INFLUENCE OF ARC DISCHARGE DURATION ON TURBULENT MASS BURNING RATE

E. J. Mushi

Dept.. of Mechanical Engineering, University of Dar es salaam,
P.O. Box 35131, Dar es Salaam, Tanzania

ABSTRACT

The influence of arc discharge duration on turbulent mass burning rate was investigated for turbulent r.m.s velocities of u'=1.73 m/s and u'=4.5 m/s. Methane air mixtures were used at equivalence ratios ranging from 0.83 to 1.25. Flame size was obtained through schlieren photography while the intensity of CH chemiluminescence emissions was used to measure mass burning rate. A variable spark duration unit was used for ignition sparks and all the experiments were done in a fan stirred bomb.

Discharge duration has no effect when the equivalence ratio is 1. For higher values longer duration increases the burning rate for the early stages of the flame up to a flame radius of 10 mm. Beyond this the duration does not affect the burning rate. Significant improvement on burning rate is observed for equivalence ratio of 0.83. This decreases as the equivalence ratio approaches 1. For equivalence ratio less than 1 and for flame radius less than or equal to 5.2 mm a decrease in discharge duration improves mass burning.

Geometric flame stretch was found to have significant influence on the burning rate.

INTRODUCTION

Ignition of a gaseous combustible mixture using a spark requires an initial electrical breakdown of the spark gap. This involves voltages of the order of 10 kV, currents of the order of 200 A and a duration of 1 to 10 ns. The breakdown produces a cylindrical channel (≥ 40 μm diameter) with high inside temperature rise. Molecules inside the channel are ionized and dissociated, processes through which energy is stored in the plasma. The channel pressure rises rapidly giving rise to an intense shockwave which carries with it some of the input energy to the unaffected mixture.

The breakdown is followed by either arc discharge, glow discharge or a combination of the two. Arc discharge is associated with voltages of the order of 100 V and a current of the order of 500 mA. It provides low ionization but maintains high degree of dissociation at the central region. The arc expands by heat conduction and mass diffusion. A glow discharge is characterised by voltages of between 300 to 500 V and a current less than 200 mA. It has low ionization and low kernel temperature. Reference (1) provides compressive characteristics of the three modes of spark discharge and their associated energy losses.

For successful ignition, the discharge must initiate hydrodynamic and conductive spreading of the spark energy. It must also initiate chain reactions in the mixture by temperature and active species. The result is a propagating flame, which if under turbulent conditions it must survive turbulent straining which increases as the flame grows. It is from this that research was directed at better understanding of spark discharge and the way inflammation is achieved ref.(1 - 12). The cited works indicate that the long term influence of the spark on flame propagation has not received wide investigation. This problem is addressed in the present work which concentrates on the influence of the arc discharge of a spark on the mass burning rate under turbulent conditions. More emphasis is placed on the period after the spark has seized.

The intensity of chemiluminescent emissions from the CH radicals formed in the flame reaction zone has been shown to be proportional to the volumetric rate of consumption of combustible mixture, (13). Abdel-Gayed et al (14) used the intensity of these emissions as a measure of the volumetric heat release rates. They also showed experimentally that the ratio of the CH emission intensity in a turbulent flame to that in laminar flame at the same radius varied linearly with the ratio of the turbulent mass burning velocity to the laminar burning velocity. This finding is an important one in that measurements of emission intensities for turbulent and laminar flames at the same radius give the ratio of the mass burning velocities.

APPARATUS AND TECHNIQUES

The experiments described in this work were conducted in a fan stirred bomb. This comprised a cylinder of 305 mm diameter and 300 mm length with a 150 mm diameter concentric windows on each end plate. These windows provided optical access for the measurement of CH emissions and schlieren photography of flames. Four identical variable speed fans provided a region of isentropic turbulence at the centre of the bomb. The turbulence intensity was varied by varying the speed of the fans.

Flame propagation was recorded by high speed cine camera using schlieren technique as shown on Fig. 1.

