Oscillations in the flame speed of globally homogeneous two phase mixtures

F. Atzler, F.X. Demoulin[$], M. Lawes[*] and Y. Lee
University of Leeds
West Yorkshire, UK
[$] **University of Marseille - France**
[*]m.lawes@leeds.ac.uk

1. 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. Nevertheless, using physical approximations, it is possible to study certain aspects of globally premixed spray flames. To this end, an experimental apparatus was developed at the University of Leeds to measure the laminar flame speed and burning velocity of such flames by extending the experimental and theoretical approaches already developed for gaseous combustion. The experiment consisted of the measurement of the speed of spherical flame growth following central ignition of a globally homogeneous combustible aerosol. Measurements of burning rates are reported elsewhere (1, 2) and are not discussed here. However, under certain conditions some flames exhibited strong periodic fluctuations in flame speed which, due to their low frequency, appeared not to be acoustic in origin. These pulsations were similar to those observed by Hanai et al. (3) on a spherical flame expanding in a cloud of solid PMMA particles.

The present work is a study of the pulsations in spherically propagating aerosol flames in which the cloud of fuel droplets is suspended in a mixture of quiescent air and fuel vapour. First, the apparatus and techniques are briefly discussed and experimental results are presented. This is followed by an analysis in terms of the variations in equivalence ratio due to phase lags between flame and droplet velocities. A simple model is presented which provides some insight into the mechanism leading to flame oscillations.

2. EXPERIMENTAL APPARATUS, TECHNIQUE AND RESULTS

The combustion vessel and technique are described in (1,2). The vessel comprised a 305mm diameter by 305mm long cylindrical bomb in which windows of 150mm diameter were provided in both end plates to provide optical access for high speed Schlieren photography of flame growth. Aerosol mixtures where prepared by the Wilson cloud chamber technique(4,5). This produced a near mono-disperse distribution of fuel drops suspended in a fuel vapour-air mixture. A range of droplet Sauter mean diameters, D_{32}, up to a maximum of 25µm could be investigated.

Shown in Fig. 1 is the variation of flame speed, S_n, with time from ignition. Data for overall equivalence ratios, f_{ov}, of 1.0 and 0.8 are presented. For each, two gaseous phase equivalence ratios, f_g, are shown such that the effect of liquid fraction could be investigated. For the cases in which f_g is close to f_{ov}, the flame speed increased with time in much the same way as that observed in gaseous mixtures (6). After a period of time during which the effect of spark ignition diminished, a flame was established and this propagated and accelerated as the stretch decreased.

As illustrated by the two cases in Fig. 1 in which the liquid fraction is high (low f_g), when the proportion of liquid was increased, the flame speed oscillated between maxima and minima. Moreover, Schlieren photographs revealed that the structure of these flames also oscillated between smooth and cellular. Although mild oscillations have been observed in gaseous flames (6), such strong oscillations as those in Fig. 1 have not been reported.

The mechanisms for such oscillations are unclear. Hanai et al. (3) observed similar oscillations in flames expanding in a cloud of solid PMMA and attributed them to radiation effects. Another mechanism may be due to cellular instabilities which is a function of flame stretch and Markstein number. However, it is not clear if the production/destruction of the cellular structure is a cause or effect of the oscillations in flame speed. Another possible mechanism for the oscillations is the variations in equivalence ratio due to phase lags between flame and droplet velocities. The purpose of the present work is to present a simple model of this process and to provide some insight into the mechanism leading to flame oscillations in aerosols.

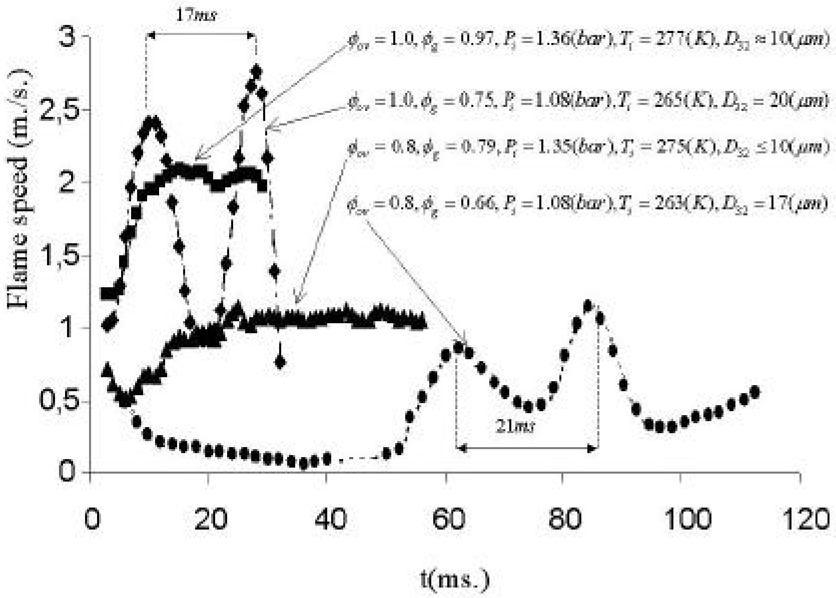

Figure 1: Variation of flame speed with time from ignition.

