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LEWIS NUMBER EFFECTS ON TURBULENT BURNING VELOCITY

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Experimental values of turbulent burning velocities for propane, hydrogen and iso-octane mixtures with air are reported under conditions of high turbulence and high turbulent Reynolds number. The measurements were made by the double kernel method during explosions in a fan-stirred bomb, with four fans, capable of speeds of up to 10,000 rpm. The ratio of turbulent to laminar burning velocity, u_t/u_ℓ, is correlated primarily with the ratio of r.m.s. turbulent velocity to laminar burning velocity, u'/u_ℓ and a Karlovitz stretch factor given by the ratio of a strain rate u'/λ to a flame gradient given by u_ℓ/δ_ℓ, where λ is the Taylor microscale and δ_ℓ the laminar flame thickness.

Asymptotic analyses of strained laminar flames, together with the two-eddy theory of turbulent burning, show the additional importance of Lewis number effects. These result in lean hydrocarbon mixtures being quenched more readily than rich ones, with an opposite effect for H_2 mixtures. This was observed in the experiments. However, full quantitative agreement between theory and experiment was not achieved, due to the inherent limitations of the two theories, which are discussed.

1. Introduction

In both engine performance[1] and explosion hazard[2] contexts a clear need has emerged for turbulent burning data for premixed gases. Two of the present authors have correlated[3] the ratio of developed turbulent to laminar burning velocity measured on burners, u_t/u_ℓ, with the ratio of r.m.s. turbulent velocity of the cold mixture to its laminar burning velocity, u'/u_ℓ, and the cold turbulent Reynolds number, R_L, $(=u'L/\nu)$, where L is the integral length scale and ν the kinematic viscosity. Highly turbulent flames present problems of flame stability on burners, which are avoided in explosive turbulent combustion. Earlier explosion measurements of u_t[4] were made in a bomb equipped with four fans, running at speeds of up to 3,500 rpm.

The fans have been coupled to new high speed electric motor drives capable of speeds of 10,000 rpm. Gaseous mixtures of hydrogen, propane and iso-octane with air have been exploded in hitherto unexplored régimes, with values of u' up to 17.3 ms^{-1} and of R_L up to 44,000. Additionally, laser doppler velocimetry has been used to characterise the turbulence, in place of hot wire anemometry, which is less reliable in rapidly reversing flows. Values of burning velocity so acquired are presented in the present paper. The ratio u_t/u_ℓ initially increases with u'/u_ℓ, levels off then, in some cases, decreases until the flame is quenched.

This relationship is examined in the light of recent theoretical asymptotic analyses of strained laminar flames,[5–9] which show a change in burning velocity (most commonly a reduction) with increasing strain. In addition to the strain rate, the Lewis number for the deficient reactant and the activation energy for chemical reaction are determining parameters. Such analyses are shown qualitatively to contribute towards an explanation of the measured turbulent burning velocity relationships. The mixtures investigated were chosen to cover a wide range of Lewis numbers in order to elucidate the effect of this parameter on flame straining in turbulent combustion.

2. Apparatus

The explosion bomb comprised a cast steel cylinder of 305 mm diameter and 305 mm length, with a 150 mm diameter concentric window, of 25.4 mm thick schlieren quality glass in each end plate. These windows enabled the whole of the explosion flame to be photographed during the pre-pressure period. Four identical eight-bladed fans, machined from a solid block of aluminum were equi-spaced around the central circumference. The mean diameter of each fan was 147 mm and with them all in position a central region of 178 mm diameter was created in which there was little mean flow and the turbulence was uniform and isotropic. Turbulent velocities were varied through changes in fan speed between 2400 and 10,000 rpm. Independent speed control of the Acomel R112-M2 induction motor coupled to each fan ensured equal speeds.

Burning velocities were found by the double kernel method, in which the closing velocity of two propagating flame fronts of separate kernels was measured.[10,11] This necessitated simultaneous ignition at two spark gaps. Each spark plug comprised two coaxial conductors and these were fitted horizontally with the gaps 120 mm apart. They were connected in series, in the same capacitative discharge circuit. A 0.05 μf capacity bank was charged to about 15 kV and discharge through the two gaps was triggered through the breakdown of an air gap by a firing pulse from a synchronisation unit.