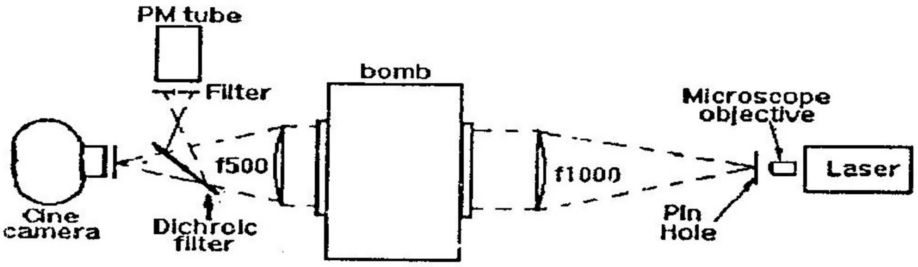

Fig. 1: Schlierren and CH measurements layout

Two markers attached on the bomb window, and simultaneously photographed with the flames provided a scale used to establish the actual size of the projected flame. These flame images were digitised and the radius of a circle with an enclosed area equal to the projected area of the flame was evaluated and considered to be the equivalent flame radius at the given time.

A locally manufactured composite spark unit was used in the experiments. It had a breakdown unit consisting mainly of a car ignition coil which was energised such that its total energy was just enough to provide breakdown at an electrode gap of 0.6 mm. This was provided by a one microsecond 300 V pulse into the primary coil of the ignition coil. The secondary coil was connected to the spark plugs via a 400 kΩ, high voltage resistor, and a high voltage diode which was only forward biased when the secondary coil voltage was high. This breakdown system was tested on air and methane air mixtures at atmospheric pressure. For both conditions the unit was found to perform reliably with a spark gap of 0.6 mm. It was further observed that the breakdown was not enough to ignite methane air mixtures within a range of equivalence ratios from 0.8 to 1.25, at atmospheric pressure.

The main spark was achieved using the discharge of a 40 µF capacitor through the spark gap via a bank of resistors which controlled the discharge current. This capacitor was charged using a 600 V D.C supply. A timing unit was used to short the capacitor and thus end the discharge. Two discharge durations, namely 0.1 and 0.9 ms were used for the study. The voltage drop across a 4.7 Ω low induction resistor in series with the spark gap, was used to evaluate the spark current. The voltage drop across the spark gap was measured directly. Oscilloscope traces of the variation of both this voltages during the discharge were photographed using polaroid camera and further digitised and processed to give a history of the gap voltage and current over the discharge period. Numerical integration of the product of the gap voltage drop and the current, over the discharge duration provided the total energy discharged.

Two identical electrodes were mounted opposite to each other in the cylindrical walls of the combustion vessel such that they met at the centre, where a gap of 0.6 mm was maintained.

Chemiluminescent emissions from the CH radicals formed in the flame reaction zone were used to measure the volumetric rate of consumption of combustible mixture. The technique used involves projection of the flame emissions on to an anode of a photomultiplier which generated a voltage proportional to the intensity of the incident radiation. The flame image was focused on the anode by one of the schlieren focusing lens, behind which was mounted a 50 mm diameter dichroic filter at 45 degrees to the axis of the vessel. This filter transmitted 90% of the spectrum above 510 nm (93% of the neon-helium laser radiation for schlieren) and reflected 90% of the spectrum below 445 nm (94% of the CH radiation wavelength of 431.5 nm). It follows from this arrangement that the schlieren image was transmitted through the filter to the cine camera while the CH flame image was reflected at 90 degrees towards the photomultiplier. A special narrow band filter (431 ± 6.5 nm) was used to eliminate almost all other radiations and transmit CH radiations to the photomultiplier. The photomultiplier output was amplified and recorded by Datalab type DL

922 transient recorder from which the digitised signal was transferred to a computer for further processing.

