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The turbulent burning velocity of iso-octane/air mixtures

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Abstract

Turbulent burning velocities of iso-octane air mixtures have been measured for expanding flame kernels within a turbulent combustion bomb. High speed schlieren images were used to derive turbulent burning velocity. Turbulent velocity measurements were made at *u'* = 0.5, 1.0, 2.0, 4.0, 6.0 m/s, equivalence ratios of 0.8, 1.0, 1.2, 1.4 and pressures of *P* = 0.1, 0.5, 1.0 MPa. The turbulent burning velocity was found to increase with time and radius from ignition, this was attributed to turbulent flame development. The turbulent burning velocity increased with increasing rms turbulent velocity, and with pressure; although differences were found in the magnitude of this increase for different turbulent velocities. Generally, raising the equivalence ratio resulted in enhanced turbulent burning velocity, excepting measurements made at the lowest turbulent velocity. The results obtained in this study have been compared with those evaluated for a number turbulent burning velocity correlations and the differences are discussed.

Introduction

The turbulent burning velocity, u_t, is a somewhat elusive parameter. Whilst general correlations for u_t exist in the literature [1,2], others have questioned its usefulness; suggesting that it is an experimentally dependent variable [3]. The concept of a turbulent burning velocity is an extension of that of the premixed laminar burning velocity, in that both laminar and turbulent premixtures may be stabilised on burners at a constant flow rate. In the case of the turbulent burning velocity its value depends on the turbulent field (usually characterised by the rms deviation from the mean velocity, u', and the integral length scale, L) and the flame chemistry (characterised by the laminar burning velocity, u_l, and flame thickness, δ_l).

For any measurement of u_t to be comparable with others, information about both the laminar flame and turbulent flowfield must also be known. How each of the usual correlating parameters are experimentally determined, is discussed, in turn, below:

(i) The laminar burning velocity, u_l. It is only since the realisation of the influence of stretch on the laminar burning velocity [4] that stretch free laminar burning velocities, u_l, have been measured that are independent of the measurement method [5]. Experimental determination of u_l is now reasonably repeatable and reproducible; whereas there was, previously, considerable spread in the measured values of u_l [6]. However, to date, most measurements of u_l have been performed at atmospheric pressure and temperature. A limited and rapidly growing amount of data is available at elevated pressures, but these become increasing difficult to obtain with increasing pressure because of the onset of laminar flame instabilities [7]. Alternatively, one dimensional kinetic models may be used to obtain data at elevated pressures and temperatures. However, these are calibrated against laminar burning velocity measurements and it could be argued that it is unwise to rely on extrapolated data derived from kinetic modelling outside the range supported by the existing experimental database.

(ii) The laminar flame thickness, δ_l. A number of definitions of the flame thickness exist; they generally depend on knowledge of the temperature profile across the reaction zone. This profile can be obtained experimentally or computed, assuming a one dimensional propagating flame. Where it is impractical to measure the temperature profile (e.g. due to high pressure) or where there are uncertainties in the chemical mechanism (e.g. for higher hydrocarbons) the expression $\delta_l = \nu / u_l$ where ν is the kinematic viscosity, is typically used [8]. This thickness is smaller than would be obtained from measurement of the temperature profile but is qualitatively correct with respect to the equivalence ratio ϕ, unburned mixture temperature *T*, and pressure *P*.

(iii) The rms turbulent velocity, *u'*. This is relatively accessible from any of the standard flow measuring techniques e.g. hotwire anemometry (HWA), laser doppler velocimetry (LDV) or particle image velocimetry (PIV) measurements.

(iv) Turbulent scales. Classically three different turbulent scales are used in combustion studies to define a turbulent flow: the Integral (*L*), Taylor (λ) and Kolmogorov (η) scales [9]. Determination of the integral length scale, *L*, entails integration of a correlation curve. Experimentally, high frequency (or small spatial resolution) measurements must be taken over sufficient time (or distance) for the turbulent eddies to be temporally or spatially correlated. All existing experimental techniques are challenged to provide sufficient spatial resolution if *L* is less 5 mm. There are additional problems in situations where the mean flow velocity is less than or of the same magnitude as *u'*, as the Taylor hypothesis cannot then be used and the spatial length scale cannot easily be determined from that derived using a time resolved technique [10]. Whilst this situation may seem unlikely it can occur in experimental apparatus where mean flows are kept low to keep a flame in a known position so it may be measured. Spatial correlations are relatively easy to obtain from PIV generated vector maps; however, it can be problematic to obtain a sufficiently large sample of velocities to enable the correlation curve to be generated [11]. The Taylor and Kolmogorov scales are typically derived from *u'* and *L* after making appropriate assumptions.

Once the parameters that are likely to influence the turbulent burning velocity are known there are still further problems with its determination, as the magnitude of u_t has been shown to depend on its definition [12]. A turbulent flame typically exists as a brush, comprising a single connected flame sheet [12]. The thickness of the brush varies, depending on the experimental rig and flowfield. In the case of an approximately spherically expanding flame, taking the leading edge of the flame brush yields a higher value of u_t than if tracking the trailing edge or some intermediate position [12]; as both the flame and flame brush are simultaneously increasing but at different 'rates'. The surface that is tracked depends on the measurement technique. In the case of an expanding turbulent flame, its propagation is usually monitored by measuring the chamber pressure or by schlieren photography. The pressure measurements correspond to a mean reaction front positioned somewhere in the middle of the flame brush, whereas schlieren imaging provides a flame front corresponding approximately to the leading edge of the brush [12]. Stationary or burner flames are now typically imaged with a laser sheet [13] and hence the reaction progress variable can be obtained and an appropriate surface well defined. The burning velocity derived from burner experiments represents (in a sense) an averaged value, as the flame fluctuates backwards and forwards; although it remains stabilised to the burner. Therefore, the local flame displacement speed will be continually varying along the reaction front although a single burnrate is invariably reported. Furthermore, the brush thickness varies along the reaction zone; it will be zero at the point of stabilisation (e.g. burner rim or wire) but increases with distance away from stabilisation point. For spark ignited flames considerable scatter can result in the burnrate of flames as they encounter variations in the turbulent field; especially when the flame is small. An alternative configuration is the cruciform burner, where a ‘large’ propagating flame passes through a turbulent flow field [14].

