ENHANCED BURNING RATES DUE TO DROPLET INDUCED FLAME INSTABILITIES

M. Lawes, Y. Lee and N. Marquez e-mail: M.Lawes@leeds.ac.uk School of Mechanical Engineering, University of Leeds, Leeds LS2 9JT, Great Britain

Abstract

The combustion of clouds of fuel droplets is of practical importance in gas turbines, diesel and spark ignition engines, furnaces and hazardous environments. However, the exploration of important parameters in practical combustion systems is difficult due to the multiplicity of dependent variables.

Combustion rates of well defined droplet suspensions have been measured using techniques employed for gaseous combustion. Comparisons of two-phase with single-phase laminar mixtures suggest that there exists, under certain conditions, an enhancement of burning velocity due to the presence of droplets. At high stretch rates, flames remain smooth and droplet enhancement is small. However, at lower rates of stretch, both gaseous and aerosol flames become unstable and cellular, and this cellularity increases the burning rate. It is shown that aerosol flames become cellular at lower Peclet numbers than do gaseous flames and this increased propensity to cellularity probably is the reason for observed increases in burning velocity due to the presence of droplets.

Introduction

The combustion of clouds of fuel droplets is of practical importance in gas turbines, diesel and spark ignition engines, furnaces and hazardous environments. So complex are the various processes of droplet formation, evaporation, mixing and chemical reaction that it is not yet possible to mathematically model them adequately. There is theoretical [1,2] and experimental [3,4,5] evidence to suggest that, contrary to expectations, flame propagation through aerosol/vapour clouds, under certain circumstances, is higher (possibly by up to a factor of 3) than that in a fully vaporised homogeneous mixture. Although this may be advantageous in giving more rapid burning, its effects on emissions is uncertain. Conversely, it is a serious disadvantage in the hazard context.

All combustion in engines takes place under turbulent conditions, as does most combustion in boilers, burners and in the hazards context. However, it is well established that the laminar burning rate plays an important role in turbulent combustion [6]. Information on laminar burning velocity is sparse, even for gaseous mixtures at conditions pertaining to engines, which range from sub-atmospheric to high pressure and temperature. At present, such data for fuel sprays and for gas-liquid co-burning [7,8,9,10] are even more sparse than for gases. As a consequence, there is little experimental data of a fundamental nature that clearly demonstrates the similarities and differences in burning rate, either laminar or turbulent, between single and two phase combustion. The present work presents measurements of laminar flame speed and burning velocity under carefully controlled conditions. It is shown that, under the conditions presented, there is little difference between single and two phase burning rates while flames remain smooth and stable. However, droplets appear to induce flame instabilities at a wider range of conditions than those for gaseous flames. In both cases, instabilities increases the burning rate. Hence, it is tentatively suggested that enhanced burning rates in aerosol mixtures is due to the 'earlier' onset of such instabilities.

Experimental apparatus and technique

The combustion vessel and mixture preparation are presented in [11,12]. The vessel comprised a 305mm diameter by 305mm long cylindrical bomb. Laminar flame propagation was observed through two windows of 150mm diameter. Temperature control was achieved by two electrical heaters attached to the inside wall of the vessel. Initially gaseous iso-octane air mixtures were prepared in-situ by injection of liquid fuel with a hypodermic syringe through a needle valve. Complete evaporation of the liquid was confirmed by comparing the change in pressure within the vessel during injection with the partial pressure expected for the mass of fuel injected.

Aerosol mixtures were prepared by a condensation technique (Wilson cloud chamber technique) [13], used in combustion studies by [14,10], to generate well defined, near mono-dispersed, droplet suspensions in-situ by controlled expansion of a gaseous fuel-air mixture into a second vessel. This caused a reduction in mixture pressure and temperature which took it into the wet regime and caused droplets to be formed. The droplet Sauter mean diameter, D_{32} , and spatially averaged drop size distribution were measured in-situ, without combustion, using a MALVERN 2600 laser diffraction instrument and a Phase Doppler Anemometer system. The Sauter mean diameter could be accurately varied between zero and 25 μ m. Simultaneously with these measurements, temperature and pressure also were recorded. Other aerosol properties, including liquid and vapour fractions, were derived from the pressure and temperature records by thermodynamic analysis.

Laminar flame propagation was initiated in the centre of the vessel by an electric spark and flame growth was monitored with a high speed camera at a rate of 5000 frames/s through the bomb windows, using a laser schlieren arrangement.