The above arrangement was tested using a 3 mm inspection lamp placed at various positions inside the combustion vessel. Within a sphere of radius of 130 mm the maximum variation of the photomultiplier output was less than ± 4% of the value at the centre of the vessel. This confirmed that throughout the field of view of diameter 130 mm the photomultiplier output will be independent of the flame position.

For each explosion, the combustion vessel was evacuated, flushed with air, evacuated again and then filled with the appropriate mixture of methane and air. Partial pressures were used for the preparation of the mixture, with a total pressure of one atmosphere. All mixtures were ignited at 328 K.

RESULT AND DISCUSSION

Figures 2 to 5 show the variation of the ratio of turbulent CH emission intensity to that of a laminar flame of the same radius against time. These are for spark discharge durations of 0.1 and 0.9 ms, turbulent r.m.s velocity of 1.73 m/s and for equivalence ratios ranging from 0.83 to 1.25.

At equivalence ratio of 0.83, Fig. 2, the ratio of intensities, I/I_l, for flames initiated by the 0.1 ms spark is on the average a constant and equal to one for durations less tha 6 ms. This implies that the turbulent mass burning velocity is equal to the laminar burning for these flames. From this observation, it is evident that the turbulence level involved is not strong enough to influence these flames. At this level of turbulence, the only influence of turbulence will be wrinkling of the surface thus increasing the entrainment area which results in increased rate of mass entrainment. If the rate of burning is low and the increase in entrainment due to turbulence is also low it is possible to have negligible influence on the flame development.

Flames initiated from the 0.9 ms spark exhibit a different behaviour. The burning rate is seen to be very low just after the spark discharge increasing to a maximum value of $I/I_l = 3.3$ at 3.2 ms after ignition. Beyond 3.2 ms some oscillations are observed but the average value is constant at $I/I_l=2.5$.

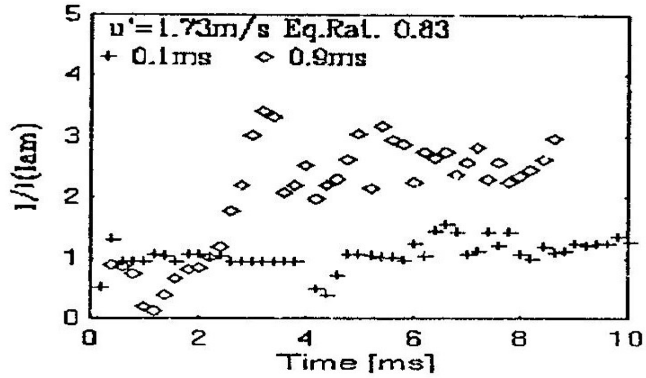

Fig. 2: Variation of ratio of intensities with time

Flames from the 0.9 ms spark exhibit turbulent mass burning velocity which is three times that observed for 0.1 ms spark. This suggest a strong influence of the discharge on the burning rate. Both flames indicate fluctuations over the average value and this can be associated with the chaotic nature of turbulence, probably the influence of the lower frequencies of turbulence.

Flames initiated from both the discharges indicate a period of growth from very low burning rates immediately after the spark. It can be argued that the duration of 0.1 ms may provide just enough energy to initiate the process of flame growth without extra energy left to influence the initial growth rate. It follows from this that the 0.9 ms discharge will provide a lot of extra energy which will increase the initial growth rate significantly. From fig. 2 the burning rate at the end of the discharge is lower for 0.9 ms duration than for 0.1 ms. This behaviour can be explained through flame stretch. It is true that the 0.9 ms discharge provides extra energy but this extra energy is expended in providing accelerated expansion of the created flame. This expansion stretches the flame but the stretch decreases as the flame grows and as the available energy decreases. At a flame radius of 3.4 mm the influence of stretch seem to seize and from this point the mass burning rate increases.

Figure 2 further shows that if the life of the flame is less than 2.3 ms then a 0.1 ms discharge initiates flames with higher burning rate. Beyond these values the 0.9 ms discharge provides higher burning rate.