3. EFFECT OF THE DROPLET INERTIA ON THE EQUIVALENCE RATIO OF A SPRAY FLAME:

The presence of fuel droplets complicates the combustion process because of the time required to evaporate and mix the liquid fuel with the surrounding medium and because of the difference between the velocity of the liquid and gas phases. Here, we consider the case of an initially quiescent and homogeneous spray in which the fuel droplets are vaporised only in the preheat zone of the flame, that vaporisation is complete, and that gaseous mixing is instantaneous. Due to the expanding flame, the velocity of the gas that surrounds the droplets is not constant and a varying drag force exists. Droplet inertia results in a lag between the gas and droplet velocities.

The flame speed depends on the equivalence ratio in the reaction zone and this depends on the number density of droplets that enter it. During a time interval, dt, the flame propagates through a volume of gas, $V_g = A_f u_n dt$, where A_f is the surface area of the flame and u_n is the stretched laminar burning velocity. During this time, the number of droplets entrained into the flame, N, is given by

$$N = nA_f \left(S_n - U_d\right) dt \qquad [1]$$

where S_n is the flame speed, n is the droplet number density at the leading edge of the flame, and U_d is the droplet velocity at the same point. Thus the number density of droplets that enter the flame,

$n_f = n\left(\dfrac{S_n - U_d}{u_n}\right)$. Finally, the equivalence ratio within the reaction zone is given by

$$\begin{aligned} f &= f_g + \frac{n}{n_i}\left(f_{ov} - f_g\right)\left(\frac{S_n - U_d}{u_n}\right) \\ &= f_g + \frac{n}{n_i}\left(f_{ov} - f_g\right)\left(\frac{r_u}{r_b} - \frac{U_d}{u_n}\right) \end{aligned} \qquad [2]$$

where n_i is the number density in the reactants remote from the flame, and r_u and r_b are the unburned and burned gas densities.

Three limiting cases are revealed from Eq. [2]

1. Clearly, f cannot be less than f_g. If $U_d > S_n$, then the droplets move away from the flame, n reduces to zero and the initial gaseous phase equivalence ratio results.
2. If U_d = the gas velocity, $U_g = S_n - u_n$, then the term in the second set of brackets becomes unity, $n = n_i$ and, hence, $f = f_{ov}$. This corresponds to the case in which the droplets have negligible inertia.
3. If $U_d = 0$, the equivalence ratio attains a maximum and we obtain $f_{\max} = f_g + \frac{r_u}{r_b}\left(f_{ov} - f_g\right)$. This corresponds to the case in which the droplets have infinite inertia. Since $r_u/r_b > 1$, $f_{max} > f_{ov}$.

4. LAMINAR BURNING VELOCITY AND FLAME SPEED

For a spray flame the laminar burning velocity is assumed to be that of a gaseous flame with the same values of f and rate of stretch. Because of the condensation method used to create the spray, the unburnt gas temperature was low and, by definition, it was not possible to have an equilibrium gaseous mixture at the same pressure, temperature and equivalence ratio as those of the spray. Therefore, the unstretched burning velocity was estimated by extrapolation of the relationship: $u_l = u_{l,0}\left(T_u/358\right)^{2.1}$ in which $u_{l,0}$ is the unstretched laminar burning velocity at 1 bar and 358 K. This, approximate relationship was proposed by (1) for iso-octane mixtures at pressures close to 1 bar and for temperatures down to 280 K.

The unstretched flame speed, S_s, is related to u_l by: $S_s = r_u / r_b \times u_l$. The stretched flame speed, S_n, is obtained from $S_s = S_n + aL_b$ in which a is the stretch rate and L_b is the burned gas Markstein length (6). From measurements in (1 & 6) an approximate value for L_b, for conditions in the present work, is given by $L_b(f) = 0.242\exp(-4.86 f)$. The gas velocity just ahead of the flame front is equal to $U_g = S_n - u_n$ and u_n is approximated by $S_n = (r_u/r_b)u_n$.

5. EVOLUTION OF THE FLAME SPEED WITH THE DROPLET VELOCITY

Equation 2, is an intrinsic equation in which the burning velocity is an input that depends on the output equivalence ratio. The flame speed is estimated by assuming that the droplet velocities at the flame front are quasi constant. Shown in Fig. 2 is the solution of Eq. (2) for $f_{ov} = 1$ and $f_g = 0.75$.

