend to increase. The results showed that the effects of gravity became more important as the lean flammability limit was approached.

V. DECLARATION

The author declared that there is no potential conflict of interest with respect to the research, authorship, and/or publication of this article. Data for this research can be made available if requested.

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