Results for the same turbulence level but at an equivalence ratio of 0.91 are presented on fig. 3. The pattern is similar to that of flames at equivalence ratio of 0.83 with some exceptions. One is that the flames do not develop to a constant growth rate but indicate increasing mass burning rate throughout. The period of superior mass burning rate for the 0.1 ms discharge is increased to 4.5 ms. Beyond this, the 0.9 ms discharge flames indicate increasing mass burning while the 0.1 ms discharge flames show little increase. At the same time after ignition the difference in mass burning rate between the flames decreased by increasing the equivalence ratio from 0.83 to 0.91. It is anticipated that this is due to increased influence of the flame stretch arising from the increase in laminar burning velocity. This implies that the 0.9 ms discharge flames will experience higher flame stretch hence suffer retardation of the mass burning velocity while the 0.1 ms discharge flames will experience less stretch initially. This also explains the prolonged period of superior mass burning rate.

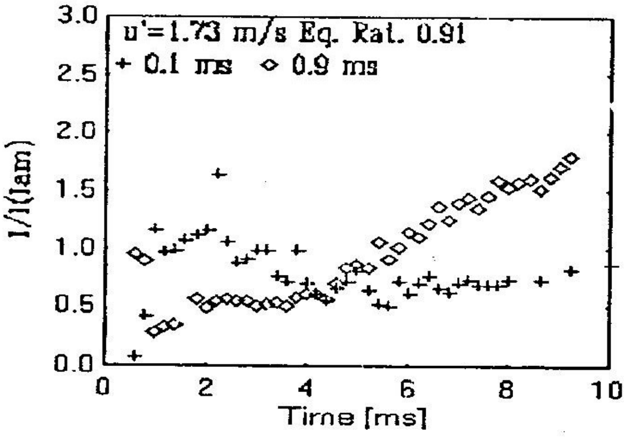

Fig. 3

At the same turbulence level but at equivalence ratio of 1.1 and 1.25, figures 4 and 5, a different behaviour is observed. Both discharge durations result in the same value for the mass burning rate i.e the ratio I/I_l, for flame duration greater than 6 ms. Below this, flames from 0.1 ms discharge indicate gradual increase of the mass burning rate while for the 0.9 ms discharge flames the burning rate exhibits initial increase to a maximum followed by a decrease to the constant value. This maximum value was observed to occur at a flame radius of 5.8 mm.