Flame propagation was recorded with a Hitachi 16 HM ciné camera at a maximum rate of 10,000 frames sec^{-1}. The schlieren technique, with a helium-neon laser, defined the flame fronts and revealed something of the structure. Turbulent velocities and integral length scales were measured, without any explosion and at different fan speeds, by a forward scattering laser doppler counting system, with an argon ion laser, rated at 100 mW. A Bragg cell gave a maximum frequency shift of 40 MHz. Fuller details of this calibration as well as of the apparatus and experimental techniques are given in Ref. 12. Values of L ranged from 36 mm at 2400 rpm to 43 mm at 10,000 rpm. In the course of the present work, calibrations were made for both air and a 60% H_2-air mixture at atmospheric pressure, over the full range of fan speeds. Both calibrations proved to be identical. At high fan speeds the rate of turbulent energy dissipation caused an appreciable rate of temperature rise of the gas. Hence the initial temperature for C_3H_8 and H_2 explosions, and for the calibration, was standardised at 328 K. This was increased to 333 K for C_8H_{18}, conveniently to achieve higher equivalence ratios, ϕ. All mixtures were made up in the explosion bomb.

3. Experimental Results

Closure rates of the two contiguous turbulent flame fronts were measured along up to three orthogonal closure lines, in any one explosion. The mixtures employed and their properties are given in Table 1. The laminar burning velocities, u_ℓ, also were measured by the double kernel method. With point initiation of an explosion, the early stages of flame propagation are not affected by the full spectrum of turbulence. It takes time to achieve a fully developed turbulent flame. During the development phase, the value of turbulent burning velocity might be approximated by multiplying the fully developed value, u_t, by $[1 - \exp(-\bar{t})]^{0.5}$, where $\bar{t}$ is the elapsed time, from spark to contact of the kernels in the present work, divided by the lagrangian eddy lifetime, $0.44L/u'$.[13] It was thus possible to apply a correction to a directly measured burning velocity to give the fully developed value, u_t.

Value of u_t for different fan speeds are shown in Figs. 1–3 for C_3H_8, H_2 and C_8H_{18}-air mixtures, respectively, at different equivalence ratios. Associated values of u' also are given on the abscissa. The curves correspond to a least square fit to a second order polynomial. The spread of values is similar to that previously observed[12] and some bounds are indicated by bars in Fig. 1. The inevitability of random spread has been discussed and quantified in Ref. 14. When a curve is terminated, it indicates

TABLE 1
Properties of mixtures, all with air

Fuel	ϕ	u_ℓ m/sec	$10^6\nu$ m^2/sec	T_b K	T_a K	β	Le
C_3H_8	1.3	0.41	16.97	2160	15 000	8.2	0.85
C_3H_8	1.1	0.548	17.17	2294	15 400	7.8	0.88
C_3H_8	0.9	0.466	17.39	2196	16 600	8.9	1.97
C_3H_8	0.8	0.39	17.50	2062	12 800	7.4	1.98
C_3H_8	0.7	0.30	17.61	1900	8 800	5.6	2.03
H_2	3.57	2.32	46.37	1666	10 300	7.7	4.71
H_2	0.42	1.04	28.46	1224	6 600	7.3	0.70
C_8H_{18}	1.2	0.40	17.93	2283	15 000	7.7	1.16
C_8H_{18}	1.0	0.446	18.10	2355	18 000	8.9	2.48
C_8H_{18}	0.92	0.42	18.17	2309	13 800	7.0	3.79
C_8H_{18}	0.85	0.393	18,22	2237	13 400	7.0	3.75

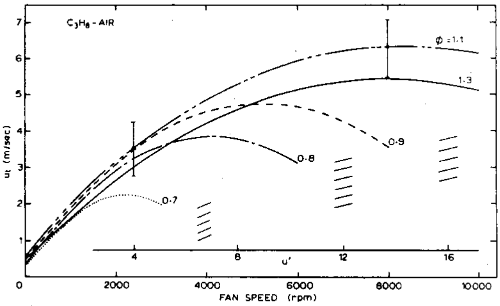

FIG. 1. Propane-air turbulent burning velocities at five equivalence ratios. Shading shows quenching regions.

