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1.1

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4.5 2.8 2.
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Results are presented from an experimental study of premixed turbulent flame propagation under atmospheric pressure, unconfined conditions. Stoichiometric propane-air flames at two turbulence conditions were studied. LDV was used to obtain ensemble averaged measurements of velocity, turbulence intensity and integral time scale through the propagating flame. The integral length scale ahead of the flame was obtained both directly from a two-point spatial correlation measurement and indirectly using Taylor's hypothesis. In addition, laser planar imaging was used to obtain two-dimensional flame structure measurements which were processed with a fractal analysis.

Both the mean velocity and the turbulence were observed to change immediately ahead of the propagating flame. The mean velocity was found to decrease due to the unconfined nature

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of the flame and the turbulence intensity was found to increase due to the turbulence-flame interactions. Sudden increases in both the mean velocity and the turbulence intensity across the flame were observed, where the absolute increase in turbulence intensity was found to be approximately the same for both turbulence conditions. Similar results have been reported by other researchers. The integral time scale was observed to decrease ahead of the propagating flame but the changes behind the flame were inconsistent. The integral length scale obtained using Taylor's hypothesis was found to be significantly larger than that observed directly from the two-point spatial correlation measurements, indicating the importance of making direct length scale measurements in such flows.

The fractal analysis of the two-dimensional flame structure measurements indicate that the flame geometry is fractal, even at the low turbulence Reynolds numbers which were tested ($Re_L < 100$). Therefore, the flame geometry can be represented by a single parameter, the fractal dimension. The results also show that the fractal dimension appears to increase monotonically with increasing turbulence Reynolds numbers. This is a significant result in that it suggests the possibility of quantifying the effects of flame structure in turbulent flame propagation models.

Additional experiments are in progress or planned which include a broader range of turbulence conditions, lean and rich fuel-air mixtures, and measurements of integral length scale, turbulence energy spectrum, Reynolds stress and vorticity through the propagating flame front.

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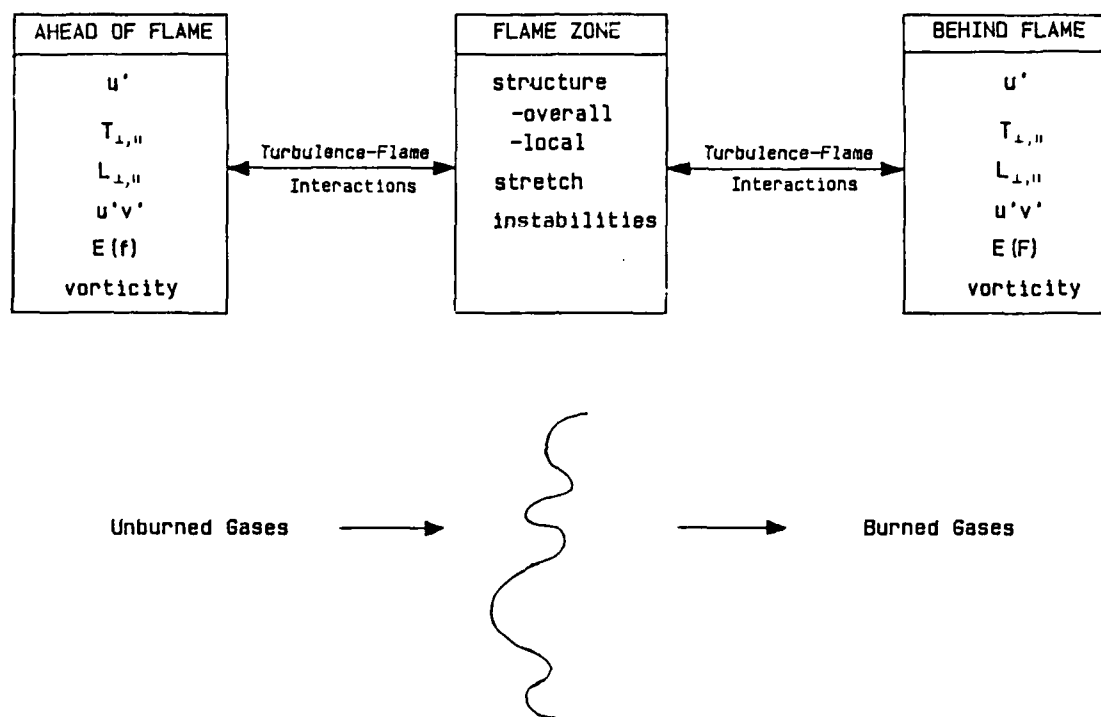| Accesion For		
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RESEARCH OBJECTIVES