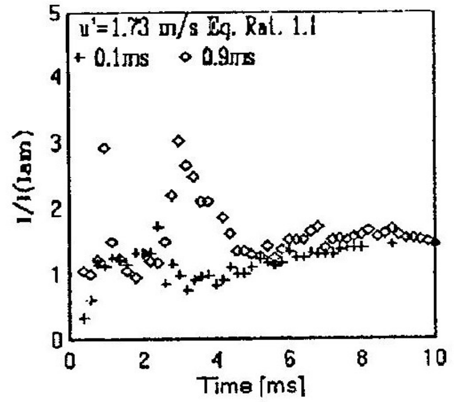

Fig. 4

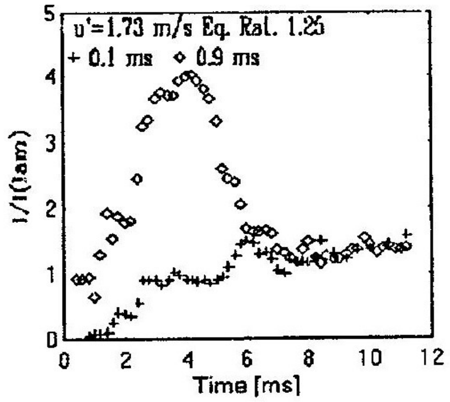

Fig. 5

Figure 6 shows the variation of the geometrical flame stretch calculated from the radius time data for u'=1.73 m/s and equivalence ratio of 1.25. Initially the stretch is very high due to the influence of the spark. This decreases to a minimum just at the end of the discharge followed by an increase which is associated with the growth of the self propagating flame. The increase continues till a local maximum is attained beyond which the stretch shows gradual decay. The initial decay and subsequent growth of flame stretch occurs in a short period for the 0.1 ms discharge flames and it ends while the radius of the flame is 3.7 mm. This explains why these flames indicate a gradual growth of the burning rate towards a constant value. It is a result of a gradually decaying flame stretch. Flames from the 0.9 ms discharge experience the initial decay of the stretch for a longer period. As the stretch decreases during the discharge and after, the burning rate will increase and this continues past the point of minimum stretch (minimum stretch occurs at 5.1 mm radius while maximum burning rate is observed to occur at 5.8 mm). This overlap is a result of the nature of the influence of stretch on flame propagation. At low stretch, an increase will increase the entrainment area when the burning rate is high hence more is burned resulting in an increase in burning rate. At higher stretch an increase will still increase the entrainment area resulting in entrainment of more mixture but the burning rate is low and cannot burn all the mixture. As a result, this entrained mixture will tend to quench the reaction and thus providing further reduction in burning rate. This behaviour of flames under varying stretch and the pattern of flame stretch given on fig. 6 explain the variation of burning rates observed on figs. 4 and 5.

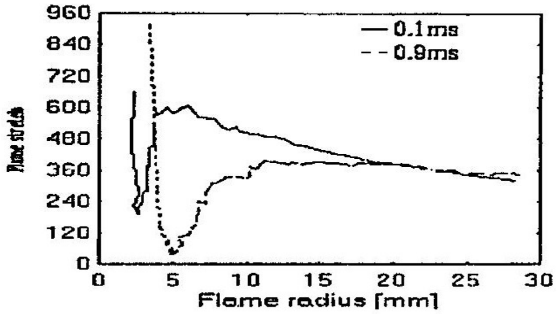

Fig. 6

Similar results are presented on figs. 7 to 10 for r.m.s

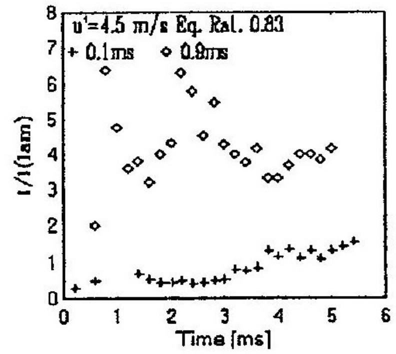

Fig. 7

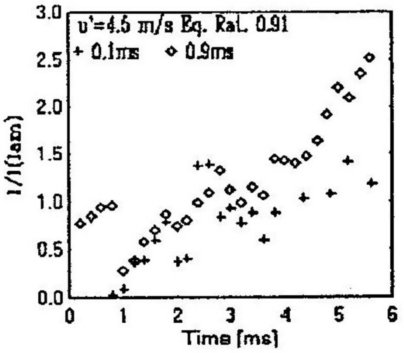

Fig. 8

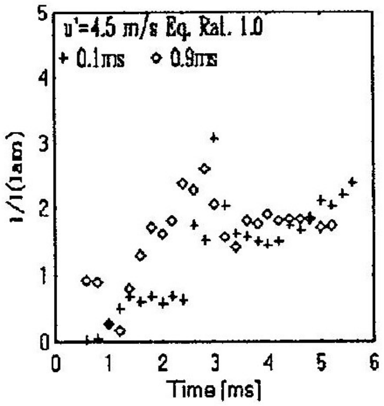

Fig. 9

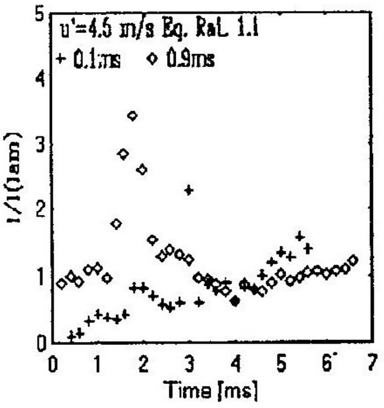

Fig. 10

turbulent velocity of 4.5 m/s. The behaviour of the flames is similar to the one observed at lower turbulence level except at an equivalence ratio of 0.83 the difference between the two groups of flames is higher indicating even better performance for the 0.9 ms discharge.

