Laminar burning velocities of Ethanol-air mixtures at elevated temperatures using the tube method

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Abstract— **Experiment test for premixed laminar combustion of ethanol-air mixtures has been conducted in a tube technique. The laminar burning velocities of premixed homogeneous Ethanol fuel and air mixtures are determined over a wide range of equivalence ratio at elevated temperatures. The experimental apparatus has been modified for apprehension of flame behaviors at 340 K with both ends open to the atmosphere. For each of the flame speeds, unburned gas velocities and flame surface areas have been measured and computed to determine burning velocity. Repeatable and reliable experimental data are obtained in this rig, showing good agreements with previous data. Laminar burning velocities are increased with elevated temperatures.**

Index Terms: **Ethanol, Laminar burning velocity, premixed flame, flame surface area and unburned gas velocity.**

I. INTRODUCTION

Recently, a great deal of attention has been given to determination of the laminar burning velocities of combustible mixtures because laminar burning velocities are of fundamental importance in regard to developing and justifying the chemical kinetics mechanism of the fuel, as well as in regard to predicting the performance and emissions of internal and external combustion systems [1]. There are many techniques for measuring experimentally the laminar burning velocity of combustible mixtures, such as burner stabilized flames [2,3], heat flux method [4,5] and closed bomb technique Measurements of burning velocities have been extensively studied in the past for a wide variety of hydrocarbon fuels including methane, ethane, propane, butane, octane etc. however, there are relatively few experimental data available for ethanol mixtures with air due to experimental difficulties. As ethanol is liquid at room temperature, the combustible mixture is limited by the vapour pressure of fuel.

Received 5 Nov, 2018; revised 19 Nov, 2018; accepted 20 Nov, 2018.

Available online November 21, 2018.

Liao et al. [12] deduce a linear function for their experimental data by means of constant bomb method. Also by means of the same method Marshall and coworkers [13] correlate them by different coefficients of 2.301 and -1.548. In order to compare power exponents with existing data.

Konnov et al. [14] depict graph, shown different variations of with respect to equivalence ratios. Their results based on Heat Flux method are close to predicted modeling using the Konnov mechanism, which has a bottom of power exponent near the stoichiometric mixtures, with data of 1.5, approximately. Unfortunately, as to the literature review work in this project, the results of the tube method have not been found, though some researchers have investigated the laminar burning velocities of ethanol at high temperatures, but they do not clarify the correlations. the first published observation that a premixed flame travels at a uniform speed using tube technique appears to be that of Mallard and Le Chatelier in 1883 [15] for a horizontal tube with a ignition a the open end and propagation towards the closed end. The measurement of flame propagation in tubes was then used by a number of researchers to determine laminar burning rates notably by Coward and Hartwell [16], Gerstein et al. [17] and Guénoche [18].

However even a casual investigation of the propagation of flame in tubes shows that there are significant intrinsic problems with this technique principally due to interactions of the gas ahead of the flame with the end of the tube and interaction between the flame and tube surface. Furthermore a large number of different configurations have been adopted, examples are, a range of different tube diameters, tube open at both ends, tube closed at one end with ignition at the open end, tube closed at one ignition at the open ends and the use of orifice plates placed in tube ends. The laminar burning velocity of the flame can be found using the following expression that was used by Gerstein et al. [17] although they attributed it to Coward and Payman [19].

$$U_l = (U_f - U_g)\, A_t/A_f \qquad (1)$$

Here, U_f is the observed flame speed, U_l the laminar burning velocity, u_g the unburned gas velocity ahead of the flame and A_t and A_f the cross sectional surface area of the tube and flame surface area. Therefore the flame surface area and gas velocity ahead of the flame must also be determined in addition to the speed of the flame down the tube. The equation to represent the unburned gas velocity linear to the flame speed is: [17].