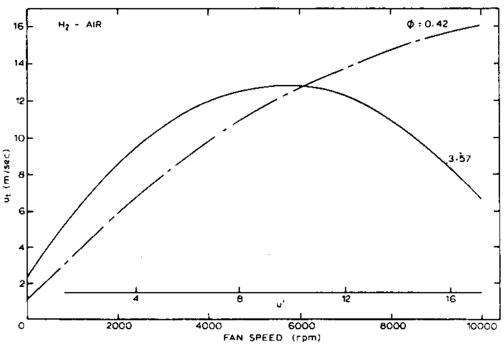

FIG. 2. Hydrogen-air turbulent burning velocities at two equivalence ratios. No quenching occurred.

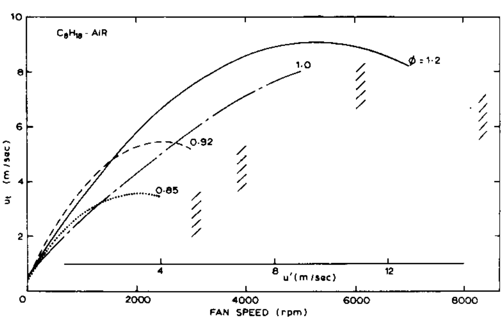

FIG. 3. Iso-octane-air turbulent burning velocities at four equivalence ratios. Shading shows quenching regions.

that at higher fan speeds, gas phase quenching was observed in the measurement volume. The severity of this increased with fan speed and in the shaded regions, for the different values of ϕ, quenching occurred in every explosion.

Values of u_t were in the region of 12% greater than the directly measured values for propane and iso-octane and about twice as much for hydrogen mixtures. Figures 4–6 show the corresponding u_t/u_ℓ versus u'/u_ℓ relationships. An additionally used dimensionless correlating parameter is the turbulent Reynolds number, R_L. For present purposes, this is conveniently contained within a Karlovitz flame stretch factor K, which is the ratio of the flow strain rate to a flame gradient given by u_ℓ divided by the laminar flame thickness, δ_ℓ. This thickness

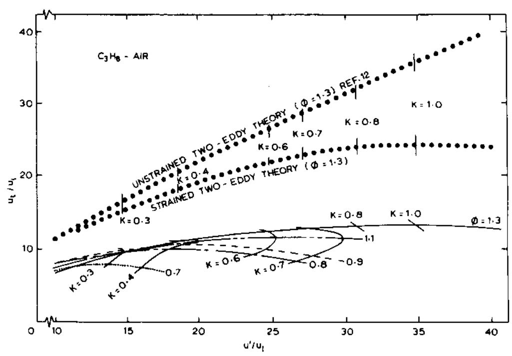

FIG. 4. Values of u_t/u_ℓ for C_3H_8-air mixtures at ϕ = 0.7, 0.8, 0.9, 1.1 and 1.3. Lines of constant K also are shown.

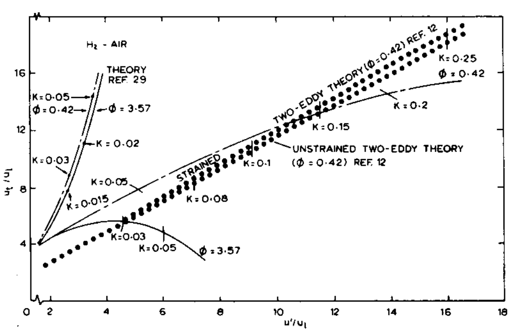

FIG. 5. Values of u_t/u_ℓ for H_2-air mixtures at ϕ = 0.42 and 3.57. Lines of constant K also are shown.