Underlying the parameters described above is the assumption that a turbulent flame consists of laminar flamelets joined together in a flame brush. However experimental and numerical studies demonstrate that this approach is not always valid: (i) at high values of turbulence the laminar flame structure breaks down as turbulent eddies enter the reaction zone and dissipate heat and species over longer lengths, this ultimately results in flame quench [8]; and (ii) for mixtures with negative Markstein number (or less than unity Lewis number) where lamella like structures (super adiabatic bulge shaped islands) have been observed in turbulent premixed flames [15, 16]. These flames do not appear to fit in with flamelet assumptions, as can demonstrated when they are plotted on a flame regime diagram [15]. For $Le < 1$ mixtures, as u' is increased, localised areas of quench can be identified along with thickening of the reaction zone. The ‘lamella’ like structures are likely to appear gradually with reducing Markstein number as the equivalence ratio is changed, although they have only been identified in highly unstable mixtures.

The object of the present work was to generate a large, well defined database of turbulent burning measurements for a range of u' (rms velocity deviation form the mean), ϕ (equivalence ratio) and pressure. Data were obtained from spark initiated expanding flames ignited in a fan stirred chamber, which had the advantage that relatively large turbulence levels and pressures could be achieved. This configuration has been identified as a distinct category of turbulent flame [17] and is particularly suited to the collection of burnrates. The vessel used in this study was designed such that a central region of turbulent flow is created but the overall mean flow remains zero, so the flame remains situated in the centre of the vessel after ignition and expands outwards. It only takes a few milliseconds from ignition for the flames to reach the walls of this vessel, therefore flame progress must be captured at high speed. A number of techniques have been tried: schlieren photography [18, 19], laser sheet imaging [12] and pressure measurement [18]. Schlieren photography provides an easily identifiable leading edge in one plane; it is useful for high speed filming, as light is directed into the camera allowing short exposure times. The volume contained inside the leading edge of the flame front contains both burned and unburned gas, and this needs to be accounted for in the analysis if turbulent burning velocities are required. High speed laser sheet imaging has also been used in the vessel [12]; this has the advantage that the turbulent flame brush thickness can be determined and so flame radius unambiguously defined. A vertical laser sheet was generated and sub micron particles illuminated. This technique is more technically difficult than others; for example, the laser sheet concentration must be correct for successful imaging. The analysis of laser sheet images is complicated because information is obtained for just a single ‘slice’ through the flame and this might not be representative of the overall flame growth rate. This is a particular problem at high fan speeds, where the flame is often convected away from the spark and hence the laser sheet may then cut a slice through the flame some distance from its centre. Thus, laser sheet imaging is not presently suited to capturing a large database of burning velocity data. Measurement of the rise in pressure associated with flame progress in the vessel yields valuable insight, in that it provides a direct measure of the production of burned gas. To convert the pressure signal into a burning velocity it is necessary to calculate a flame radius [20]. In the apparatus adopted in the current study, significant pressure rise does not occur until the flame achieves a radius of approximately 40 mm. A flame of this size will be approaching the fans and the turbulent flowfield can no longer be assumed the same across the whole surface of the flame. When considering which technique to use to capture flame progress both experimental convenience and quality of information were considered, and high speed schlieren imaging was selected. Comparisons between schlieren imaging with pressure measurements [18] and laser sheet imaging [12] have been performed, the burning velocities from these three techniques have been found to be consistent. Other turbulent flame parameters that have been identified as useful (such as stretch factor, flame surface density and turbulent brush thickness [18]) are difficult to capture in this experimental configuration (as the flame propagates and only relatively few tests can be performed at each condition); although flame brush thicknesses have been previously obtained in this vessel with propane/air flames [12]. Renou et al. have obtained extensive data on expanding flames, albeit for a slightly different configuration [22]. In this work, the results are presented in their dimensional form and the interdependence of u', ϕ and pressure was examined to determine whether, for example, the relationship between u_t and ϕ varies with u'. Iso-octane was selected as the studied fuel due to its use as a surrogate gasoline in engine research and because its laminar burn rate changes dramatically with stretch rate between fuel lean and rich conditions, see Table 1 [5, 18].

Experimental

Experiments were performed in a 30 litre spherical stainless steel vessel. Three pairs of orthogonal quartz windows of diameter 150 mm could be mounted in the vessel, providing excellent optical access. Turbulence was generated in the vessel by four identical eight bladed fans in a regular tetrahedron configuration. The fans were directly coupled to electric motors with separate speed controllers. Each fan was separately adjustable between 3.3 to 167 Hz (200 to 10,000 r.p.m.). The speed of individual fans were maintained within $\pm$5% of each other and adjusted to attain the required turbulence intensity.

The mean, rms velocities and integral length scale have been determined using Laser Doppler Velocimetry. Previous workers found a central region of reasonably uniform isotropic turbulence in this vessel corresponding to the region of optical access (150 mm diameter) [19]. Here the rms. turbulence velocity, *u'*, was found to be represented by

$$u' \text{ (m/s)} = 0.00119\, f_s \text{ (rpm)} \qquad (1)$$

where f_s is the fan speed. The estimated maximum deviation of *u'* calculated by Eq. 1 with measurements in the vessel is 10%. This correlation was found valid for all operating pressures and temperatures. The Taylor, λ, and Kolomogorov, η, scales were determined by calculation using the relationships [23]

$$R_\lambda = \frac{u' \lambda}{\nu} \qquad (2)$$

where R_λ is the Reynolds number and ν is the kinematic viscosity,

$$\frac{\lambda}{L} = \frac{A}{R_\lambda} \qquad (3)$$

here A is a constant, $A = 16 \pm 1.5$ [23]

$$\eta = \frac{\lambda}{15^{0.25} R_\lambda^{\ 0.5}} . \qquad (4)$$

The turbulence properties at the experimental conditions are given in Table 2. The integral length scale, L, was measured by (two-point correlation [19]) to be 0.02±0.001 m and was independent of all operating variables from 1000 to 10,000 rpm. At 500 rpm L has been measure to be 0.024 mm. The Taylor and Kolomogrov scales decreased with both *u'* and pressure. These results have been confirmed by more recent PIV measurements [24].