Flame speed and Burning Velocity

The procedures for obtaining the flame speed and burning velocity were similar to those used for gaseous mixtures [15,16,17]. The laminar flame speed of a gaseous mixture, as a function of flame stretch, was obtained from photographic observation of a spherically expanding flame. The stretched flame speed, S_n , is given by

$$S_n = dr/dt \tag{1}$$

and the stretch rate on a flame of surface area $A = 4\pi r^2$, is

$$\alpha = \frac{1}{A} \frac{dA}{dt} = \frac{2}{r} \frac{dr}{dt} = \frac{2}{r} S_n$$
(2)

The unstretched laminar flame speed, S_s , is obtained by extrapolating a curve of S_n against stretch to zero to yield the unstretched flame speed, and the gradient of this curve yields the burned gas Markstein length, L_b , such that

$$S_n = S_s - \alpha L_b \tag{3}$$

The unstretched flame speed is related to the unstretched burning velocity, u_l , by

$$u_l = S_s \frac{\rho_b}{\rho_u} \tag{4}$$

where ρ_b and ρ_u are the burnt and unburnt gas densities. Equation (4) should include a term for the flame thickness [16]. This is more complex for aerosol mixtures than for the gaseous due to the presence of droplets and the associated evaporation and mixing processes. However, as with gaseous flames, extrapolation to zero flame stretch reduces to zero the effect of flame thickness. Hence, the analysis used for single-phase flames to yield u_l also is appropriate for aerosol mixtures.

Results and discussion

Shown in Fig. 1 is the variation of flame speed with flame stretch for two, nominally identical, two phase mixtures of iso-octane and air with an overall equivalence ratio, ϕ_{ov} , of 1. The pressure and temperature were nominally at 185 *kPa* and 273 *K*. The Sauter mean droplet diameter was about 23 μm and the gaseous phase equivalence ratio, ϕ_g , was 0.8. The flames propagated from right (high stretch) to left in the Figure. At high rate of stretch, the flame front was smooth and free from instabilities. As the flame stretch reduced, a point was reached at which the flames became unstable and exhibited a cellular appearance. This was associated with an increase in flame speed. There are significant differences between the two curves in Fig. 1. This, in part, is probably due to the random variations in the onset of instabilities which are probably influenced by small perturbations in the flow field caused by the spark and by the small flow fields induced by the expansion technique. However, it is probable that the cycle to cycle variations in mixture preparation and rate of expansion also are important. The point at which the flame speed begins to accelerate rapidly with decreasing stretch defines a critical Peclet number, Pe_{cl} , (15) given by the flame radius at the onset of flame acceleration, normalised by the laminar flame thickness.

Following the procedure for gaseous flames [15], the part of the curve prior to the unset of instabilities was used for extrapolation to zero stretch to yield S_s , and from Eqs. (3) and (4) L_b and u_l . For the two flames in Fig. 1, values of S_s , L_b and u_l are presented in Table 1.

$S_s (ms^{-1})$	$L_b(mm)$	$u_l (ms^{-1})$	$u_l(ms^{-1})$ Eq.	[5]
2.018	0.257	0.228	0.203	
1.792	-0.384	0.233	0.203	
Table 1 Values of S	S_s , L_b and u_l for	the data in F	ig. 1 and values	of u_l from Eq. [5].

An objective of the present work is to investigate the difference in flame speed and burning velocity between single and two-phase mixtures. However, it is not possible to have a single phase mixture at the same conditions as a thermodynamically generated aerosol. Hence, from measurements of the burning velocity of gaseous iso-octane mixtures at a range of pressures and temperatures by [15] and by the present authors, an empirical relationship between these and the burning velocity was obtained as

$$u_{\ell} = 0.43 \left[\frac{T}{358} \right]^{2.107} \left[P \right]^{-0.282}$$
⁽⁵⁾

for 273 < T < 450 K and $P \sim 100 kPa$.

Values of u_l from Eq. (5) for the pressures and temperatures used for Fig. 1 are shown in Table 1. It shows that the laminar burning velocity of the present aerosol mixture is higher than that for a gaseous one by only about 13%. %. This indicates that, for the present conditions, when flame instabilities and turbulence are not present, there is only a small difference in the burning velocity of an aerosol and a gaseous mixture at the same overall equivalence ratio. Indeed, this difference may lie within the limits of uncertainty in the measurements. However, flame instabilities enhance the burning rate above that for a smooth flame. This is discussed below.