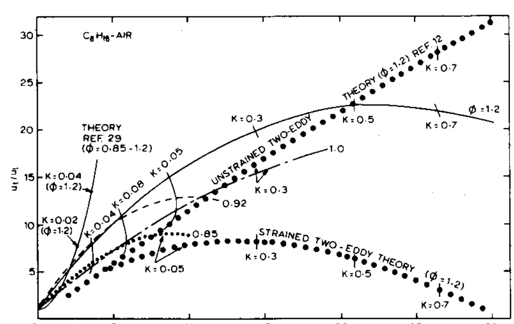

FIG. 6. Values of u_t/u_ℓ for iso-octane-air mixtures at ϕ = 0.85, 0.92, 1.0 and 1.2. Lines of constant K also are shown.

can be approximated by

$$\delta_\ell = \frac{\nu}{u_\ell} \tag{1}$$

In a laminar flame the strain rate is given by velocity gradients, but in a turbulent flame it is given by u'/λ, where λ is the Taylor microscale. This gives a Karlovitz flame stretch factor, K, where

$$K = \left(\frac{u'}{\lambda}\right)\left(\frac{\delta_\ell}{u_\ell}\right) \tag{2}$$

For isotropic turbulence the two length scales are related by

$$\frac{\lambda^2}{L} = \frac{A\nu}{u'} \tag{3}$$

where A is a numerical constant, assigned a value of 40.4 by Abdel-Gayed and Bradley (3). With this value, Eqs. (1)–(3) yield

$$K = 0.157\,(u'/u_\ell)^2 R_L^{-0.5} \tag{4}$$

Values of K, so derived, are shown on the curves of Figs. 4–6. The viscosity was found from the data of Svehla[15] and the mixture expression of Wilke.[16] Densities were found from the Beattie-Bridgeman equation.

4. Discussion

Earlier work[3,12] has shown the greatest increase in u_t/u_ℓ with u'/u_ℓ to occur at the lower values of the latter. Figures 4–6 show the later levelling off that occurs in the values of u_t/u_ℓ, sometimes followed by a reduction and flame quenching, as also observed by Karpov and Severin.[17] Quenching is associated with higher values of K.

The mixtures were chosen to demonstrate Lewis number quenching effects. The high values of u_t/u_ℓ at high R_L in Fig. 17 of Ref. 3 rest heavily upon the data of Ref. 18. However, the present work and the previous results reported in Ref. 12 do not support such high values of u_t/u_ℓ and some explanation for this has been tentatively offered in Ref. 2.

Several theories of turbulent burning postulate that locally the flame propagation is laminar-like.[3,12] It is therefore appropriate to examine the effects of high strain rates in the present work in the light of those predicted for laminar flames. We shall use the asymptotic analysis of Tromans[6] for this purpose. This shows that for Lewis numbers greater than 0.85[12] straining of the flame reduces the laminar burning velocity. The ratio of strained to unstrained laminar burning velocity, $u_{\ell s}/u_\ell$ becomes a function of a K factor for a laminar flame, the Lewis number, Le, of the deficient reactant, and a dimensionless activation energy, β, for the assumed single step reaction. This energy is the activation temperature for the reaction, T_a, divided by the difference between the mixture adiabatic temperature, T_b, and the temperature of the reactants, T_u. These values are given in Table 1. The diffusion coefficient for the deficient reactant, D, in the Lewis number expression ($=k/\rho C_p D$) was found using the procedure of Ref. 19. Values of specific heat, C_p, and thermal conductivity, k, were taken from Ref. 15, whilst the expression of Ref. 20 was used to obtain the conductivity of mixtures. Values of T_b were calculated from JANAF data[21] and of T_a by plotting the logarithm of u_ℓ against $1/T_b$, as previously described.[12] Values of T_a for the mixtures of H_2 were taken from Ref. 12, whilst those for C_3H_8 and C_8H_{18} were obtained from the curves in Fig. 7(a) and (b). The figure beside each experimental point for air mixtures is the equivalence ratio of the mixture and the pressure was 1 atm. throughout. In near-stoichiometric flames problems arise in asigning a value of Le, because the reaction rates are governed not only by the diffusion of the deficient component but also by the more abundant