The mixture temperature was measured using a K-type thermocouple situated inside the vessel. The entire vessel was preheated by a 2 kW heater positioned close to a wall within the vessel. A piezoresistive pressure transducer was employed to measure the pressure during mixture preparation. This transducer was situated outside the vessel and was isolated just prior to ignition.

Mixtures were prepared in the vessel. After an experiment the vessel was flushed several times with compressed air and evacuated. Dry cylinder air was provided for the combustible mixture. The calculated volumes of liquid iso-octane were injected into the vessel using a gas tight syringe. The fans were run during mixture preparation, both to ensure full mixing and to assist heat transfer from the vessel's electrical heater. For laminar studies the fans were switched off for a period of 60 seconds, following mixture preparation, before ignition. In turbulent tests the fans were maintained at the set speed, to produce the desired rms turbulence intensity throughout the mixture preparation, ignition and combustion period. The mixture temperature for all experiments reported here was set at 360±10 K. This temperature was selected to ensure complete evapouration of the fuel at all pressures.

Ignition was initiated by a purpose built stainless steel/ceramic sparkplug, this had a set gap of 0.5-1 mm (dependent on the pressure) positioned at the centre of the vessel. A Lucas 12 V transistorised automotive ignition coil system was connected to the spark electrode assembly. The average spark energy to the electrodes was measured to be 23 mJ.

The flames were imaged using a high speed schlieren photography system, comprising a 20 W tungsten element lamp, 1000 mm focal length lens, a pinhole and high speed cameras. In this work two cameras were used, a Kodak 4540 framing at 4500 fps and a Photosonics Phantom 4 framing at 3800 fps. The resulting images were alternatively hand traced to extract the flame contour or processed using Adobe PhotoShop 6.0. Processing was performed by subtracting a background (pre-explosion) image from the subsequent images and applying a threshold; a binary image was produced for each frame, where the burned area was white and the remainder black. The spark image was removed using hand tracing. Flame areas were then determined by counting the number of pixels behind the flame front. Mean flame radii were derived as those of a circle of equal area to that measured. Further details are available in reference [25], where deviations in measured turbulent burning velocity associated with the processing method were found to be approximately 0.02 m/s. Examples of laminar and turbulent schlieren ciné films are given as Supplementary Content.

The unstretched laminar burning velocity and Markstein length at each combination of pressure and equivalence ratio were derived from high speed schlieren images of spherically expanding flames obtained in the same vessel but with the fans stationary. Details of the processing are given in reference [5]. Values of Markstein length/number that characterise the influence of stretch rate on a laminar flame, are provided here for reference. A number of Markstein lengths have been defined depending on the definition of the burning velocity [5], two are given in Table 1. The first of these is L_b, which characterises the effect of stretch rate on observed flame speed (which includes gas expansion). This parameter was selected as, apart from the determination of a gradient (of the observed flame speed with flame stretch), it entails no further processing/assumption. Also shown in Table 1 are values of Markstein number Ma_{sr} (a Markstein number is a Markstein length normalised by the laminar flame thickness). This parameter characterises the influence of the stretch rate associated with the burning velocity (no gas expansion) based on the production of burned products. For flames with a positive Markstein number the burning rate decreased as stretch rate is increased. For flames yielding a negative Markstein number, the burn rate increased with increasing stretch rate. Flames with a negative Markstein number (or length) were generally cellular under laminar conditions, making measurement of the laminar burning velocity problematic [5]. Markstein numbers have been shown to useful in interpreting turbulent burning velocity measurements [18].

Results

Shown in Fig. 1 are derived mean flame schlieren radii plotted against time for stoichiometric flames at 0.5 MPa for increasing u'. Five deflagrations were monitored at each condition. These curves were differentiated to yield the turbulent flame speed, S_{sch}, the observed speed at which the developing flame travelled from the spark outwards; these are shown in Fig. 2, plotted against radius. The experimentally derived flame radii with turbulent burning velocities are provided in the Supplementary Content.

The turbulent flame speed increased continuously with radius (and time) throughout the measurement period, this has been attributed to turbulent flame development [10]. A flame can only be wrinkled by those turbulent eddies smaller than itself, eddies much larger than the flame will merely convect it. The proportion of turbulent eddies smaller than the flame has been determined, using the power spectra density of turbulence, by previous workers [10]. Therefore, as flames grow they experience a greater proportion of the turbulent spectrum; this is expressed in terms of an increasing effective rms velocity, u'_k which results in more flame wrinkling and higher flame speed. On the basis of this argument, one might expect the flame speed to continue to increase until the flame kernel encompasses the entire turbulent spectrum. Estimations of flame development in this rig suggest that the flames growing to the window edge typically encompass less than 60 % of the turbulent scales within the vessel, and would therefore, be expected to be continually accelerating within the optically accessible region in the vessel.

Visible shot to shot variation in flame propagation between combustion events at a given set of conditions can be observed in Fig. 1. Each flame has a slightly different radius-time curve, as the instantaneous flow field at the point of ignition in the vessel was different for each event. The ignition is not believed to have any influence on this shot to shot variation; in experiments performed on laminar flames, with the same ignition unit, flame radius variations (the radius at a specific time) as low as 1% were found. Consistent with the flame development argument advanced in the previous paragraph, as each flame grew it encountered turbulent eddies of differing size, at different times and in different positions; these were responsible for modifying the instantaneous burn rate due to changes in flame wrinkling and strain rate as well as, in some cases, convecting the flame. Theoretically, when a flame becomes sufficiently large, it can experience the full spectrum of eddies of all sizes and the burn rate might attain a single characteristic value [2]; however this was not achieved in this vessel and, indeed, it has been suggested that such a single value may not exist [21]. Thus flame development and the observed scatter are closely linked and characteristic of premixed turbulent flames, ignited within an existing turbulent field.