$$U_g = 0.236\ U_f - 10.47 \qquad (2)$$

The surface area is obtained by photography of the flame and then fitting with an appropriate function. The main problem with this is that for horizontal tubes the flames are often non-symmetrical in the vertical plain as the flame takes on a characteristic 'tipped shape'. A number of slightly differing approaches have been used but no definitive method has been settled on. The gas velocity ahead of the flame has generally been acknowledged to be a possible influence on the propagation speed of flames down tubes but there have been few measurements. The speed will be strongly influenced by the experimental configuration, for a flame propagating from a closed end the gas velocity is likely to be larger than for an open ended tube. Gerstein et al. presented measurements for tube with orifice plates on both ends and found the gas velocity to be relatively small (10 % of the propagation rate) [17].

In this paper, the laminar burning velocity of liquid fuel (ethanol) at elevated temperatures as a function of the equivalence ratio, using tube method open at both ends is presented, including a reliable error estimate. Also, Study flame dynamics and propagation behaviors; measure their flame speeds, surface areas and then laminar burning velocities. The accurate measurements of the observed flame velocity and the flame front area are improved by removing any immaturity and complication from the experimental rig and process, as a result obtaining reliably experimental data of laminar burning velocities. The results have are compared with findings by previous experimental, analytical and modeled studies.

II. EXPERIMENT PROCEDURE

A scheme to display the present experimental apparatus is shown in Figures.1and 2. The propagation of flames down a 20 mm diameter quartz tube have been measured. In order to prepare for an experiment all the tubes are flushed thoroughly with compressed air. The three way valves positioned at either end of the quartz tube were then positioned such that a closed loop was formed. Inline fans are then turned on and in the air in the tubes recirculated around the loop, this is used to mix the fuel and air. The fuel is injected in to loop using a syringe. Once fuel has been injected the fuel and air are allowed to mix for at least a 1 minute, after which the fans are turned off and the three way valves turned such that both ends of the tube are open to atmosphere. The premixed fuel air can then be ignited with either a spark or flame from a gas lighter and a flame can be observed to propagate along the tube, this is captured using a Casio EX-FH100 camera which has a CMOS chip capable of framing rates up to 1000 fps. In this work a framing rate of 420 fps was mostly used, the camera resolution was 224 x 168 pix. The flame progress was typically captured over the central tube length of 130 mm. Close up images were also captured in order that the flame shape could be better resolved. No attempt was made to synchronise the flame images with the ignition, which means there is no reference 'zero time' for all the images. This is not a significant issue if a burning velocity is required but it is not possible to compare the distance achieved after a set time from ignition. Two 5mm diameter orifice plates are used at both ends of the tube to absorb the shock waves as the flame propagates, reducing disturbance and obtaining uniform stable flames. Heater and thermocouples are employed for testing the gas and liquid fuels at high temperatures. This rig is set in horizontal in this work.