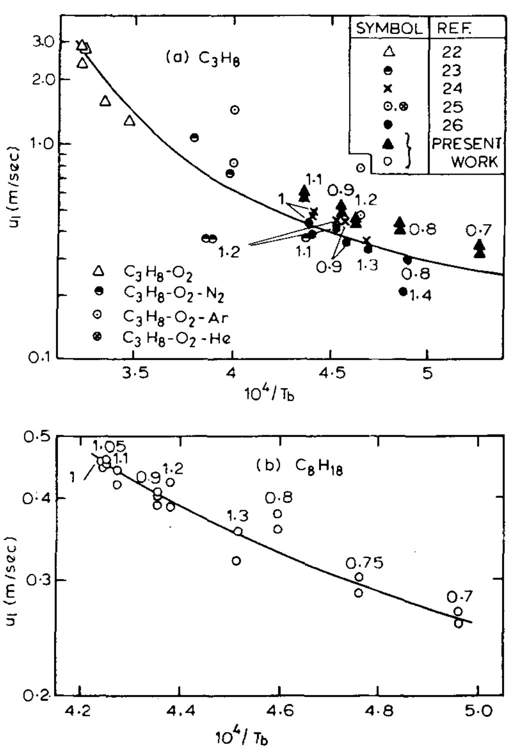

FIG. 7. Determination of activation temperature from u_ℓ. (a) propane mixtures. (b) iso-octane mixtures. The ordinate has a logarithmic scale.

one.[27] For the stoichiometric iso-octane mixture and the methane mixture of Fig. 9, the order of reaction for both components was taken to be unity and Ref. 27 was followed, which suggests the value of Le is the mean of the values obtained when both reactants are considered separately.

Values of $u_{\ell s}/u_\ell$, with K given by Eq. (4), were calculated for values of Le and β relevant to the present study, from the expressions of Tromans.[6] These are shown as the theoretical curves of $u_{\ell s}/u_\ell$ against K, in Fig. 8 (appropriate to C_3H_8 mixtures), Fig. 9 (appropriate to previous CH_4 mixtures[12]) and Fig. 10 (appropriate to H_2 and iso-octane mixtures). Figures 8 and 10 show striking differences, due to Le and β, between lean and rich mixtures. They suggest lean mixtures of C_3H_8 and C_8H_{18} are more easily quenched. On the other hand, with H_2 mixtures, because of the high diffusion coefficient of H_2, the effect is the opposite, and rich H_2 mixtures are more easily quenched. Shaded regions in these figures are those in which theoretical solutions are inapplicable.[6]

These predictions are in qualitative agreement with the observed behaviour of u_t/u_ℓ. Figure 4 shows lean mixtures of C_3H_8 to exhibit a greater decline in u_t/u_ℓ with an increase in K than do rich mixtures. Figure 6 shows a more striking decline with the weak C_8H_{18} mixtures. On the other hand, as predicted by the asymptotic theory, the rich mixture of H_2 shows the greater flame straining effects in Fig. 5.

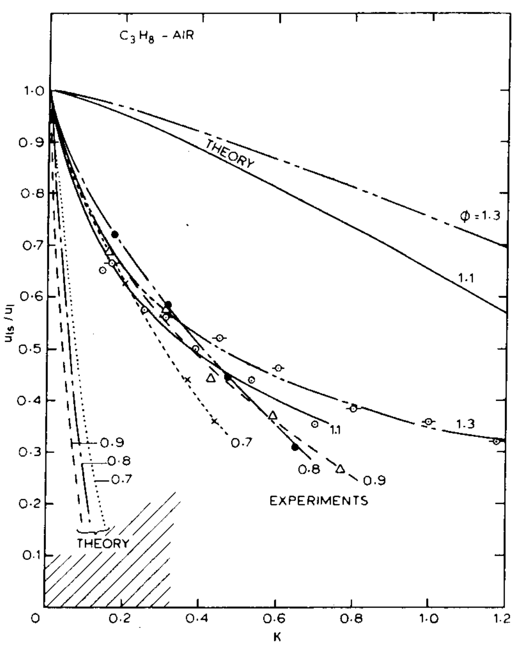

FIG. 8. Straining effects on laminar burning velocities of C_3H_8-air mixtures.