The highest flame speed observed varied from 4 to 14 m/s; with increasing *u'*, Fig 2. However, the magnitude of these achieved speeds was mainly associated with the expansion of the burned gases; which expand approximately seven fold (it varies with equivalence ratio and pressure) relative to the unburned mixture. This is the main factor to be accounted for in translating the observed flame speed to the propagation rate of the flame. As discussed previously, there has been confusion between expressing the propagation rate in terms of the rate of entrainment of unburned mixture and the production of burned gas [2, 12]. To determine the position of the leading edge of the flame front an entrainment velocity is required; however, if the pressure rise of a process is wanted, then the velocity associated with the rate of production of burned gas is more appropriate. In this work turbulent burning velocities, expressing the mass rate of consumption of unburned fuel/air mixture, u_{tr}, were calculated using the empirically derived expression [12]:

$$u_{tr} = 0.9 \frac{\rho_b}{\rho_u} S_{sch} \tag{5}$$

where the burned to unburned gas density ratio, ρ_b/ρ_u, accounted for the expansion of hot gases behind the flame front. Equation 5 was developed based on simultaneous high speed schlieren and laser speed imaging [12]. In that work, the magnitudes of a number of different turbulent burning velocities, based on various alternative definitions, were compared to the schlieren flame speed. The empirically derived constant, “0.9” was found to relate the burning velocity derived from entrainment rate to one based on a radius associated with the mass burning rate. In practice is unlikely that a singular relationship between the schlieren derived and mass consumption burning velocity applies and that a variation with radius might be expected; however, the scatter in the experimental results was such that this could not be detected.

Simultaneous high speed schlieren imaging and pressure measurements have also been performed and reported previously [18]. The disadvantage of this technique for the vessel adopted in the current work was that significant pressure rises could only be detected at large radii at which point the flame was nearly as large as the imaging area permitted by the available window. The turbulent burning velocities derived from pressure measurements, which correspond to the mass consumption of the unburned fuel/air mixture [12], were compared with u_{tr} found using high speed schlieren imaging and Eq. 5. The burning velocities obtained using the two techniques were similar for a range of equivalence ratios and fuels [18]. In summary, finding a good agreement between turbulent burning velocity magnitudes based on high speed schlieren imaging with laser sheet flame imaging and pressure measurements justified the use of the more convenient schlieren method for the wide range of conditions explored in the current study.

Shown in Fig. 3 are plots of u_{tr} with time, for increasing u' at 0.5 MPa. A plot is shown for each equivalence ratio. For $\phi = 1.0$, 1.2 and 1.4, u_{tr} increased consistently with u'. For the lean case ($\phi = 0.8$) are less clear. At the lower values of u', the lean flames grew outward from the spark plug gap. However, at turbulence levels above $u' = 1$ m/s, a number of these lean flames quenched completely shortly after ignition. Difficulties with flame quench immediately after ignition are a particular problem with this type experiment. Those lean flames that did not quench shortly after ignition had large variations in u_{tr}. In other studies, increased ignition energies have been employed to enable measurements to be captured at these conditions [25]. This was not done here, a single ignition unit was employed. Even those lean flame kernels that did go on to burn across the whole chamber tended to be convected away from the ignition position. As a result there was considerable scatter in u_{tr} at higher u' and $\phi = 0.8$ flames could not be ignited at and beyond $u' = 6$ m/s.

The corresponding values of u_{tr} plotted versus mean schlieren flame radius (rather than time as in Fig. 3) are shown in Fig. 4. The effect of increasing u' was again to increase u_{tr}. This method of visualising the turbulent flame propagation rate (plotting against radius rather than time) has been generally adopted throughout the rest of this paper, as it was found easier to perform comparisons at a fixed radius, as radius plots resulted in less visual shot to shot scatter and differences between operating conditions were more apparent. From this it could be suggested that comparison using the flame radius encompasses a wider range of turbulent scales compared to time from ignition. Whether the acceleration in the burning velocity is primarily a function of the time elapsed from ignition (i.e. the turbulent timescale) or the flame radius (i.e. length scale) is uncertain, both are likely to have an effect. The longer the lifetime of the flame the more time there was for turbulent eddies to wrinkle the surface (a reflection of the history of the flame [21]); however, flames may only be wrinkled by eddies smaller than the flame diameter (controlled by the rig geometry and flame size).

Shown plotted in Fig. 5 are turbulent burning velocities u_{tr} versus mean (schlieren derived) flame radius at each ϕ for constant values of u' of 1 and 4 m/s at 1 MPa. In each plot the flowfield properties were the same; however, the measured laminar burning velocity and Markstein number (or Lewis number) for a given mixture both changed, see Table 1. The laminar burning velocity was similar for ϕ = 1.0 and 1.2 but was lower for the lean and rich flames. The Lewis and Markstein lengths were largest for lean mixtures, falling to negative values of L_b at the richest mixtures. A number of researches have investigated thermo-diffusive effects by selecting flames with the same laminar burning velocity but different Lewis/Markstein numbers [26, 27]. Flames with the lowest Lewis/Markstein number have been found to burn faster under turbulent conditions. At both values of u' tested, the ϕ = 0.8 flames were slowest; as expected, as they had the lowest laminar burning velocity. Next fastest was ϕ = 1.0, with the ϕ = 1.2 and ϕ = 1.4 mixtures yielding similar values of u_{tr}.