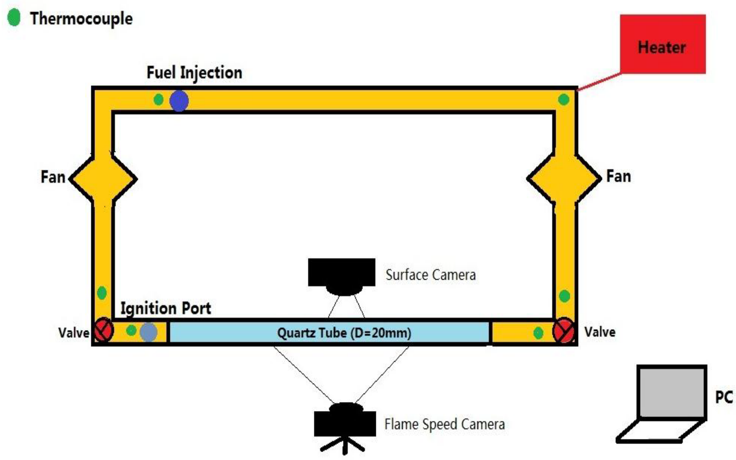

Figure 1. Schematic Illustration of Present Apparatus

Figure 2. Experimental Apparatus Image

In order that the equivalence ratio can be accurately calculated the volume of the rig must be known. Calculations have been made but the actual volume is uncertain. Thus the quoted values of equivalence have an uncertainty of ± 0.1. The resulting .avi files from the filming were image processed in Paint Shop Pro. This involved conversion from a colour to a binary (black and white) image. The leading flame edge was then found, the flame progress was defined as the progress of the leading edge of the flame. Before commencing a systematic study of flame propagation the influence of the ignition source was investigated. Two types of ignition were used an electric spark from a 12 V automotive coil and a gas lighter directed in an opening in the tube. The electric spark significantly higher flame speeds, that is may be due to the interaction between the flame and pressure waves generated by the spark.

III. RESULTS AND DISSCUSION

Due to uncertainty of temperature of the whole rig, the average temperature, T=340 K, was chosen to utilise in determination of fuel flammability, referring to six temperature sensors as shown in Figure.1. A wide range of volumes had been implemented on ethanol in the horizontal tube apparatus, from 130 to 280 microL with 10 microL volume intervals, instead of different equivalence ratios. which could also converted to volumes by a given temperature in the profile, vice versa. As shown in Table1

Table 1. Equivalence Ratio Against Quantity of Ethanol

Equivalence ratio, Ø	Volume, micro L
0.7	130
0.8	150
0.9	170
1.0	190
1.1	200
1.2	220
1.3	240
1.4	260
1.5	280

With processing of images information transferred from video clips by software, the data of observed flame speeds showing in Figure.3. The data was collected from a series of ethanol tests. The speeds each test, average speeds for each volume intervals, and the tendency were clearly shown in the graph. As the amount of fuel increased the flame speeds climbed rapidly from the lean-burn up to the top U_f =1.194 m/s, around Ø = 1.24; and then fell down slowly due to absence of oxygen in the rich-burnt. Most tests demonstrated the repeatability of the results however some cases were not in the expected region so shown with error bars of flame speeds.

Theoretically, the flame is expected to proliferate within a uniform speed. As the actual flame propagated along the tube, the flame speeds by means of the least squares method showed high linearity but varied with fluctuations and slightly decreased from the beginnings of the region videos taken to the ends.

