INFLUENCE OF TURBULENCE ON METHANE-AIR FLAME SPEED

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ABSTRACT

Experimental study of the influence of turbulence on flame speed for methane-air mixtures has been conducted in a fan stirred bomb using schlieren photography. It has been observed that turbulence increases flame speed but above KLe=0.18 (KLe is the product of the dimensionless Karlovitz flame stretch factor and the Lewis number) turbulence quenches the flame. Laminar flame kernel is observed to prevail in the early stages of flame development in a turbulent mixture. Further, the laminar burning velocity plays a significant role in turbulent combustion. It is proposed that the increase in flame speed is a result of flame wrinkling.

INTRODUCTION

Practical flames are nearly all turbulent. Examples include combustion in engines, heavy oil furnaces, industrial burners as well as environmental hazards such as wind driven forest fires, or gas explosions. Where the flames are a necessity there is a need for better management to reduce environmental pollution and increase efficiency. To counter fire hazards, prevention measures are necessary, as is also limitation of the resulting damage should fire occur.

Clearly, a fundamental understanding of turbulent combustion is necessary and this involves the interaction between turbulent flow and chemical kinetics. Early efforts concentrated on the understanding of turbulent flow which started about a century ago. The pioneers were Boussinesq [1] and Reynolds [2]. These were followed by a multitude of other scientist. At present, the availability of high speed computers has facilitated simulation of turbulent flows, i.e Kerr [3], Yamamoto and Hosokawa [4] and She et al [5].

Early efforts to understand turbulent combustion were based on experimental study ranging from measurement of burning velocities to influence of the turbulence spectrum on the flame. Abdel-Gayed et al [6] used published experimental data to provide a correlation from which the turbulent burning velocity could be established. This correlation was further improved, Bradley et al [7], using additional data and further knowledge of turbulent flows. With the emergence of high speed computers, efforts are now being concentrated on computer modelling. But the mathematical models will need experimental data for their validation.

The present work seeks to provide further insight into the interaction between turbulent flow and chemical kinetics as well as providing experimental data for validation of mathematical models.

APPARATUS AND TECHNIQUES

The presented experimental work was 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 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.

Two electrodes, one negative and the other positive, were mounted opposite to each other in the cylindrical wall of the combustion vessel such that they could meet at the centre, where a spark gap of 0.6 mm was maintained. These electrodes were connected to a spark unit, utilising capacitive discharge to provided a spark. The arrangement was such that a cine camera, for schlieren photography, was activated manually and on attaining the required framing speed it automatically fired the spark.

Partial pressures were measured to control the composition of the combustible mixture. Prior to preparation of the mixture the combustion vessel was evacuated to 25 mm of mercury. Methane of 99% purity was the fuel used throughout this work. It was supplied to the vessel from a cylinder to the appropriate partial pressure. Filling of the vessel to atmospheric pressure was completed using air from a compressor. An electric heater inside the vessel was used to heat the mixture when the fan speed was low to ensure uniform temperature distribution, which was monitored using a thermocouple. The pressure inside the vessel was measured by using a mercury manometer which was also used for the measurement of partial pressures during mixture preparation. All explosions were at an initial temperature of 328 K and a pressure of one atmosphere, and all the measurements were taken during the pre-pressure period. After each explosion the vessel was evacuated and flushed with air twice before further mixture preparation. Five explosions were done for each condition and the results averaged.

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

The images on the developed film were digitised one frame at a time, and after scaling to reflect actual size, the enclosed flame area was evaluated.

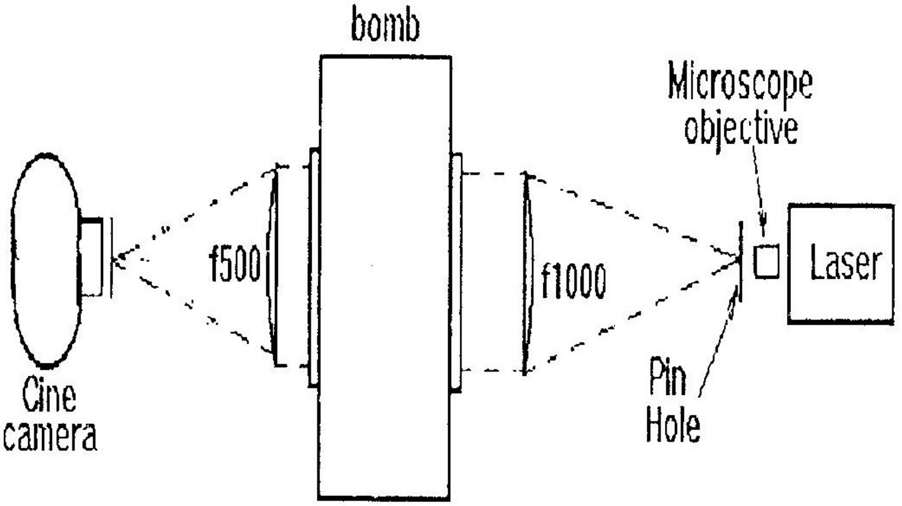

Fig. 1. Schlieren photography layout

The radius of a circle with an enclosed area equal to the actual projected area of the flame was evaluated and considered to be the equivalent flame radius. Time marks on the film, facilitated coupling of each flame radius to its appropriate time after ignition. The resulting time-radius data was differentiated to give the history of the flame speed.