Increasing the pressure altered some of the turbulent scales and the laminar flame properties. In these tests the pressure was increased and u' kept constant. Turbulent scales do different things as the pressure increases; L, which is primarily a function of the vessel size, remains constant; however, the Taylor and Kolmogorov scales fall. Flame curvature has been shown to increase with pressure as a result of increased wrinkling [28]. With regard to the laminar flame properties, u_l decreases in proportion to the pressure to the power a third; this appears to be a reasonably universal rule irrespective of fuel or equivalence ratio. The laminar flame thickness also decreases, permitting the flame to wrinkle more. The Markstein number also falls, although the magnitude of the drop depends on ϕ [5]. In the case of rich mixtures, Ma_{sr} was not quantifiable at higher pressures. This was because the flames became cellular from ignition and, although a laminar burning velocity could be estimated based on the initial burn rate, the Markstein length could not be determined. The effect of increasing pressure is shown in Figs. 6 and

7. The turbulent burning velocity did not change significantly with pressure. At u' = 1 m/s, increasing the pressure from 0.1 to 1 MPa had no observable effect on the burning velocity at any of the equivalence ratios tested. At u' = 4 m/s, increasing the pressure resulted in an observable increase in u_{tr}. Lean mixtures could not be reliably ignited at 0.1 and 0.5 MPa and u' = 4 m/s. In conclusion (despite changes to the laminar burning velocity, turbulent length scales and the possible influence of laminar flame instabilities) increasing the pressure 10 fold generally had little influence on the turbulent burning velocity, although some increase was observed for rich mixtures at high turbulent intensities (u' = 4 m/s).

Data reduction and comparison

The objective of the current study has been to generate a consistent database of experimental turbulent (and comparable laminar) burning velocity information for a representative hydrocarbon fuel over a much wider range of conditions (particularly elevated pressure) than hitherto available. Reasons (presented earlier in the Introduction) associated with definition of turbulent burning velocity, experimental techniques and rig dependency render it problematic directly to compare the present data with those currently available for more restricted conditions. Hence, comparisons have been made with data derived using some of the turbulent burning velocity models and correlations (based on earlier experimental data) available in the literature. The list of these is not extensive, nor is the purpose here to critically review or rank these. The object has been to justify the need for the current data by demonstrating that none, as interpreted by the authors, can completely reproduce the trends observed here over the full range of conditions investigated. Hopefully this will stimulate and help validate improved future models.

The flames observed in this study accelerated continuously from initiation to window edge; hence a flame velocity at a convenient fixed mean flame radius was selected to provide a single representative value of u_t. A radius of 30 mm (1.5 L) was chosen; sufficiently large that spark/ignition effects could be discounted, yet small enough that most of the flames grew to this radius, before parts of the flame edge extended beyond the window as a result of bulk flame convection effects. In addition, the flowfield had been previously well characterised in this region. Also the flame brush thickness could be estimated on the basis of laser sheet data for propane-air flames obtained in a earlier study [12]. High speed laser sheet images were captured for rich and lean propane air flames for a range of u'. In that work, a distance a_j was found that was the distance of the local flame front from the mean flame front. The mean flame front was assumed a circle whose centre was at the centroid of the laser sheet image [29]. A flame wrinkling parameter a', was found as the rms deviation of the local flame front from the mean flame front, this is shown in Fig. 8 plotted against mean flame radius for a number of propane-air flames at a range of conditions. The flame brush thickness (distance from completely burned to completely unburned gas) was approximately $3a'$. Values of a' can be seen to increase systematically from ignition, for a schlieren radius of 60 mm ($r_{sch}/L = 3$) the flame brush thickness can be calculated to vary between 15 and 36 mm (calculated as $3a'/L$). In the current study, some significantly higher turbulent intensities were encountered (u'/u_l ~ 25); such that the universal applicability of the a' measurements in Fig. 8 maybe questionable. Nevertheless, in the majority of the experiments performed u'/u_l was < 11. At a schlieren radius of 30 mm the average value of a' was 6 mm, which corresponds to a typical flame brush thickness of ~ 18 mm.

The current measurements of u_t have been compared with those generated using five selected turbulent burning velocity expressions and the influence of u' (pressure and equivalence constant), ϕ (pressure constant) and pressure examined. Comparisons of, and the issues of correlating, turbulent burning velocity measurements have been discussed in the seminal work of Chomiak and Lipatnikov [2].

(i) Kobayashi et al. [30]. This correlation was derived from a number of measurements performed on a high pressure burner (up to 1.0 MPa) fuelled with methane. It was observed that the turbulent burning velocity increased with a pressure and a correlation was derived to fit the experimental data, using the equation below:

$$\frac{u_t}{u_l} = 5.04\left(\left(\frac{P}{P_o}\right)\left(\frac{u'}{u_l}\right)\right)^{0.38} \qquad (6)$$

where P_o is 0.1 MPa. Without the pressure terms in Eq. 6 this correlation is similar to the classical turbulent burning velocity expression proposed by Damkohler [9]. This correlation should not necessarily be expected to agree with the results presented here as they were for burner measurements and the fuel was different; hence, both the geometry and history of the flames in the two experiments were different. However, Eq. 6 was particularly developed to demonstrate the influence of pressure on u_t and is included here to contrast the influence of pressure between burners and bombs.

(ii) Bradley et al., [1]. This correlation was developed from experimental data generated using numerous different measurement techniques and a wide range of conditions and fuels. The following expression was presented as a reasonable representation of the dataset:

$$u_t \quad = \quad 0.88 u'_k \left(KLe\right)^{-0.3} \tag{7}$$

for the range $0.01 < KLe < 0.63$, where K is the Karlovitz stretch factor which is defined for this correlation as:

$$K = 0.157 (u'/u_l)^2 R_L^{-0.5} . \tag{8}$$

where R_L is the turbulent Reynolds number, $u'L/\nu$. Flame development was accounted for with the use of u'_k which was obtained from integration of the turbulence power spectra density and represents the proportion of the turbulent flowfield experienced by the flame. Here u' was substituted for u'_k in Eq. 7 thus the turbulent burning velocity of a theoretically fully developed flame is found. The Lewis number was included to account for thermal diffusive/strain effects so it might be expected that the differences seen between the fuel lean and rich flames might be predicted using this expression. The measurements correlated were predominately performed at atmospheric pressure, therefore the influence of elevated pressure on the turbulent burning velocity was not correlated directly.

