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Cheng, R.K.

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Lawrence Berkeley Laboratory
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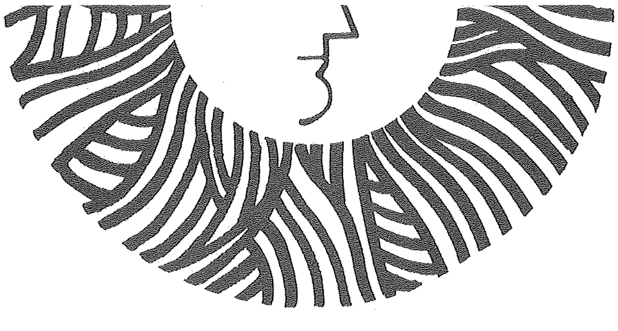

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R. K. Cheng and T. T. Ng

Lawrence Berkeley Laboratory
University of California
Berkeley, Ca 94720

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R. K. Cheng and T. T. Ng

Lawrence Berkeley Laboratory
University of California
Berkeley, California

ABSTRACT

The flowfield of a V-shaped, premixed ehtylene/air flame in grid induced turbulence has been studied using Laser Doubler Velocimetry. The experimental conditions covered free-stream velocities of 5 and 7 m/s and equivalence ratios ranging from 0.6 to 0.78. The two-dimensional velocity vectors obtained indicate that flow deflection in the free stream was significant and seemed to correlate with the flame angle. The influence of the flame holder wake on the flame was demonstrated. In the presence of the flame, an increase in the turbulence level in the free stream was found and was attributed to fluctuations in flow deflection induced by the fluctuating flame.

1. INTRODUCTION

The study of premixed turbulent flame propagation has been a focus of attention in combustion research for a long time. Although a number of theoretical turbulent flame models have been proposed, for example, Bray and Libby[1], and Calvin and Williams[2], there have not been sufficient experimental data obtained to check the validity of these models. With the development of advanced laser-based experimental techniques, progress has been made in obtaining time- and space-resolved measurements through the flame zone. In the studies of Moss[3], Kennedy and Kent[4], and Yanagi and Mimura[5], attention was focused on measuring cross-correlations between velocity and scalar properties, such as temperature and density, as appear in the Favre-averaged[6] formulations for turbulent reacting flow. Andrews et al.[7], Abdel-Gayed et al.[8], and Smith and Gouldin[9], on the other hand, concentrated their efforts on measuring turbulent burning speed and correlated their results with turbulent flow parameters ahead of the flame zone. A two-eddy theory of turbulent combustion[10] and a wrinkled laminar flame model[9] were developed as a result of these investigations.

In our previous study of flame propagation in grid-induced turbulence[11], mean and fluctuation intensities of density and streamwise component of velocity were measured in an unconfined, rod-stabilized, premixed V-shaped turbulent flame. This experimental set-up is similar to that used by Smith and Gouldin[9] and Ho et al.[12]. The results indicated the dominance of the flame holder wake on flame propagation under certain conditions when the flame is highly oblique, and also suggested that there was significant deflection of streamlines through the flame region.

The objective of the present study was to survey the flowfield of the unconfined V-shaped turbulent flame in greater detail to better quantify its overall features and characteristics. Mean and root-mean-square values (rms) of streamwise (U) and cross-stream (V) velocity were measured using laser Doppler velocimetry (LDV). In addition, the time-averaged Reynolds stress ($\overline{u'v'}$) and evolution of length scales through the flame were also deduced. Mean velocity vectors and rms fluctuation data relevant to the influence of the flame front on the flowfield were also obtained. A more comprehensive description of the Reynolds stress variation and the evolution of length scales through the flame and turbulent burning speed results will appear in a subsequent publication[18].

2. EXPERIMENTAL SYSTEM

The details of the experimental set-up and the computer controlled data acquisition system were described earlier[11]. Figure 1 is a schematic depicting half of the flame plane and the coordinate system used. Turbulence in the 5.0 cm diameter coaxial jet with a 2.5 diameter inner core of ethylene/air mixture and outer flow of air is generated by a grid placed 50 mm upstream of the exit of the nozzle. The mesh size of the grid, M, was 5 mm and the diameter of the grid elements was 1 mm. The V-shaped flame was stabilized by a 1 mm diameter rod placed at the center of the nozzle exit.