RESULTS AND DISCUSSION

Figures 2 (a) and (b) present the flame speed against both the time after ignition and flame radius, for different r.m.s turbulent velocity. These results indicate a high initial growth rate which decreases with time to a minimum before increasing again. The minimum growth rate is observed to occur at 1 ms after ignition when the flame radius is approximately 4.0 mm.

All the flames were initiated from a spark discharge of 0.9 ms. This initial high growth rate can be attributed to the spark. The spark discharge creates a volume of highly ionized gas which accelerates chemical reactions, Vosen et al [8]. The ions and exited molecules diffuse outwards to promote chemical reaction. In addition, the breakdown phase of the discharge is known to create a shockwave which propagates radially from the spark gap and which contributes to an enhanced kernel growth [9, 10, 11,12,13, 14, 15, 16]. All flames, turbulent and laminar indicate similar behaviour during the discharge influenced period. This supports earlier observation by Akindele et al [11] that laminar flame kernel development prevails in the early stages of flame development in a turbulent mixture.

For the laminar flames, the second increase in growth decreases with time to a constant growth rate at a flame radius of approximately 10 mm. After the initial decrease in flame speed, the turbulent flame speed increased continuously throughout the measurement duration, suggesting that the development period for these flames was longer than the duration of the measurements. This continuous increase may be attributed to the temporal development of the instantaneous turbulent burning velocity due to increased wrinkling, Abdel-Gayed et al [(6].