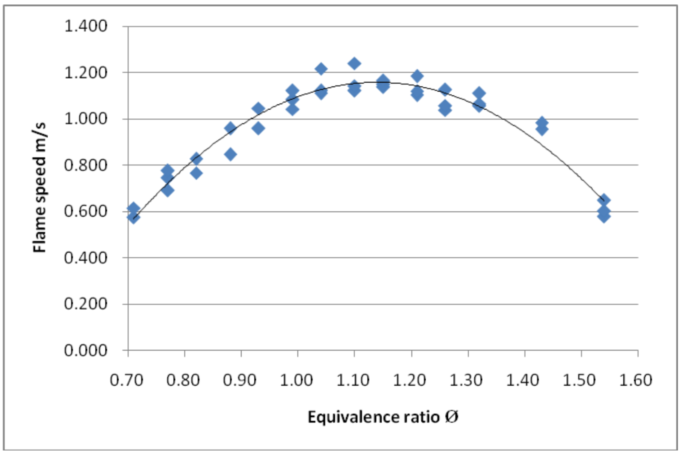

Figure 3. Relationship between Equivalence Ratio and Flame Speed

As the flames moves in the tube, not only could characteristics of their movements be noticed obviously, but also the curvature lengths of flames could be calculated and as a result the ratio A_t/A_f would be produced. The first feature of flame surface was vertical rotation that the flame surface was rotating on an assumed vertical axis of the tube, which had been presented in Figure.4. The back half of hemisphere surface seemed to be larger in the left picture but smaller in the right picture than the front half from the camera view. However, this might attribute to the angle of camera lens view from left to right. The second feature was flame tilt which happened more apparently in the lean and rich burnings, especially in the image for ethanol (280 microL) shown in Figure.4. Near equilibrium reaction, the flame shapes performed more perpendicular and semi-ellipsoid. According to the results, it would be linked the relationship with flame speeds that flames with slower speeds could lead to more tilted flame shapes. Some flammability limitations were found during experiments. For horizontal tests, ethanol/air mixtures performed easily to be ignite and the range of equivalence ratio were varied more extensively from 0.71 (130 mircoL) to 1.54 (280 microL). The one limitation was that flame brightness in videos was too weak to measure by software Corelpaint for either leaner or richer gases. Owing to temperature uncertainty of the rig and photographic measurements, observed flame speeds had unforeseen variations relative to the second order polynomial fit lines. Deviations were represented from -7.32% to 8.97% for 48 horizontal ethanol tests. Flame front speeds travelled at uniform speeds with high confidence of linearity. Nevertheless, deflagration flame waves caused slightly unstable flame speeds which were periodically accelerated and decelerated as they spread along the tube. The aim for settling orifice plates between two ends of the tube is to effectively stabilize the flame speeds and filter acoustic waves which, however, were still existed in present data. By analyzing results combined with the change of flame front areas, it could be obviously noted that the oscillations of flame speeds might attribute to changes of flame front curves, since the image processing gave an observed flame speed by the biggest x-pixel in the image.

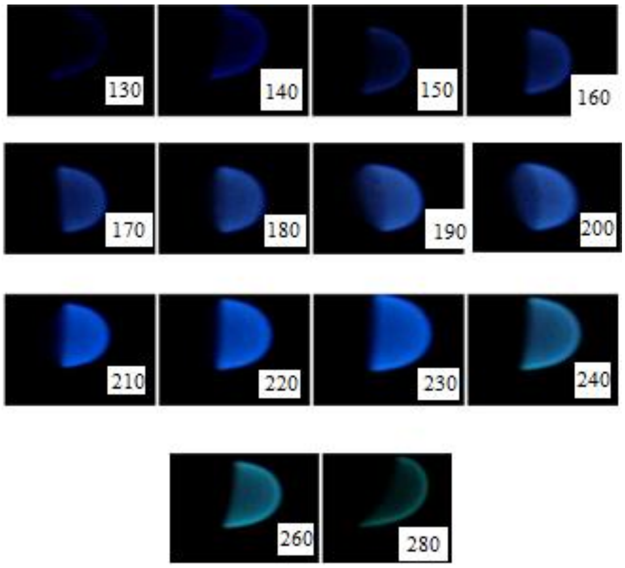

Figure 4. Front Surface Observation by Volume of Ethanol (micro)

The method to measure flame front area was employed the development from Hoare and Linnett [20] which is used an additional image from top of the tube to minimize error from the assumption that flame is a symmetrical semi-ellipsoid. All surface area had been viewing and recording from a close position in order to increase the accuracy of area measurements and the curvature of each flame shape was created by a six order polynomial fit on pixels data in Excel file. With a high resolution camera, enlarged images, and high order fit curvature, the data of flame front area was accurate and reliable enough to be used for the laminar burning velocity's calculation. The objective was to investigate whether the differences between the largest and smallest area along the tube had such an effect on measurements as differences between the top and side flame area.

Figure.5 showed a representative set of flame films of ϕ = 1.15 ethanol from side in the horizontal configuration at 340 K. It was to elucidate the process of measuring the flame front area due to high symmetry and reliability of this flame

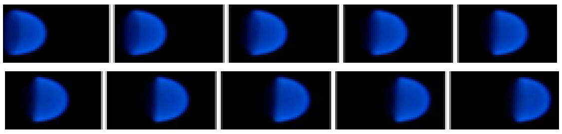

Figure 5. Flame Shape Images of Ethanol for Ø = 1.5

In order to reduce any errors and deviations in measurements, the camera was settled closer than speeds camera to record directly when the flame travelled. Image information was converted to ten flame coordinates which had been presented in Figure.6. Thereafter, the arc length of the front area could be calculated as same as previous.