The propagation rate of a premixed turbulent flame is determined by the complex interaction between the incident turbulent flow field and the turbulent flame front. The nature of this interaction and the relevant flow field parameters are illustrated schematically in Figure 1. The primary consequence of the turbulence-flame interactions is an increase in the flame area and a proportional increase in the burning rate, due to wrinkling of the laminar flame front. The local flame geometry, however, also affects the burning rate through variations in the local laminar flame speed caused by flame stretch effects. In addition to the direct effect of the incident turbulence on the burning rate through changes in the flame structure, the local velocity field produced by the flame itself alters the turbulence both ahead of and behind the flame, which in turn effects the flame structure and therefore the burning rate. Thus, a complete characterization and understanding of turbulence-flame interactions is essential for the formulation and validation of phenomenologically correct models of premixed turbulent flame propagation.

The objective of this research is to develop an improved understanding of turbulence-flame interactions and their effect on premixed turbulent flame propagation. More specifically, the objectives of this research are to experimentally characterize and, in turn, develop an improved understanding of the relationships between the incident turbulent flow field, the upstream and downstream generated turbulence, the turbulent flame structure, and the mass burning and flame propagation rates in premixed turbulent flames. The experiments are conducted in a turbulent flow reactor over a range of pressures, temperatures and turbulence conditions which include those encountered in practical combustion systems, such as gas turbine combustors. The mean velocity and turbulence are characterized both upstream and downstream of the propagating flame using laser Doppler velocimetry. This includes measurements of the turbulence intensity, time scale, length scale and energy spectrum, as well as Reynolds stress and vorticity. The turbulent flame structure is characterized using laser planar imaging techniques and processed using a fractal analysis.

Through interactions with other researchers, the results of this study will be used to develop improved and phenomenologically correct models of premixed turbulent flame propagation.

FIGURE 1. Turbulence - Flame Interactions

AHEAD OF FLAME	FLAME ZONE	BEHIND FLAME
u'	structure	u'
$T_{\perp,\parallel}$	-overall	$T_{\perp,\parallel}$
$L_{\perp,\parallel}$	-local	$L_{\perp,\parallel}$
$u'v'$	stretch	$u'v'$
$E(f)$	instabilities	$E(F)$
vorticity		vorticity

Turbulence-Flame Interactions

Turbulence-Flame Interactions

Unburned Gases ⟶ ⟶ Burned Gases

STATUS OF RESEARCH

During the past year experiments have been conducted in the pulsed-flame flow reactor shown schematically in Figure 2 for the case of atmospheric pressure, unconfined, propagating, one-dimensional premixed turbulent flames. In particular, stoichiometric propane-air flames have been studied over a range of turbulence Reynolds numbers. The measurements which have been made include ensemble averaged velocity, turbulence intensity and integral time scale as a function of time through the propagating flame. The integral length scale has also been measured in the cold flow upstream of the flame. In addition, two-dimensional flame structure measurements have been made and the resultant flame boundaries processed using a fractal analysis. The results of these measurements are presented and discussed below.

Measurements were made at two turbulence conditions which are defined in Table 1.

Table 1

Case 1: $u'/s_\ell = 0.26$ L = 3.7 mm

Case 2: $u'/s_\ell = 0.54$ L = 4.3 mm

The integral length scale, L, was obtained from the two-point spatial correlation measurements shown in Figure 3, where the integral scale is equal to the area under the spatial correlation curve. A value of 46 cm/sec was used for the laminar flame speed, s_ℓ, in stoichiometric propane-air.