(iii) Zimont, as described in detail in [2]. This expression incorporates both empirical correlations and theoretical concepts; it is presented below in the form given by Driscoll [21]:

$$\frac{u_t}{u_l} = 1 + A_z \left(\frac{u'}{u_l}\right)^{1/2} \left(\frac{u' L}{\nu}\right)^{1/4}. \tag{9}$$

where A_z is an adjustable constant, a value of 0.4 was used here [2]. As it is included within FLUENT, it might be argued that this, currently, is the most widely used turbulent burning velocity expression. It is included here to act a reference with which to contrast our experiments. It should be noted that this model has been extended to the situation where Le $\neq$ 1 [27]; however, this extension was not used here.

Other turbulent burning velocity expressions, based on fundamental concepts and modelled results have relatively recently appeared in the literature, two are included here.

(iv) Peters [8] derived an expression for the turbulent burning velocity based on a solution to the flame surface area ratio where flame wrinkling is modelled using a non reacting scalar, *G*. Its is shown here in the form given by Bradley [6],

$$\frac{u_t}{u'} = \frac{u_l}{u'} + \frac{0.39 Da}{b_1}\left[\left(1 + \frac{5.13 b_1^2}{Da}\right)^{1/2} - 1\right]. \tag{10}$$

Here b_1 is a constant derived from experimental data and is assigned a value of 2, and *Da* is the Damköhler number which equals $u_l L/u'\delta_l$. This model does not include thermo-diffusive effects and is strictly only applicable to planar flames. Peters [8] compared Eq. 10 with data collected by Bradley et al. [1]; good agreement was found.

(v) A turbulent flame speed model derived from a model of the mean scalar dissipation rate has been reported by Kolla et al. [31],[32]

$$\frac{u_t}{u_l} = \left\{ \frac{18C_\mu}{(2C_m - 1)\beta'} \left[\left[2K_c^* - \tau C_4 \right] \left(\frac{u' L}{u_l \delta_L^o} \right) + \frac{2C_3}{3} \left(\frac{u'}{u_l} \right)^2 \right] \right\}^{1/2} \quad (11)$$

The model constants were obtained from DNS data and represent the scalar mixing physics, values are given in [31] and [32]. The u_t parameter here is that of a planar leading edge displacement speed; thermo-diffusive effects are not included in the model. Equation 11 has been compared with data from a number of experimental studies; particularly good agreement was found with the experimental data of Savarianandam and Lawn [33] for lean methane-air flames stabilised in a wide angled diffuser.

The effect of increasing *u'* on u_t (at a radius of 30mm) is shown for all ϕ at 0.5 MPa in Fig. 9. Experimental data points and second order curve fits are displayed; there was significant scatter in the measured values. As expected and observed in all cases, u_{tr} increased with *u'*. For $\phi = 0.8$ the fitting line does not go beyond *u'* = 1 m/s as the flames could not be reliably ignited (100%) above that value. The burning velocities can be seen to 'bend over' at higher *u'*. This can particularly be seen for $\phi = 1$ between *u'* = 4 and 6 m/s. Up to and including *u'* = 2 m/s, the two rich mixtures produced similar values of u_{tr}; however, at *u'* = 4 and 6 m/s the richest mixture ($\phi = 1.4$) burned noticeably faster than at the other equivalence ratios.

The effect of increasing *u'* on u_t for the five burning velocity expressions is shown in Fig. 10, for stoichiometric mixtures at 0.5 MPa. All five expressions predict magnitudes of u_t somewhat higher than the values presented in Fig. 9. This is to be expected as these expression yield fully developed turbulent burning velocities, whereas as discussed previously, the experimental flames at 30 mm mean flame radius are less fully developed. The expressions of Bradley et al. (Eq. 7) and Zimont (Eq. 9) predict similar values of u_t. The trend in values generated using the expression of Kobayashi et al. (Eq. 6) can be seen to be qualitatively similar, but produces u_t magnitudes consistently higher by approximately 2 m/s. The first three expressions 'turn down' between *u'* = 2 to

3 m/s, after which u_t becomes less sensitive to changes in u'; this is similar to the behaviour noted in the experimental measurements. The equations of Peters (Eq. 10) and Kolla et al. (Eq. 11) both predict a more rapid increase of u_t with u' with less evidence of 'turn down'. Equation 11 results in significantly higher values of u_t than the other expressions; similar findings have been shown in [31], where Eq. 11 was compared with other turbulent burning experiments.

Experimental values of u_{tr} at 30 mm are plotted against ϕ in Fig. 11, for all u' at 0.5 MPa; second and first order fits are also displayed. For u' = 2 m/s, experimental data from an earlier (where a wider range of ϕ were tested) are shown [18]. At the lowest u' tested, u' = 0.5 m/s, the maximum turbulent burning velocity was found at ϕ = 1.2. As u' increased, the burning velocity of the ϕ = 1.4 flames approached those at ϕ = 1.2 and then exceeded them for u' = 4 and 6 m/s. The richest flames appeared to 'cope with' the highest turbulence levels much more successfully than the stoichiometric and (particularly) the lean mixtures, which quenched. The lean mixtures were not guaranteed to propagate from u' = 1 m/s onwards, and a quench region is indicated on the figure. Five attempts to ignite each mixture were made, some did ignite and these are shown.

The predicted values of u_t plotted against equivalence ratio are shown in Fig. 12; quite different behaviours are suggested. Equations 6, 9 and 11 all appear to generate similarly shaped curves, the peak occurring at ϕ = 1.1; where u_l also peaks. For Eq. 7, which incorporates the Lewis number, the primary difference seems to be at lean equivalence ratios; where a sharp decrease in u_t can be observed compared to the other equations. Overall, the fuel lean values of u_t are much lower for Eq. 7 than for Eqs. 6 and 9. Application of equation 10 results in much flatter curves, with little difference in u_t from ϕ = 0.9 to 1.2. None of these equations demonstrate the differing changes in the velocity of the flames with ϕ, i.e. the peak value of u_t changes with increasing u'.