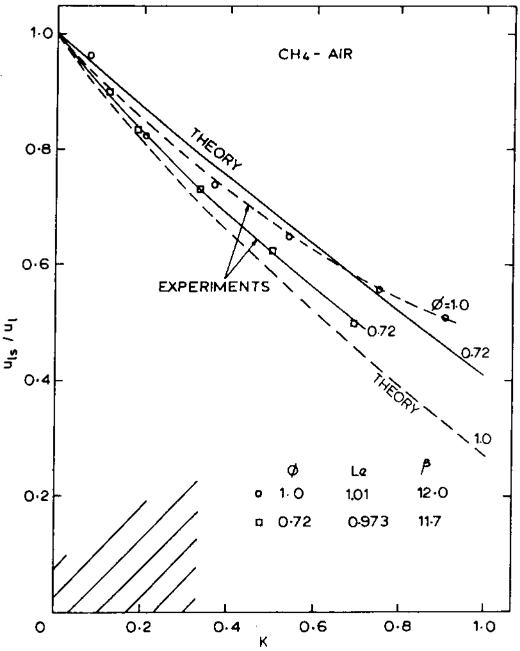

FIG. 9. Straining effects on laminar burning velocities of CH_4-air mixtures.

In the two-eddy theory, the rate of turbulent burning is given by the product of the rate of decay of eddies and the proportion of them burnt during their lifetime.[3,12] Figures 4 to 6 show values of u_t/u_ℓ obtained from this theory corresponding to one of the mixtures studied experimentally. One dotted curve in each figure does not allow for the effects of strain on the laminar burning in flamelets. The other dotted curve allows for straining, through calculation of the change of u_ℓ to $u_{\ell s}$ at the known values of K, Le and β, as described in Ref. 12. Comparison with the experimental values shows a tendency of the theory to overestimate values of u_t/u_ℓ for the rich C_3H_8 mixture and to underestimate values for the rich C_8H_{18} mixture.

The application of another quantitative test can be seen in Figs. 8 to 10. The points and curves described there as experimental show, for the different mixtures, at values of K given by Eq. (4), the ratio of the measured values of u_t/u_ℓ to the corresponding values from the unstrained two-eddy theory in which laminar flamelets have a burning velocity, u_ℓ. This ratio should represent the effects of straining on the flamelets and be equal to $u_{\ell s}/u_\ell$. Comparisons of these values, for the different mixtures, with those given by the corresponding curves arising from the asymptotic laminar flame straining theory, indicate the accuracy of the combined two-eddy and asymptotic theory. Reference to Fig. 8 shows that for C_3H_8 mixtures the asymp-