A set of twelve two-dimensional flame structure measurements were obtained for each turbulence condition. The individual images were processed to define the flame boundary separating the burned and unburned gases. The flame boundary was then processed using a fractal analysis procedure suggested by Mandelbrot [1] and Sreenivasan [2] in order to obtain the fractal dimension. A typical two-dimensional flame boundary and the corresponding fractal analysis are shown in Figure 4. For all of the measurements, the fractal analysis yielded a linear curve. This indicates that the flame structures are self-similar which is a characteristic

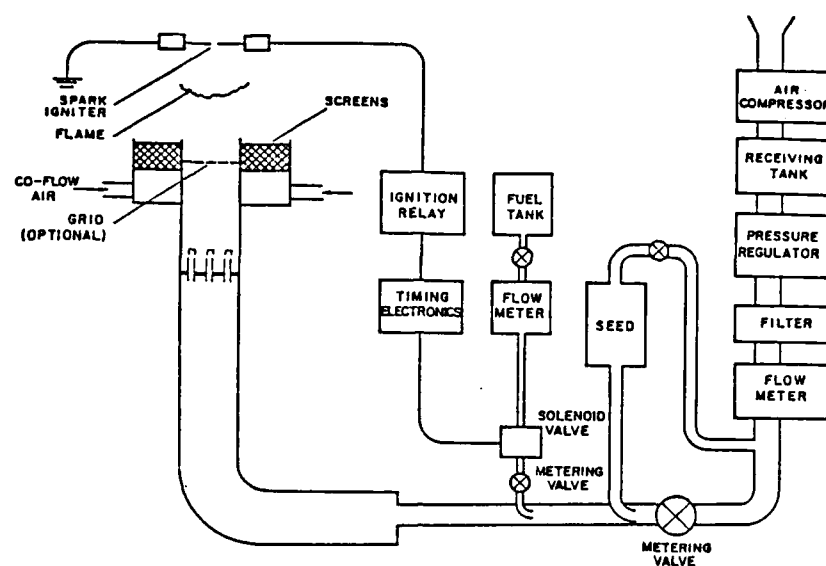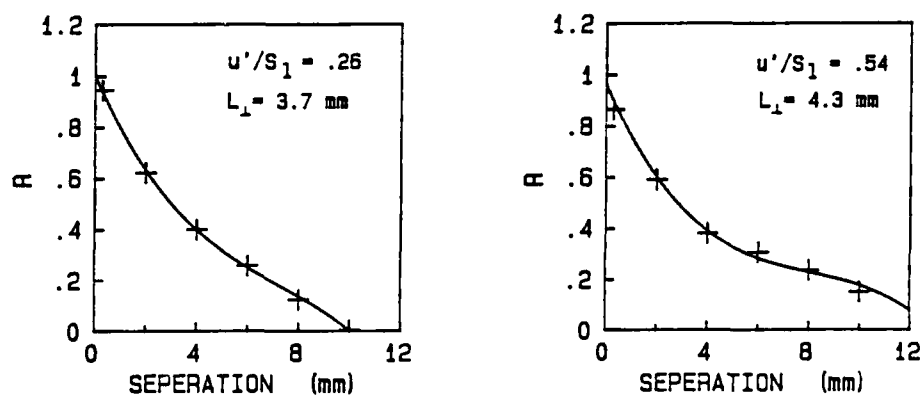FIGURE 2. Pulsed Flame Flow Reactor

FIGURE 3. Two-Point Spatial Correlation Measurements

of fractal geometries. For this particular method of fractal analysis the resultant fractal curve is defined by the following relationship,

$$A = 2 \epsilon^{3-D} L$$

where A is the area defined by all points which lie within a distance ϵ from the flame boundary, L is the length of the flame boundary for a given ϵ, and D is the fractal dimension. Therefore, the slope of a plot of log A versus log ϵ is equal to 3-D, which can then be used to determine the fractal dimension.