The effect of pressure on u_{tr} at a flame radius of 30 mm is shown in Fig. 13. At u' = 1 m/s the changes in u_{tr} with pressure are of a similar order as the experimental scatter and therefore, to a first approximation, increasing the pressure to 1 MPa did not result in an increase in u_{tr}. At u' = 4 m/s, mixtures at ϕ = 0.8 could only be ignited at 1 MPa. However, at the other equivalence ratios the turbulent burning velocity increased with pressure. The effect of increasing pressure on turbulent burning velocity predicted by the five selected expressions is shown in Fig. 14. Overall the influence of pressure on u_t is captured, u_t shows little sensitivity to or a slight increase with pressure for all the expressions. Equation 6 (which was designed to predict pressure effects) and Eq. 11 yield remarkably qualitatively similar results despite their different derivations. In most cases the models predict that pressure has a lesser effect on the values of u_t for $\phi = 0.8$ at $u' = 4$ m/s; this could not be confirmed experimentally, as the flames quenched shortly after ignition at 0.1 and 0.5 MPa.

The combined experimental influences of ϕ, u' and pressure result in complex behaviour that are not completely reproduced by the turbulent burning velocity expressions given here. Not tested here, as all the measurements were performed on one rig, is the influence of changing the turbulent length scale; although there are uncertainties concerning its impact on u_t [2]. All five turbulent burning velocity expression are easily implemented as source terms in mathematical models. The differences observed between these experimental results and the modelled turbulent burning velocity could be due to differences in the definition or geometry for the turbulent burning velocity (e.g. planar vs. curved flames); or it might be that thermo-diffusive effects are not properly accounted for in the models. That the influence of u' and pressure are reasonably well predicted by all the models/correlations indicates that differences in geometry and definition may not be that significant when looking at qualitative trends in the turbulent burning velocity. If quantitative agreement between experiments and model is required, they may be more important. Thermo-diffusive effects are explicitly not included in the theoretically derived expressions (Eq. 10 and 11) and Eq. 6 is derived from methane-air experiments where the Lewis number will be close to 1 at all conditions. The shift in peak turbulent burning velocity to rich equivalence ratios for heavy hydrocarbons was demonstrated as far back as 1955, by Whol and Shore [34] on the basis of burner experiments; thus, the effect of Lewis number on u_t has been demonstrated for a different geometry to that adopted in this study. In this work the choice of fuel and equivalence ratios ($\phi = 1.4$ might be considered unrealistically fuel rich) highlight the influence of thermo-diffusive effects, and it might be argued that they do not reflect the conditions in practical combustion systems.

It is likely that localised variations in the flow field strain rate will impact on the local burn rate [1],[27]. This influence can be characterised by a mixture's Markstein number [6] which has been shown to vary with equivalence ratio and pressure (this is not the case with *Le* which does not change with pressure). However, there is still much controversy and uncertainty surrounding this experimentally determined parameter; in particular, its magnitude is not known for the majority of fuels, temperatures and pressures. The rapid transition of laminar flames to cellular structure renders experimental determination of Markstein numbers particularly problematic for most hydrocarbon fuels at elevated (engine like) pressures.

Are the variations that are shown in this study of any significance? The most obvious observation from these results is how effectively the fuel rich flames cope with increasing turbulence. A recent study performed in a similar type of vessel concluded that flames characterised with a negative Markstein number have a higher turbulent burning velocity than those with a positive Markstein number but that as turbulence was increased the differences between the two flames decreased [35]. Those workers reasoned, on the basis of flame wrinkling parameters, that as the turbulence increased the flame ceased to respond to increasing oscillations in the flow. The current experimental results seem to contradict those conclusions, as it was at the highest u' that the rich (negative Markstein) number flames were seen to burn fastest, although the integral length scale was larger here (20 mm compared to ~4mm). Further tests (in particular for different geometries and high turbulent intensities) are necessary on fuel-air mixtures with low Markstein number to characterise how these turbulent flames behave. The significance of the results depends on the application; in the case of internal combustion engines and explosions, where it is required that the flame position is known at increasing time from initiation, small errors in the predicted burnrate can result in significant differences between predicted and modelled flame position. In real systems there may be strong variations in u', ϕ and pressure through a combustion event and if the interdependence of these parameters is not properly accounted for it is unlikely that any sort of representative model is possible. The next step is to produce a u_t expression that can account for the complex behaviour seen here. However, this cannot be done without accounting for continuous flame acceleration, which has been demonstrated as being a characteristic to premixed turbulent combustion [2].

Conclusions

Iso-octane-air flames have been ignited in a turbulent bomb and the flame progress tracked using high speed schlieren photography. The flames were observed to accelerate continually from ignition this was attributed to turbulent flame development. Five measurements were performed at each condition, shot to shot variation was observed throughout the dataset. The flame progress was expressed as turbulent burning velocity, u_{tr}, plotted against the mean flame radius, this form of presentation reduced some of the shot to shot variation.

The effects of the turbulent (rms) velocity, equivalence ratio and pressure have been investigated. The majority of tests were performed at 0.5 MPa, with a fewer number of tests performed at 0.1 and 1 MPa.

- The turbulent burning velocity of the flames at all equivalence ratios increased as the turbulent velocity was increased. For of the leanest equivalence tested the quenched shortly after ignition from u' = 2 m/s upwards.
- The peak burning velocity occurred at $\phi = 1.0$ at the lowest turbulent velocity (u' = 0.5 m/s) tested but as u' was increased the peak turbulent burning velocity occurred at richer equivalence ratios, until at u' = 6 m/s the flames at $\phi = 1.4$ were noticeably faster than at other equivalence ratios.
- As the pressure was increased from 0.1 to 1.0 MPa the turbulent burning velocity remained constant at u' = 1 m/s but increased slightly at u' = 4 m/s.

This interdependence of u', ϕ and pressure on the turbulent burning velocity is likely to explain some of variations in reported trends although other parameters such as length scale and are likely to have an influence.