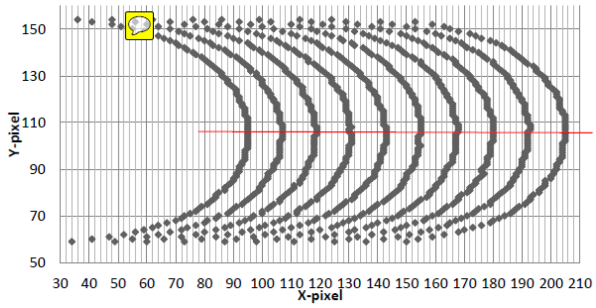

Figure 6. Representative Flame Coordinates of Ethanol for Ø = 1.15

From the red line shown, it could be found the distances between each two flames were not constant, with differences, which was convinced the fact that the observed flame speeds oscillated slightly along its propagation due to the surface changes. The results of surface area had been illustrated in Table.2. All ratios of tube cross-section against flame surface area, A_t/A_f , were around 0.60 except for ϕ =1.43 which had the smallest ratio of 0.547. The gaps between minimum and maximum curvature lengths were not of such disparities as a result the surface area recorded along the side of tube would not have a significant effect on laminar burning velocity. The biggest difference was 2.52% happened when 220 microL fuels were injected, and the smallest was 0.31% relative the average values.

Table 2. Flame surface area of Ethanol in horizontal tube

ϕ	V (microL)	Flame Curvature Length (mm)				At/Af
		Min.	Max.	Average	σ (%)	
0.71	130	32.78	33.48	33.13	1.07	0.604
0.77	140	34.15	34.95	34.55	1.16	0.579
0.82	150	33.26	33.46	33.36	0.31	0.600
0.88	160	32.65	32.92	32.78	0.42	0.610
0.93	170	33.24	33.56	33.40	0.48	0.599
0.99	180	32.16	32.83	32.50	1.03	0.615
1.04	190	33.82	34.21	34.01	0.57	0.588
1.10	200	32.90	33.28	33.09	0.58	0.604
1.15	210	33.56	34.92	34.24	1.98	0.584
1.21	220	34.14	35.90	35.02	2.52	0.571
1.26	230	34.60	34.89	34.75	0.42	0.576
1.32	240	35.31	35.33	35.32	0.04	0.566
1.43	260	36.21	36.97	36.59	1.03	0.547
1.54	280	33.87	34.27	34.07	0.60	0.587

A. *Laminar burning velocity*

Overall, all the variables required to form Equations (1) and (2) had been resolved hence the laminar burning velocity could be calculated. The data had been plotted in Figure.7.

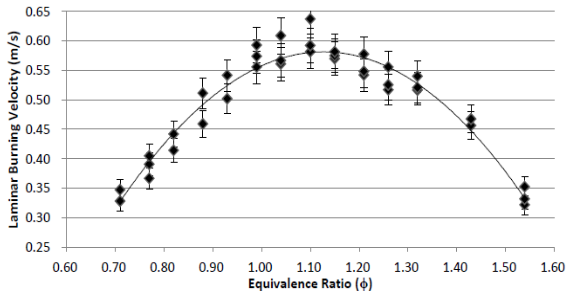

Figure 7. Laminar Burning Velocity of Ethanol in Horizontal Tube

The experiment data showed the peak of laminar burning velocities at 1.10. By fitting a second order polynomial line, the laminar burning velocities had a flat maximum at equivalence ratio of about 1.10 to 1.15, with data of $U_l = 0.582$ m/s. Due to intensive testing points, 10 microL intervals, the curve performed smoothly with respect to equivalence ratios. Deviations were existed in the real figures, shown with error bars. To be specific, they were quantified from -7.32% to +8.97% relative to the fitted data.