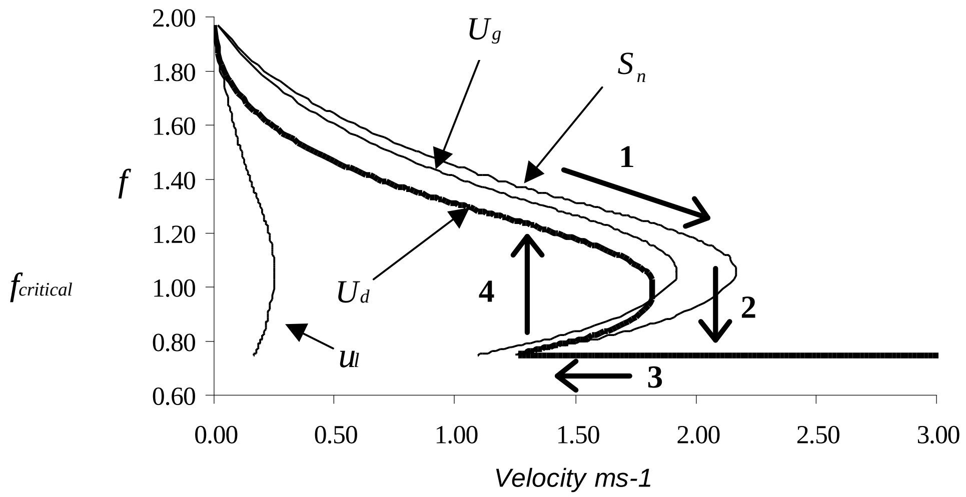

Figure 2: Graphical representation of Eq. 2. Variations of f, S_n, U_g and, u_l with U_d. $f_{ov} = 1$, $f_g = 0.75$.

It shows the variations of f, S_n, u_g and u_l as a function of droplet velocity. At low droplet velocities, there is a unique solution. For droplet velocities between about 1.25 and 1.8 ms^{-1}, there are three solutions. For the highest value of f: if f increases, the burning velocity reduces. Hence, fewer droplets are entrained and f reduces again to yield a stable solution. Similarly, the lowest value of f yields a stable solution. However, the middle value corresponds to a range of f in which the burning velocity increases with f. In this range, if f increases, the burning velocity increases, more droplets are entrained into the flame and f increases further. Similarly, if f decreases, the burning velocity decreases, fewer droplets are entrained and f decreases further. Hence, this solution is unstable.

Figure 2 shows a possible mechanism to explain the pulsating expanding spherical flame. Initially, following ignition, the droplet velocities near the flame front are equal to zero. Therefore, the equivalence ratio in the reaction zone is $f_{\max}$. The flame causes a gas velocity ahead of the flame front and the droplets accelerate due to the drag force. Hence, fewer droplets are entrained by the flame and the equivalence ratio decreases as in regime (1). As the stoichiometric equivalence ratio is approached, the droplets continue to accelerate towards that of the gas velocity, while the burning velocity and gas velocities reduce as their peak values, at the critical equivalence ratio, $f_{critical}$, are passed (regime (2)). At f_{ov} (=1.0), the droplet and gas velocities become equal. After this, inertia results in droplet velocities that are higher than the gas velocity as the latter continues to reduce. Therefore, the equivalence ratio within the reaction zone tends towards $f = f_g$ (regime (3)), but would attain this value when $U_d = S_n$. Eventually, the droplets approach equilibrium with the surrounding gas and more droplets are entrained as f begins to increase through f_{ov} and $f_{critical}$ regime (4)) as the droplets once again lag behind the gas velocity. The cycle then is repeated.

A necessary condition for this mechanism is that f_{ov}, at which the droplet velocities are equal to the gas velocity, must be less than $f_{critical}$. If f_{ov}, were greater than $f_{critical}$, then as the droplet and gas velocities became equal at f_{ov}, the burning velocity and gas velocity still would be accelerating as $f_{critical}$ was approached. Hence, it would be unlikely that the droplet velocity would exceed the gas velocity and steady state would be attained at f_{ov}. This critical value occurs at approximately $f = 1.05$ for iso-octane (6). Hence, it might be expected that flame oscillations, by the proposed mechanism, occur only with overall lean flames. This is supported by experimental observations in the present work in which oscillating flames were not observed at f_{ov} =1.2. Finally as f_g tends towards f_{ov}, the regime (3) becomes small and diffusivity effects probably will damp out an oscillating flame. This is supported by Fig. 1.