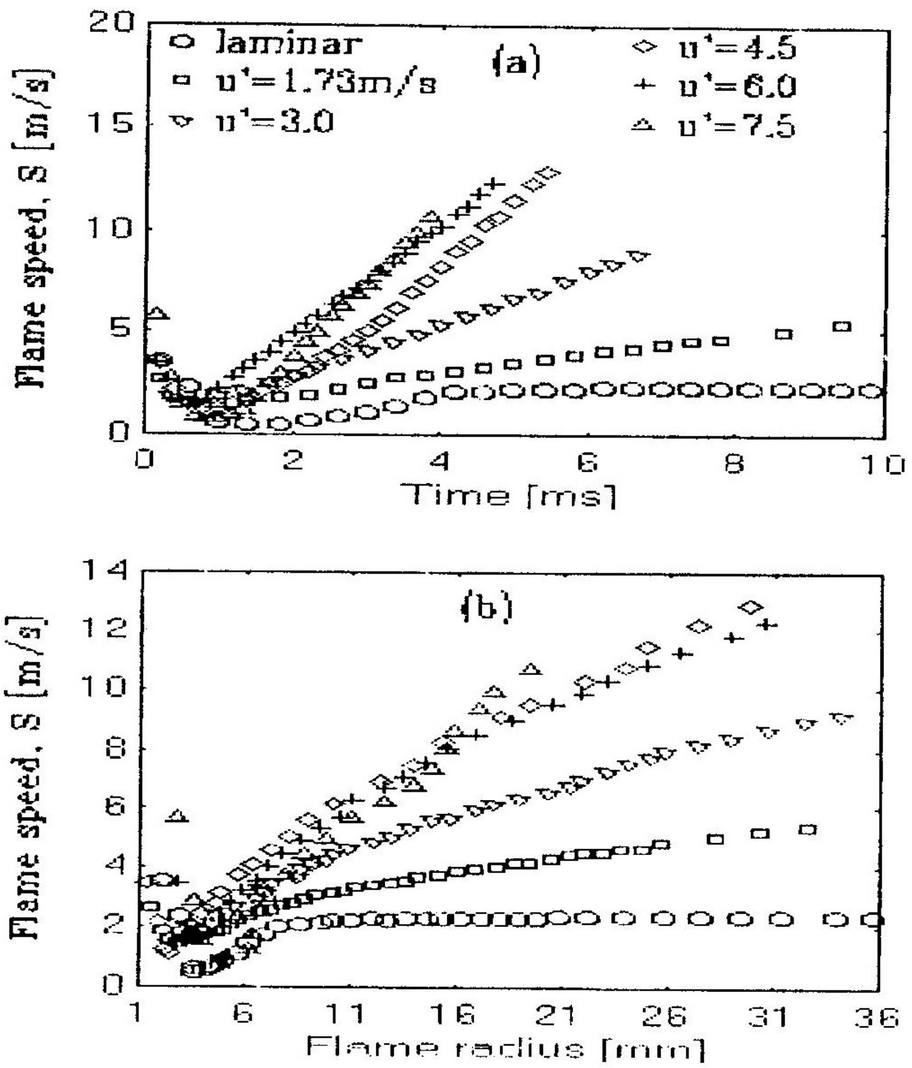

Fig 2 Influence of turbulence on flame speed

The variation of flame speed with r.m.s turbulent velocity is presented on fig. 3. On fig. 3(a) the data is presented for different times after ignition, i.e 2, 3 and 4 ms, while the same is presented for different flame radii (5, 11, 16 and 21 mm) on fig. 3(b). Generally, the flame speed increases with turbulence for u' <4 m/s and decreases for values of r.m.s turbulent velocity, u', higher than 4 m/s. The increase for u' ≤ 4 m/s provides further support for the increase in burning velocity due to increased wrinkling, Abdel Gayed et al [6]. However, the decrease in flame speed with turbulence for u' ≥ 4 m/s suggests significant quenching by flame stretch.

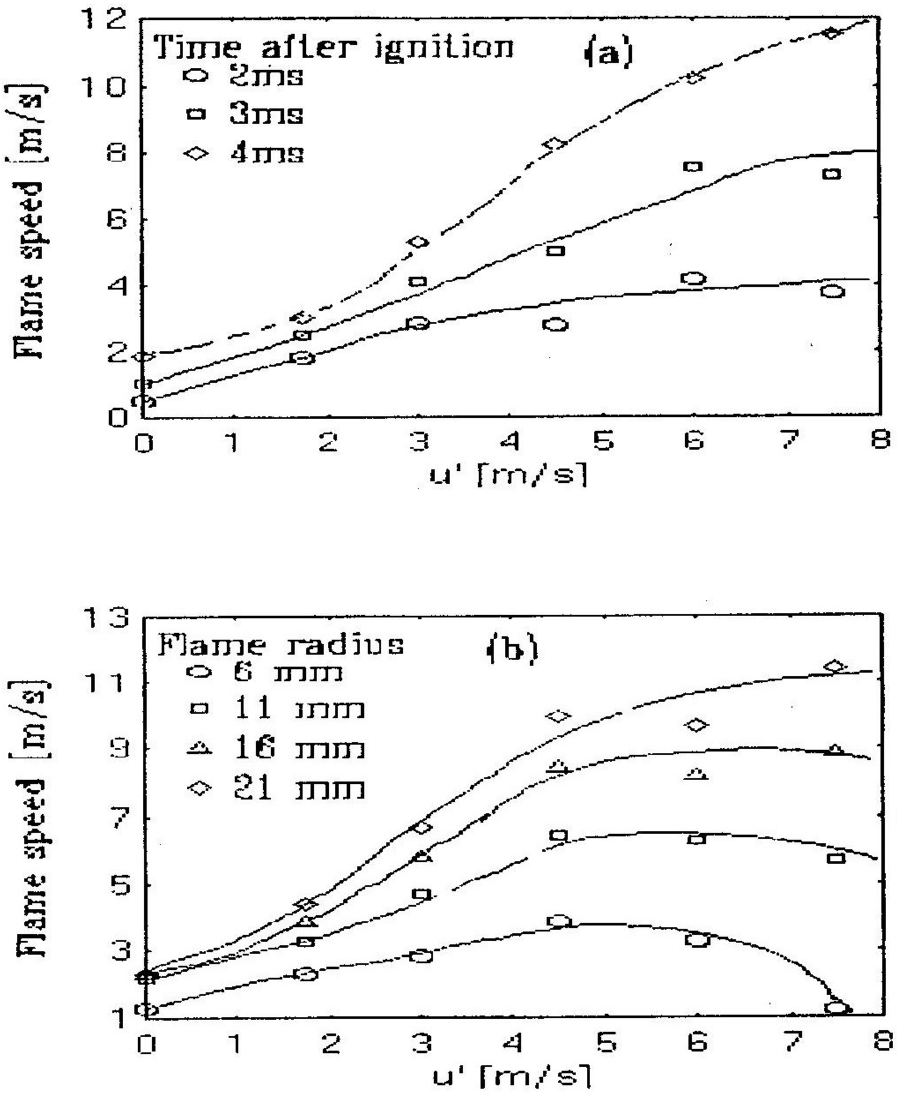

Fig. 3 Flame speed versus r.m.s. turbulant velocity

Bradleyet al [7] suggested that turbulent flame quenching is dependent on the product of the Karlovitz stretch factor, K, and the Lewis number, Le, corresponding to the combustible mixture. The value of this product, KLe, for u'= 4 m/s is 0.18. It therefore follows from this that significant flame quenching occurs for KLe $\geq$ 0.18. This has significant implications to engine combustion. For values of KLe $\geq$ 0.18 serious flame quenching is to be expected and this may increase unburned hydrocarbon emissions, reduce efficiency and driveability.