Figure.8 shows a comparison of laminar burning velocities measured in this work with literature data.

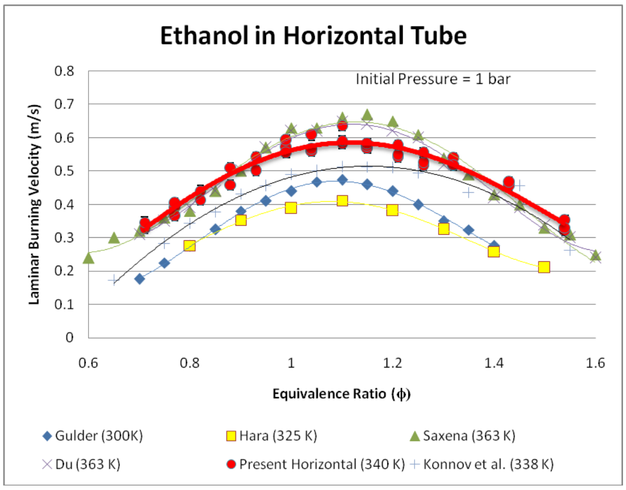

Figure 8. Ethanol Laminar Burning Velocity Comparison

These tests had been investigated not only at alternating, but also at the same equivalence ratios, shown in this and subsequent fit curves by the second order polynomials. Due to limitation of rig, the maximum of testing elevated temperature was averaged 340 K, whereas it was difficult to directly compare to limited quantity of ethanol data published of the same method at the same conditions. Graphed figures showed a good agreement between present data and data by Konnov et al. [14] who measured non-stretched ambient laminar burning velocity employing Heat Flux method at 338 K. Bearing in mind there was an estimated mean error of 6% in present data.

Another representative comparison with data using Counterflow method by Saxena and Williams [21] was performed similarity for all the equivalence ratios, expect for the equivalence ratio between 0.9 and 1.4, where present horizontal data gave smaller values, although present initial temperature was 23 K lower than theirs'. Theoretically, such a 23 K temperature gradient might give an obvious decrease in laminar burning velocity, which indicated that high inaccuracy appeared in measuring lower laminar flames with larger front areas. Liquid fuel evaporability restricted the rig testing ethanol at lower temperature. In order to show the inherent nature of ethanol burning velocities clearly, two previous series of experiments using the constant bomb method were presented that Hara and Tanoue's data [22] were extrapolated smaller than Gülder's [23], though with higher temperature. The basic reason was that they observed flames using schlieren system with high speed camera while Gülder had implemented ionization probes to specify the flame position.

IV. CONCLUSION

The tube method has been successfully applied to determine the laminar burning velocity of ethanol fuel with different equivalence ratio at 340 K. Flame fronts between burning and unburned gases appear to be more symmetrically hemispheric or semi-ellipsoidal, from the top than the side around the horizontal axis of the tube. The slower the horizontal flame speeds are, the more tilted the flame shapes tend to be. Convection between burning and unburned gases occurs more rapidly for fast flames, resulting in small flame front surfaces. Performance of tilted flame shapes ascribes to raised temperature by combustion allowing for flow convection between hot and cool gases. By means of the tube technique, resultant laminar burning velocities achieve satisfactory agreements with the literature although present data are normally performed higher than others. However, the fact is that the laminar burning velocity might have, and indeed has, lain in an acceptable range of magnitude, depending on different experimental apparatus and numerical methods employed. Analytic errors have been categorized in aspects of equivalence ratios, flame speeds, and surface areas, and finally given the overall errors of ±8 % for horizontal data.

ACKNOLOGEMENT

The author would like to thank **Mr**. Malcolm Nettleship for his help in building the test rig in the lab at Sheffield University in the UK.

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