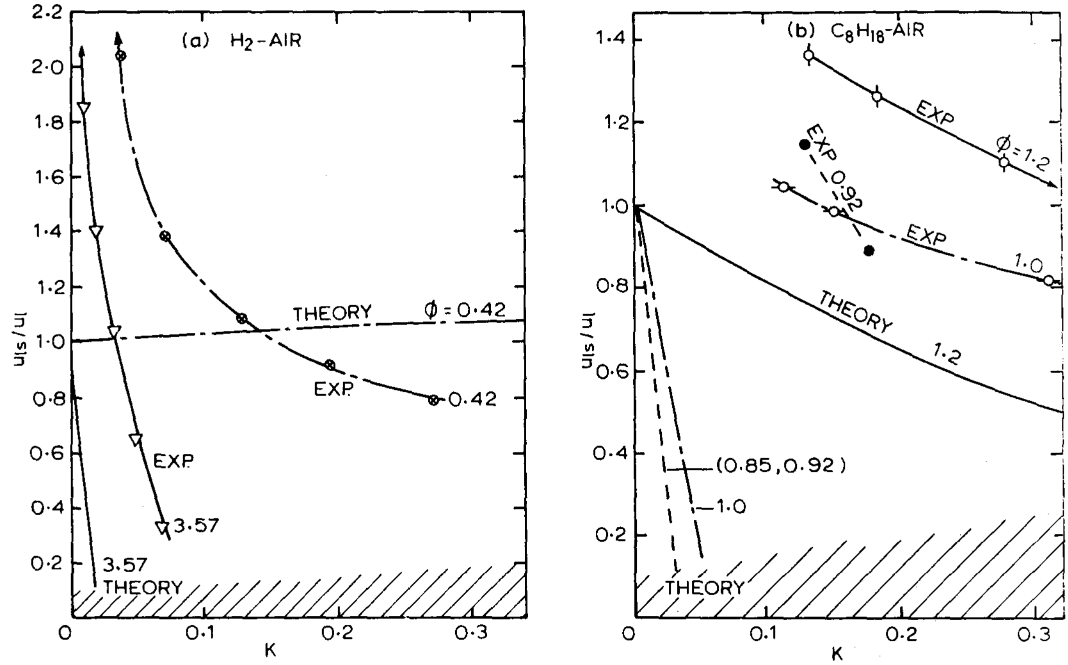

FIG. 10. Straining effects on laminar burning velocities. (a) H_2-air mixtures, (b) iso-octane-air mixtures. Values of ϕ given on each curve.

totic theory suggests a greater difference in the effects of Le and β on lean and rich mixtures than was observed in practice. Figure 9 shows that, for the previously studied CH_4 mixtures[12] there is good agreement between the theoretically predicted and experimentally measured reductions in burning velocity due to straining. However, no measurements were made with rich mixtures and the range of Lewis numbers is insignificant.

Figure 10 shows that for the $\phi = 1.2$, iso-octane mixture, the underprediction of u_t/u_ℓ by the two-eddy theory leads to the erroneous implication that $u_{\ell s}/u_\ell$ might be greater than unity, when the asymptotic theory shows that, for this mixture, flame straining must reduce $u_{\ell s}/u_\ell$ below unity. As with C_3H_8 mixtures, the asymptotic theory suggests a greater difference, due to Le and β influences, between lean and rich mixtures than, in fact, was observed. Probably the rather simplistic approach to the evaluation of Le, based upon the diffusion solely of the deficient reactant, over-accentuates Lewis number effects between weak and rich mixtures. The theory also suggests big differences between the two H_2 mixtures, with the lean one having an increased burning rate as a consequence of flame straining. Experimentally, large differences were observed, qualitatively in the right direction, in that the rich mixture displayed a greater reduction in the laminar burning velocity due to strain. It should be noted that the values of K for the hydrogen flame are relatively low. The work of Akindele et al[28] suggests that when $K < 0.28$ flame propagation might occur in a continuous, unfragmented, wrinkled laminar flame front. The two-eddy theory is unlikely to apply in this regime.

Clavin and Williams[29,30] have analysed the effect of Le on the propagation of wrinkled flames in turbulent flows of large scale and low intensity, and demonstrated the effects of mean stretch and mean curvature on u_t. In the present work, curvature effects can be neglected[31] and theoretical values of u_t/u_ℓ from Ref. 29 are shown in Figs. 5 and 6. The tendency is for u_t/u_ℓ to be over-estimated.

The present discussion rests on a compounding of two separately developed theories, both with inherent limitations. The two-eddy theory requires a value to be assigned to fix the intermittency of dissipative eddies. This value may not remain unchanged for all conditions. The assumed single step reaction in the asymptotic analysis is clearly unrealistic, as also may be the requirement that the value of Le should not depart too far from unity.

In practice the detailed kinetics and the diffusion of active chain carriers will be influential. Warnatz and Peters[32] employed the detailed chemical kinetics for the two hydrogen mixtures used in the present work, in a numerical analysis of stretched laminar flames. The effects of Lewis number on burning velocity were no less marked than those suggested by the present experiments. A further problem that arises in turbulent flow is the correct definition of the strain rate. Under isotropic and isothermal conditions it is appropriate to express it by u'/λ, but this may not always be valid.

5. Conclusions

(i) Values of u_t/u_ℓ have been measured in a regime of high turbulence and high R_L for C_3H_8, H_2 and C_8H_{18}-air mixtures.
(ii) As quenching is approached, there is a decrease in values of u_t/u_ℓ with increase in u'/u_ℓ.
(iii) Quenching effects are greater with the leaner hydrocarbon and the richer H_2 mixtures. This can be ascribed to the effects of Lewis number in strained laminar flames.
(iv) Comparisons have been made between the implied reductions in laminar burning velocity due to straining and those predicted by asymptotic analysis. There is good qualitative agreement.
(v) Quantitative limitations probably arise from those inherent in the theoretical models.

Acknowledgments

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