Comparison of flame speed with laminar burning velocity for different equivalence ratios is presented on fig. 4(a) at 6 ms after ignition, and fig. 4(b) at 15 mm flame radius. Similar variation is observed for both turbulent flame speed and laminar burning velocity. This suggest an influence of the laminar burning velocity on flame development even under turbulent conditions. This observation supports the argument that the laminar burning velocity has an influence on flame development even under turbulent conditions.

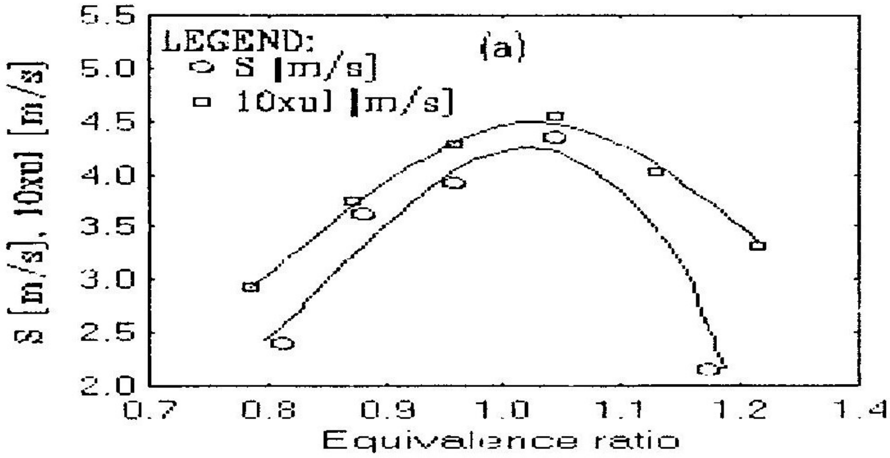

Fig. 4(a): Flame speed and laminar burning velocity vs Equivalence ratio

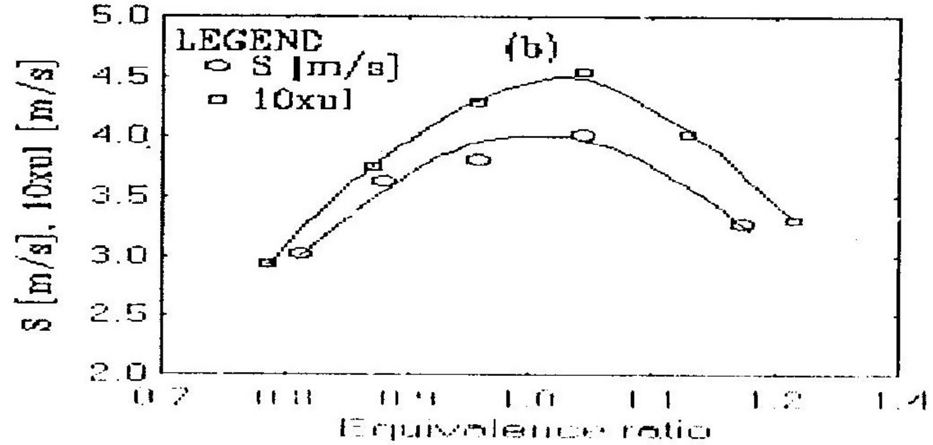

Fig. 4(b) Flame speed and laminar burning velocity vs Equivalence ratio

This observation supports the argument that because the molecular rate processes of transport and chemical reaction are generally faster than the processes associated with turbulent motion, it is possible that the structure of a laminar flame is preserved, even in a turbulent field.

CONCLUSION

Significant quenching by flame stretch occurs for values of KLe above 0.18. This condition implies increased hydrocarbon emissions, reduced efficiency and driveability in internal combustion engines.

At low turbulence, increase in turbulence increases flame kernel development through flame wrinkling while at high turbulence an increase will decrease kernel development through quenching.

Laminar flame kernel prevails in the early stages of flame development in a turbulent mixture. This supports the postulate that the influence of turbulence on the flame is gradual starting from the high frequency components toward the lower frequencies, Abdel-Gayed et al [6].

Even under turbulent conditions the laminar burning velocity plays a significant role in the combustion process.

NOMENCLATURE

K	Dimensionless Karlovitch flame stretch factor $(= 0.157 (u'/u_l)^2 R_L^{-0.5})$
Le	Lewis number
R_L	Reynolds number (based on integral lenth scale)
S	Flame speed [m/s]
u_l	Laminar burning velocity [m/s]
u'	Turbulent r.m.s velocity

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