Shown in Fig. 2 are experimental data from [15] which show the variation of flame speed with flame stretch for stoichiometric mixtures of gaseous iso-octane and air at higher pressures and temperatures than those for the aerosol mixtures in Fig. 1. Figure 2 is similar in character to Fig. 1. However, it is interesting to note from Fig. 2 that the unset of cellularity is a function of pressure and, within the period of measurements reported in [15], the flame at 100 kPa did not become cellular, with no resultant increase in flame speed. This suggests a possible explanation for previously reported increases in aerosol burning rate when compared with gaseous flames. It is suggested that aerosol flames become unstable, and hence have faster burning rates, at conditions that would not result in unstable gaseous flames.

Shown by the symbols in Fig. 3 is the variation of measured with equivalence ratio for a range of aerosol mixtures, from the present work. As with the gaseous measurements in [15], there is considerable scatter in measured values of L_b for the present aerosol mixtures. From consideration of the gaseous phase data by [15] and by the present Authors, a suitable empirical correlation for the variation of L_b with temperature and ϕ is given by

$$L_b = 28000T^{-1.669} + 13.6\phi^2 - 36535\phi + 22847 \tag{6}$$

for 270 <T <450 K and $P \sim 100 \ kPa$. This is shown by the solid curve in Fig. 3 for a temperature and pressure of 270 K and 100 kPa. It is interesting to note that the present measurements have values of L_b that are have similar trends to those for gaseous phase mixtures, but are slightly lower, suggesting a slightly lower dependence of flame speed on flame stretch.

In [15] and [17] it was shown that the Pe_{cl} can be correlated with a Markstein number, Ma_{sr}, which quantifies the effect of flame strain rate on the laminar burning velocity. Here, the Markstein number is given by a Markstein length divided by the flame thickness and Ma_{sr} can be obtained from L_b as described in [16].

Shown in Fig. 4 is the variation of Pe_{cl} with Ma_{sr} for the present aerosol mixtures and for gaseous data, using several fuels reported by [15] and [17]. The upper curve represents a best fit curve through all the gaseous data [17] and demonstrates some generality in the unset of cellular instabilities in gaseous flames. The lower curve is a best fit through the present aerosol data. It is clear from Fig. 4 that aerosol mixtures become cellular at smaller radii (smaller Peclet numbers) that do gaseous flames, and from Fig. 1, when they do become cellular the burning rate can be considerably enhanced. The magnitude of such enhancement still has to be quantified. Mechanisms for the increased propensity to cellularity have been discussed elsewhere (e.g. [18]) but require further investigation.

Conclusions

- A novel fan stirred combustion vessel has been used to study spatially homogeneous, near monodispersed aerosol combustion in a fundamental and well controlled manner.
- Aerosols of iso-octane and air with D_{32} between 5 and 25 μ m, with resulting variations in gas phase equivalence ratio, have been investigated.
- Flame speeds and burning velocities have been obtained for various two phase mixtures of iso-octane and air and these have been compared with those of gaseous mixtures. The burning velocities of aerosol mixtures, prior to flame cellularity, are up to 25% higher than for similar gaseous mixtures. However, this value may be within the limits of experimental uncertainty.
- Following spark ignition, both gaseous and aerosol mixtures begin as smooth, stable flames and at a critical Peclet number, flame cellularity begins to develop. This cellularity increases the burning rate.

- Aerosol flames become cellular at lower Peclet numbers than do gaseous flames. This suggests a possible mechanism for the enhanced burning rates of aerosol flames reported elsewhere.
- Mechanisms for the increased propensity to cellularity have been discussed elsewhere but require further investigation.

Acknowledgements

The authors would like to acknowledge the EPSRC for funding the research and for the loan of the PDA system through their equipment loan pool. Thanks are due to Dr Chris Wilson of DERA for his support and valuable discussions.

Nomenclature

Α	area	m^2	t	Time	S	
D	diameter	μm	Т	temperature	Κ	
L	integral length scale		и	burning velocity	m/s	
р	Pressure	Pa, kPa, MPa	α	Stretch	1/s	
Pe	Peclet number		ϕ	Equivalence Ratio		
r	radius	mm	ρ	Density	kg/m ³	
S	flame Speed m/s		v	kinematic viscosity		
Sub	scripts					
b	burnt		n	Normal		
cl	Critical point		и	Unburnt		
g	Gas		32	Sauter mean diameter		