The LDV system used is an intersecting dual-beam type incorporating a TSI 1990 frequency counter unit. The procedure to measure U, V, their root-mean-square (rms) fluctuation ($(\overline{u'^2})^{1/2}$ and $(\overline{v'^2})^{1/2}$), and the Reynolds stress ($\overline{u'v'}$) using a single component LDV system is described by Durrani and Greated[13]. It involves the measurements of mean and rms fluctuation of three different velocity components. For our study, the three components measured were oriented at 0° and ± 30° with respect to the x-axis, and were labelled as U, U_1, and U_2 as shown in Fig. 1. This technique had been used by Durst et al.[14], Moreau and Boutier[15], and Cheng and Ng[16], and was found to be quite satisfactory.

3. RESULTS AND DISCUSSION

Experiments were carried out at four different conditions with unburnt gas velocity, U_∞(UFT), at 5 or 7 m/s and equivalence ratio, ϕ(PHI), ranging from 0.6 to 0.78. Measurements were made at predetermined transverse positions at several axial locations.

In Figure 2(a) through Figure 2(e), the two-dimensional mean velocity vectors in the flowfields for all the experimental conditions are shown. The mean flame positions, determined by least square parabolic curve fits of the locations of maximum cross-stream velocity gradient, $(\delta v/\delta y|_{max})$ are illustrated by the broken lines. The mean flame positions so determined, also correspond to the positions of of maximum Reynolds stress and velocity fluctuation; consequently, they also correspond to the schlieren position measured by others[9]. The influence of the flame on the flowfield is apparent. As shown in Fig. 2(a), the non-reacting flow remains parallel to the x-axis. Significant changes in the gas flow direction are observed when a flame is present, as shown in Figs. 2(b) to 2(e). The entire cold reactant flow in the free-stream is deflected away from the flame. The degree of flow deflection across the jet is quite constant and seems to correlate with the local flame angle. This suggests that characteristics of the flow entering the flame locations downstream of the flame holder is affected by the presence of the flame. Through the flame region, expansion of the reacting gases accelerates the flow and changes its direction from outward away to inward towards the flame. In the post-flame region, symmetry of the flow configuration causes the accelerated flow to converge and eventually align with the x-axis. These changes in the flow direction through the flame are similar to those observed by particle tracking methods in a laminar V-shaped flame[17].

In the post-flame region near $y = 0$, the wake of the flame holder induces a velocity deficit in the flow; at the same time, the combined effect of the flow convergence and symmetric boundary condition is to accelerate the flow in the x-direction. At positions immediately downstream of the flame holder, both effects influence flame propagation. Further downstream, depending on flow conditions, either one or the other of the effects becomes predominant, as seen in Figs. 2(b) and 2(c). For a flame with relatively large flame angle as in Fig. 2(b) ($U_\infty = 5$ m/s, $\phi = 0.78$) the velocity deficit completely disappears at $x = 70$ mm, indicating that the combustion-induced acceleration dominates the wake. On the other hand, for a highly oblique flame as shown in Fig. 2(c) ($U_\infty = 7$ m/s, $\phi = 0.6$), which corresponds to a condition of increased drag and decreased reaction rate, the wake dominates flame propagation throughout. Turbulent burning speed measured under this conditions should be interpreted with caution for the results may not be typical for flame propagation in grid-induced turbulence. The cases of Figs. 2(d) and 2(e) show that the velocity deficit disappears at about $x = 90$ mm. It is of interest to note that increase in Reynolds stress due to the wake near $y = 0$ persists up to $x = 100$ mm even though the velocity deficit is not apparent there.

The rms fluctuation levels of both streamwise and cross-stream components in the cold reactant region are found to be equal. This agrees with the isotropic turbulence assumption for grid-induced turbulence. In the flame region, maximum fluctuations occur at the mean flame position with $(\overline{v'^2})^{1/2}{}_{max}$ slightly higher than $(\overline{u'^2})^{1/2}{}_{max}$ in most cases. These peak values increase with x. As pointed out in our previous paper, this increase is due to an increase in flame front movement. In the post-flame region, the fluctuations drop to a level lower than those in the free-stream, indicating a decrease in turbulent kinetic energy. In the case of the highly oblique flame, the fluctuations remain essentially constant through the flame region and peak at $y = 0$, demonstrating the dominance of the wake in this flame.

Streamwise fluctuaion levels along streamlines in the unburnt gas upstream of the flame region are shown in Fig. 3 as $U^2/\overline{u'^2}$ vs. x/M. The case of nonreacting flow is also included here for comparison. As predicted for grid-generated turbulence[16], the fluctuation intensity decays with increasing x. The presence of the flame, however, has significant effect on the characteristics of the turbulence. For all cases with the flame present, the overall turbulence levels are increased. Furthermore, the decay rates are reduced substantially. In the case of $U_\infty = 5.0$ m/s and $\phi = .78$ (Fig. 2(b)), the turbulence level at $x = 60$ mm increases to 6% and does not show any observable decay further downstream. These changes in turbulence level are attributed to the effect of the fluctuating flame on the free-stream flow. As pointed out earlier, the flow deflection in the free-stream seems to correlate with the mean flame angle. Thus, a fluctuating flame, with its flame angle changing continuously, could also induce fluctuations in flow deflection in the free-stream. This is supported further by the fact that the increase in turbulence level correlates with the increase in the thickness of the flame region which indicates the extent of the flame front movement.