6. DESCRIPTION OF THE DROPLET MOTIONS

In order to simulate a spherical flame propagating in a globally premixed spray the droplet velocities ahead of the flame front and their number density are required. It is assumed that the problem has spherical symmetry and the problem is considered only in the radial direction. The mass equation leads to

$$U_g(r) = \frac{r_f^2}{r^2} U_g(r_f), \qquad [3]$$

where $U_g(r)$ is the gas velocity ahead of the flame front at the radial distance, r, and r_f is the flame radius. Since it is difficult to follow each droplet until it is entrained by the flame, a mean velocity, $\overline{U_d(r,t)}$ and a mean droplet number density, $\overline{n(r,t)}$ are used. The following modelled equations are obtained

$$\frac{\partial \bar{n}}{\partial t} + \frac{1}{r^2}\frac{\partial r^2 \overline{U_d}\bar{n}}{\partial r} = 0 \qquad [4]$$

and

$$\frac{\partial \bar{n}\overline{U_d}}{\partial t} + \frac{1}{r^2}\frac{\partial r^2 \bar{n}\overline{U_d}\quad \overline{U_d}}{\partial r} = \frac{3}{t_u}\left(U_g(r,t) - \overline{U_d}\right). \qquad [5]$$

7. RESULT AND DISCUSSION

The maximum flame speed in the simulation does not correspond to the one measured. This probably is because the experimental flame was wrinkled by cellularity which increased its velocity but this was not modelled. Nevertheless the simulation was able to reproduce the pulsations in the flame. The time scale of the pulsations is similar to that of the experiment. This time scale is driven by the drag on the droplets.

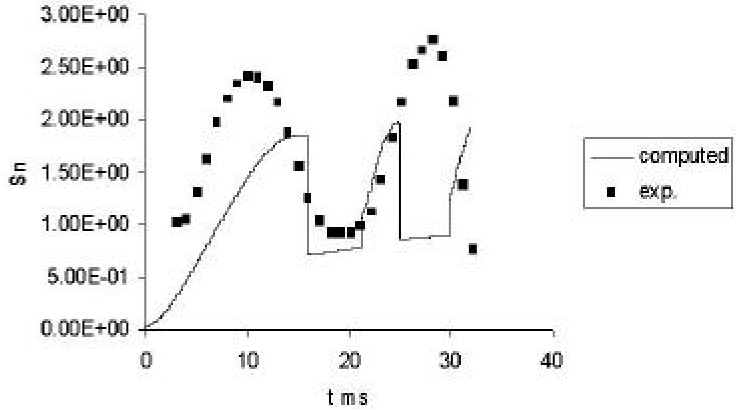

Figure 3: Variation of flame speed with of time. f_{all} = 0.95 in simulation and 1.0 in experiment. ϕg = 0.75.

The model was initially not able to reproduce the pulsation at an initial equivalence ratio of unity, as used in the experiment. However, at $f_{all}=0.95$, the simulation reproduced an oscillation in the flame speed as represented in Fig. 3.

8. CONCLUSIONS

Measurements of the propagation of a laminar spherical spray flame revealed oscillations in its flame speed. A simple model is proposed to explain the oscillations in terms of droplet inertia. Due to inertia, the real equivalence ratio within the reaction zone can be larger than the overall equivalence ratio. This influences the flame speed and can lead to oscillations. These oscillations result in burning rates that, locally, can be higher than those for an equivalent gaseous flame. The minimum burning velocity is equivalent to that of a gaseous flame with an equivalence ratio equal to f_g. The maximum burning rate can correspond to that of a gaseous flame that is richer than the overall equivalence ratio of the spray.

The mechanisms that explain the pulsation of the flame could lead to extinction of the flame if the equivalence ratio in the gas phase is not large enough to permit flame propagation. In this case the flame would be extinguished after regime (2) of Fig. 2.

9. REFERENCES

1 **Atzler F,** *Burning velocities in droplet suspensions*, PhD Thesis, School of Mechanical Engineering, University of Leeds, 1999

2 **Atzler, F., and Lawes, M.,** 'Burning velocities in droplet suspensions',ILASS-Europe 98, Manchester 6-8 July 1998.

3 **Hanai H, Maruta K, Kobayashi H & Niioka T,** *Pulsating Flame Propagation of PMMA Particle Cloud in Microgravity,* 27th Symposium (International) on Combustion, The Combustion Institute, pp. 2675-2681, 1998

4 **Wilson C.T.R**., *On a method of making visible the paths of ionising particles through a gas,* Proceedings of the Royal Society, London, A85, pp. 285-288,1911.6

5 **Nakabe K, Mizutani Y, Akamatsu F, Fuchihata M & ElEmam SH,** *Spark Ignited Spherical Flames propagating in a suspended droplet cloud*, NIST Special Publications, 5th Int. Conf. on liquid Atomization and Spray Systems ICLASS-91, Gaithersburg, 1991

6 **Bradley, D, Hicks, R A, Lawes, M, Sheppard, C G W and Woolley, R:** 'The Measurement of Laminar Burning Velocities and Markstein Numbers for iso-octane-n-heptane-air Mixtures at Elevated Temperatures and pressures in an Explosion Bomb', Combustion and Flame, 115, 126-144, (1998).