The aim of this study was to generate a consistent database of experimental turbulent burning velocity information over a wide range of conditions. Uncertainty associated with the definition of the turbulent burning velocity, experimental technique and rig dependency rendered it problematic to compare the present data with those of other workers. Hence comparisons were made with data derived using five turbulent burning velocity models and correlations available in the literature. Each of the expressions yielded an increase in u_t with u' and pressure; none reproduced the increase in u_t noted in experiments at rich equivalence ratios. This is possibly associated with missing or imperfect representation of thermo-diffusive effects; either because they are purposely excluded (for example, it would be necessary to include further physics in a model) or because insufficient experimental data exists, particular at high turbulence levels, to fully characterise the behaviour of these flames. Since the majority of practical combustion devices work at lean equivalence ratios, perhaps rich heavy hydrocarbon high turbulent intensity flames have not been a research priority. However, thermo-diffusive effects might also be expected to be important in light, lean flames (e.g. hydrogen-air flames) and further experimentation and theoretical studies are to be expected in this area.

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P (MPa)	ϕ	Density ratio	ν (m^2/s)	u_l (m/s)	Le	L_b (mm)	Ma_{sr}
0.1	0.8	6.09	2.11×10^{-5}	0.43	2.98	4.0	14
0.1	1.0	6.84	2.09×10^{-5}	0.51	1.43	3.1	12
0.1	1.2	6.96	2.07×10^{-5}	0.44	0.93	0.9	4
0.1	1.4	6.80	2.06×10^{-5}	0.31	0.90	-0.1	1
0.5	0.8	6.11	4.22×10^{-6}	0.20	2.98	0.9	8.0
0.5	0.9	6.59	4.20×10^{-6}	0.26	2.94	0.7	7.6
0.5	1.0	6.95	4.18×10^{-6}	0.30	1.43	0.5	6.5
0.5	1.1	7.05	4.16×10^{-6}	0.31	0.94	0.4	5.3
0.5	1.2	6.99	4.15×10^{-6}	0.30	0.93	0.0	1.1
0.5	1.4	6.80	4.11×10^{-6}	0.24	0.90	NA	NA
0.5	1.6	6.60	4.08×10^{-6}	0.15	0.88	NA	NA
0.5	1.8	6.39	4.05×10^{-6}	0.073	0.86	NA	NA
0.5	2.0	6.16	4.01×10^{-6}	0.050	0.84	NA	NA
1.0	0.8	6.12	2.11×10^{-6}	0.16	2.98	0.5	7
1.0	1.0	6.99	2.09×10^{-6}	0.25	1.43	0.2	5
1.0	1.2	7.00	2.07×10^{-6}	0.24	0.93	NA	NA
1.0	1.4	6.81	2.06×10^{-6}	0.21	0.90	NA	NA

Table 1. Laminar flame properties.

NA denotes flame cellular from ignition so the response to stretch could not be found.

Lewis numbers calculated using data from Hirschfelder et al. [36].

u' (m/s)	P (MPa)	L (mm)	λ (mm)	η (mm)
1	0.1	20	2.6	0.12
4	0.1	20	1.3	0.042
0.5	0.5	20	1.6	0.060
1	0.5	20	1.2	0.035
2	0.5	20	0.82	0.021
4	0.5	20	0.58	0.012
6	0.5	20	0.47	0.0092
1	1.0	20	0.82	0.021
4	1.0	20	0.41	0.0074

Table 2. Turbulent flowfield properties.

Figure Titles

Figure 1. Flame radius against time from ignition with increasing *u'* at ϕ = 1.0 and 0.5 MPa.

Figure 2. Flame speed against mean flame radius from ignition with increasing *u'* at ϕ = 1.0 and 0.5 MPa.

Figure 3. Turbulent burning velocity, u_{tr} against time from ignition at 0.5 MPa for increasing *u'*.

Figure 4. Turbulent burning velocity, u_{tr} against flame radius at 0.5 MPa for increasing *u'*. Filled triangles = 0.5 m/s, open squares = 1 m/s, filled circles = 2 m/s, open triangles = 4 m/s, plus sign = 6 m/s.

Figure 5. Turbulent burning velocity, u_{tr} against flame radius at (a) *u'* = 1 m/s and (b) *u'* = 4 m/s for different equivalence ratios at 1 MPa. Filled squares ϕ = 0.8, open diamonds ϕ = 1.0, filled triangles ϕ = 1.2, crosses ϕ = 1.4.

Figure 6. Turbulent burning velocity, u_{tr} against flame radius at u' = 1 m/s for increasing pressure. Filled squares = 0.1 MPa, open triangles = 0.5 MPa, crosses = 1 MPa.

Figure 7. Turbulent burning velocity, u_{tr} against flame radius for *u'* = 4 m/s for increasing pressure. Filled squares = 0.1 MPa, open triangles = 0.5 MPa, crosses = 1 MPa.

Figure 8. Flame brush thickness vs. schlieren radius for propane-air flames, both normalised by the integral length scale. The equivalence ratio, pressure and *u'* are given. Data obtained from simultaneous laser sheer and schlieren photography, details in [12].

Figure 9. Turbulent burning velocity, u_{tr}, at a schlieren radius of 30 mm against u' for different ϕ.

Figure 10. Predicted turbulent burning velocity, u_t, against u' at $\phi = 1$.

Figure 11. Turbulent burning velocity, u_{tr}, at a schlieren radius of 30 mm against ϕ for increasing u'.

Figure 12. Predicted turbulent burning velocity, u_t, against ϕ for increasing u'. Filled squares – u' = 0.5 m/s, open circles – u' = 1 m/s, crosses – u' = 2 m/s, filled triangles – u' = 4 m/s, open diamonds – u' = 6 m/s.

Figure 13. Turbulent burning velocity, u_{tr}, at a schlieren radius of 30 mm, against pressure for different ϕ. Data fitted with full lines u' = 1 m/s, data fitted with dashed lines u' = 4 m/s.

Figure 14. Predicted turbulent burning velocity, u_t, against pressure. Full lines u' = 1 m/s, dashed lines u' = 4 m/s. Filled squares – $\phi = 0.8$, open circles – $\phi = 1.0$, open triangles – $\phi = 1.2$, crosses – $\phi = 1.4$.