CONCLUSIONS

Our results have demonstrated that in an unconfined, premixed, V-shaped turbulent flame, flow deflection throughout the whole flowfield is significant and cannot be ignored in determining the burning velocity. The influence of the flame holder wake on flame propagation is also shown.

The turbulence level in the unburnt gas is increased by the presence of the flame. This is attributed to the fluctuating flame front which induces fluctuations in flow deflection in the free-stream. The changes in the turbulence level, as demonstrated by our study, can be substantial, and may have to be taken into account in turbulent flame modeling.

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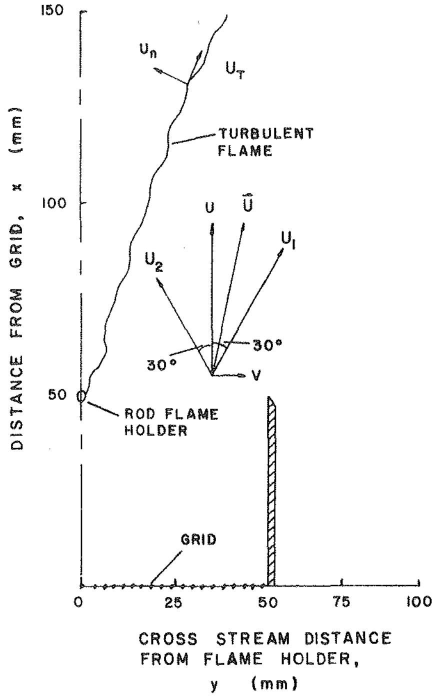


Fig. 1 Schematic of the Experimental Set-up.

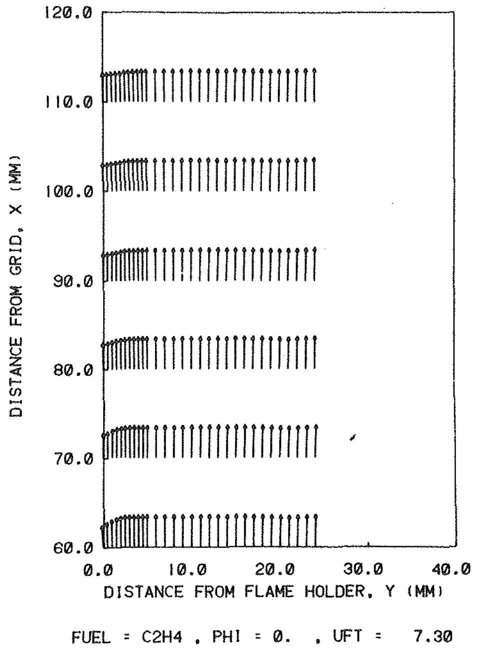
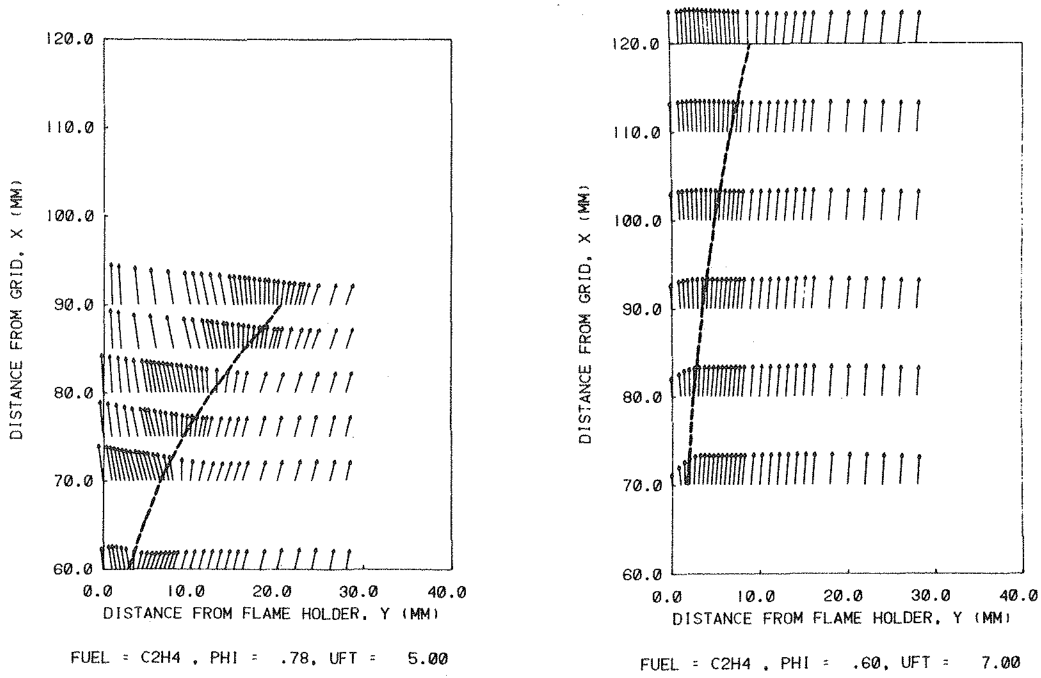