CONCLUSION

Increased arc discharge duration improves the turbulent mass burning rate of flames when the equivalence ratio is less than 1. The improvement increases with turbulence and with decrease in equivalence ratio. However, short discharge duration provides improved burning rate during the early stage of flame development (for the first 2 - 4 ms). Discharge duration has no influence when the equivalence ratio is 1 but for higher equivalence ratios there is improvement in the early stages of the flame development which ends when the flame radius is 10 mm. Beyond this the discharge duration has no influence on the rate of mass burning. During the study the discharge duration was increased and this implied more energy was discharged. Further investigation is required to isolate the contributions of the duration, the total energy discharged and the power.

Geometrical flame stretch has strong influence on the mass burning rate. When the stretch is low, an increase in stretch will increase the mass burning rate, this improvement decreases with stretch. At high values of stretch an increase in stretch reduces the mass burning rate. Defining the geometrical stretch as the increase in area per unit area, an investigation of flames at equivalence ratio of 1.25 and u'=1.73 m/s indicated that increase in stretch increases mass burning rate for values of stretch below 110 and decreases burning for values above. It must be emphasised that the study was done on a single case, at equivalence ratio of 1.25 and r.m.s turbulent velocity of 1.73 m/s, further work is required to ascertain the limit.

REFERENCES

1. R. Maly, Spark Ignition: Its Physics and Effect on the Internal Combustion Engine in *Fuel Economy* ,Plenum, New York 1984, pp 91-148.
2. J.F. Sayers, G.P. Tawari, J.P. Wilson, P. Jessen, Spark Ignition of

Natural Gas, Theory and Practice *Gas Council Res. Comm.* GC 171, 1970.

3. C.G. De Soete, *International Conference on Combustion in Engineering I.* Mech. E. Conference Publications I. Mech. E. London 1983, pp 93.
4. M. Kono, S. Kumagai, T. Sakai, *16th Symposium (Int.) on Combustion*, Pittsburg: The Combustion Institute, 1977, pp 757-166.
5. M. Kono, S. Kumagai, T. Sakai, *Combust. Flame* Vol. 27 1976, p. 85.
6. C.C. Swett, *6th Symposium (Int) on Combustion, 1956,* p 523.
7. C.C. Swett, Spark Ignition of Flowing gases, *NACA Report No. 1287,* 1956.
8. D.R. Ballal, A.H. Lefebvre, *15th Symposium (Int) on Combustion;* Pittsburg: The Combustion Institute, 1974, p 1473.
9. S. Rafael, E. Sher, *Combust. Flame*: vol. 59, 1985, p 17.
10. F.K. Lung, Ph.D Thesis University of Leeds, 1986.
11. G. Joulin, Preferential diffusion and the initiation of lean flames of light fuels, *SIAM J. Appl. Maths* vol. 17, 1987, p 998.
12. M.T. Lim, R.W. Anderson, V.S. Arpaci, Prediction of spark kernel development in Constant Volume Combustion, *Combust. Flame,* vol. 69, 1987, pp 303-316.
13. I.R. Hurle, R.B. Price, T.M. Sugden, A. Thomas, *Proc. Royal Soc.* London, vol. A 303, 1968, pp 409-427.
14. R.G. Abdel-Gayed, D. Bradley, M. Lawes, F. Lung, *21st Symp. (Int.) on Combustion,* Pittsburg: The Combustion Institute, 1986, pp 497-504.

The manuscript was received 26th May 1994 and accepted for publication 6th December 1994