- g Gas
- 1 Unstretched laminar

References

- Greenberg, J.B., Silverman, I. and Tambour, Y., "On droplet enhancement of the burning velocity of 1 laminar premixed spray flames", Combust. Flame, 113, 271-273, (1998).
- Myers, G.D., Lefebvre, A.H., "Flame Propagation in Heterogeneous Mixtures of Fuel Droplets and Air", 2 Combust. Flame, 66, 193-210, (1986).
- Ballal, D.R., Lefebvre, A.H., "Flame Propagation in Heterogeneous Mixtures of Fuel Droplets, Fuel 3 Vapour and air", 18th Symp. (Int.) Combust., pp.321-328, (1980).
- Richards, G.A., Lefebvre, A.H., "Transient Flame Speeds of Hydrogen Fuel Droplets in Air", Combust. 4 Flame 78, 299-307, (1989).
- Lin, T.H. and Sheu, Y.Y., "Theory of Laminar Flame Propagation in Near Stoichiometric Dilute Sprays", 5 Combust. Flame 84, 333-342, (1991).
- Bradley D, Lau AKC & Lawes M, "Flame stretch rate as a determinant of turbulent burning velocity", 6 Phil. Trans. R. Soc. Lond. A338, 359-387, (1992).
- 7 Mizutani Y & Nakajima A, "Combustion of fuel vapour-drop-air systems: Part I, Open Burner Flames", Combust. Flame, 20, 343-350, (1973).
- Mizutani Y & Nakajima A, "Combustion of fuel vapour-drop-air systems: Part II, Spherical flames in a 8 vessel", Combustion & Flame 21, 351-357, (1973).
- Akamatsu, F., Nakabe, K., Mizutani, Y., Katsuki, M. and Tabata, T., "Observation of Structure of 9 Spherical flames Formed in Suspended Droplet Cloud by Spark Ignition", Nippon Kikai Gakkai Ronbunshu.B Hen/Transactions of the Japan Society of Mechanical Engineers (JSME) 61 (Part B), 752-758., Tokyo, Japan, (1995).
- Nakabe, K., Mizutani, Y., Akamatsu, F., Fuchihata, M.and Elemam, S.H., " Spark Ignited Spherical 10 Flames Propagating in a Suspended Droplet Cloud", 5th Int. Conf. on liquid atomisation and spray systems ICLASS-91, NIST Special Ptablications Gaithersburg, (1991).
- Atzler, F. and Lawes, M., "Burning velocities in droplet suspensions", Proc. 14th Int. Conference On 11 Liquid Atomisation and Spray Systems, Manchester, England, July 1998, pp. 578-583.
- 12 Atzler F, Burning velocities in droplet suspensions, PhD Thesis, School of Mechanical Engineering, University of Leeds, (1999).
- Wilson C.T.R., "On a method of making visible the paths of ionising particles through a gas", Proc. R. 13 Soc. Lond. A85, 285-288, (1911).
- 14 Hayashi S, Kumagai S & Sakai T, "Propagation velocity and structure of flames in droplet-vapour-air mixtures", Combust. Sci. Tech. 15,169-177, (1976).

- 15 Bradley D, Hicks RA, Lawes M Sheppard CGW & Woolley R, "The measurement of laminar burning velocities and markstein numbers for iso-octane-air and iso-octane-n-heptane-air mixtures at elevated temperatures and pressures in an explosion bomb", *Combust. Flame* 115, 126-144, (1998).
- 16 Bradley D, Gaskell PH & Gu XJ, "Burning velocities, Markstein lengths, and flame quenching for spherical methane-air flames: a computational study", *Combust. Flame*. 104, 176-198, (1996).
- 17 Gu, X.J., Haq, M.Z., Lawes, M., and Woolley, R., "Laminar burning velocity and Markstein lengths of methane-air mixtures", *Combustion & Flame* 121, 41-58, (2000).
- 18 Atzler, F., Demoulin, F.X., Lawes, M. and Lee, Y., Oscillations in the flame speed of globally homogeneous two phase mixtures, 18th International Colloquium on the Dynamics of Explosions and Reactive Systems. 29 July-4 Aug. (2001).



Figure 1. Measured flame speeds at different flame stretch rates. Iso-octane aerosol at $\phi_{ov}=1$



Figure 2. Measured flame speeds at different flame stretch rates and pressures. Gaseous Iso-octane and air at $\phi_{ov}=1$ and initial temperature of 358 K. (Reproduced from [15])



Figure 3. Variation of burned gas Markstein length with equivalence ratio for various iso-octane aerosol mixtures and for gaseous iso-octane and air.



Figure 4. Variation of critical Peclet number with Markstein number for gaseous and aerosol mixtures. Gaseous phase data reproduced from [17].