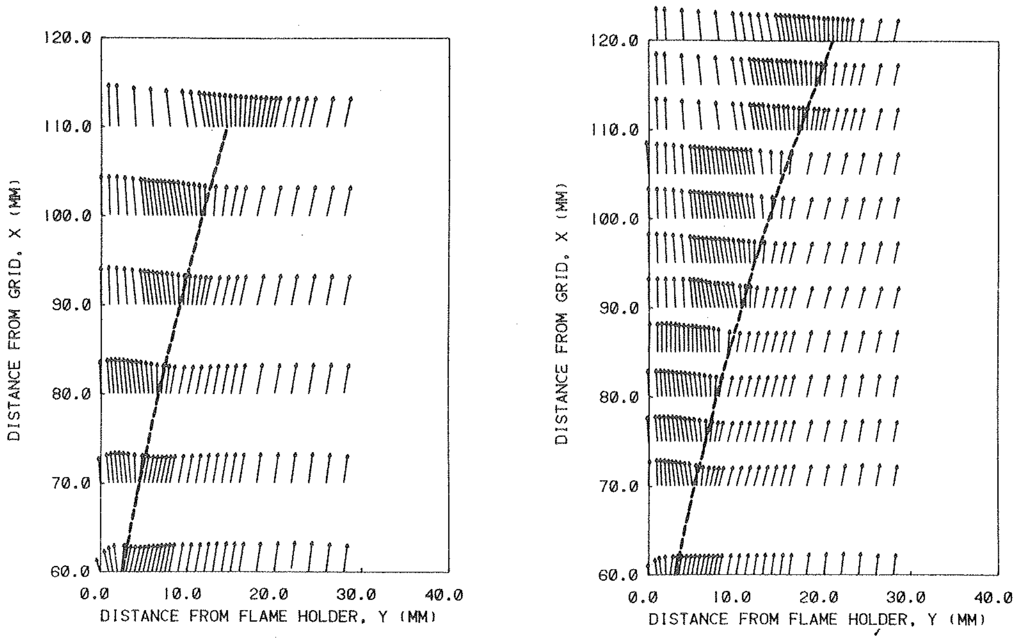
Fig. 2(a) Velocity field of the non-reacting flow.



(b)

(c)

Fig. 2 Velocity fields of the V-shaped flames.



FUEL = C2H4 , PHI = .75, UFT = 7.00

(d)

FUEL = C2H4 , PHI = .70, UFT = 5.00

(e)

Fig. 2 Velocity fields of the V-shaped flames.

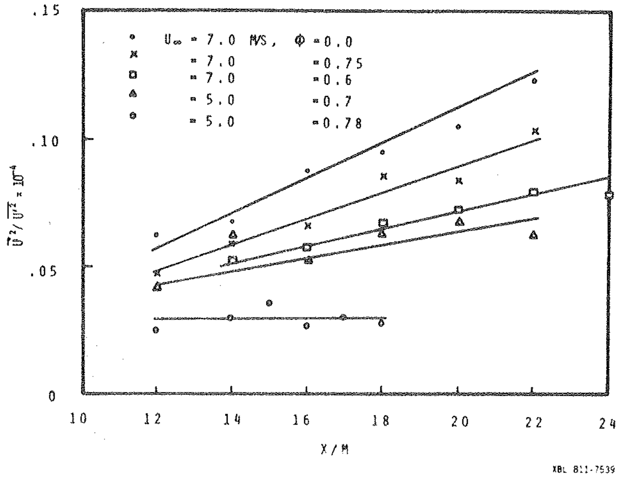


Fig. 3 Turbulence Level as a Function of Downstream Positions.

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