The fractal dimension was determined for each measurement as described above and then an average fractal dimension was calculated for each turbulence condition. This average fractal dimension is plotted versus an integral length scale based turbulence Reynolds number in Figure 5. Also shown are the fractal dimensions which were obtained previously for other turbulence conditions. The combined results show a monotonic increase in fractal dimension with increasing turbulence Reynolds number, where the line at D = 1.37 represents a high Reynolds number limit for the fractal dimension as proposed by a number of researchers [3,4]. These results are significant in that they clearly demonstrate, even at low turbulence Reynolds numbers, the fractal nature of premixed turbulent flame structures. They also suggest the existence of a functional dependence of fractal dimension on turbulence Reynolds number. Such a relationship would be important for developing a model of turbulent flame propagation which explicitly accounts for changes in flame structure.

The LDV velocity measurements are made at a fixed location as a function of time as the turbulent flame passes through the measurement location. Measurements are typically made over 400 or more flame events and the individual velocity time records are shifted to match flame arrival times. The shifted velocity-time records are then used to calculate the ensemble averaged velocity, turbulence intensity and temporal autocorrelation function as a function of time through the propagating flame.

The ensemble averaged velocity results are shown in Figure 6. Both cases show the expected sudden increase in velocity after flame arrival, however, the velocity increase is less

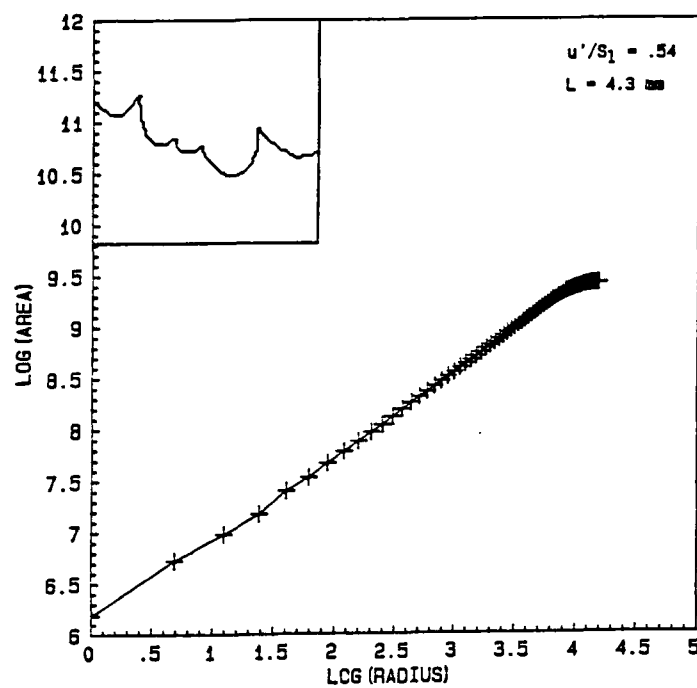FIGURE 4. Two-Dimensional Flame Boundary and Fractal Analysis

FIGURE 5. The Effect of Turbulence Reynolds Number on Fractal Dimension
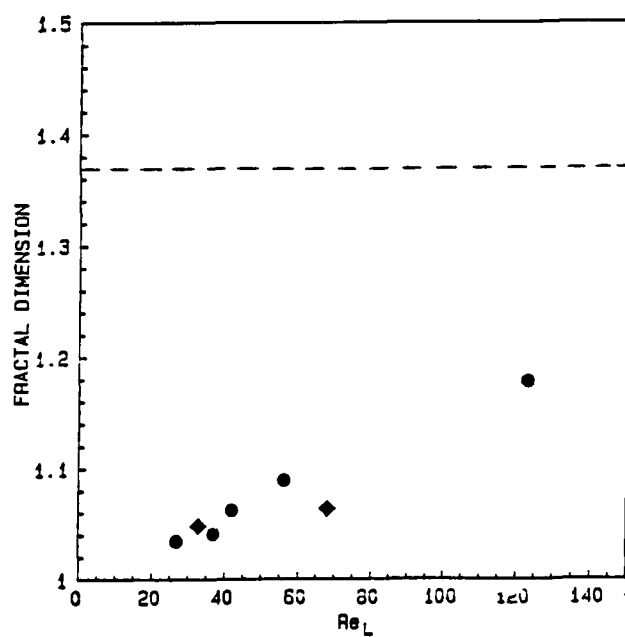
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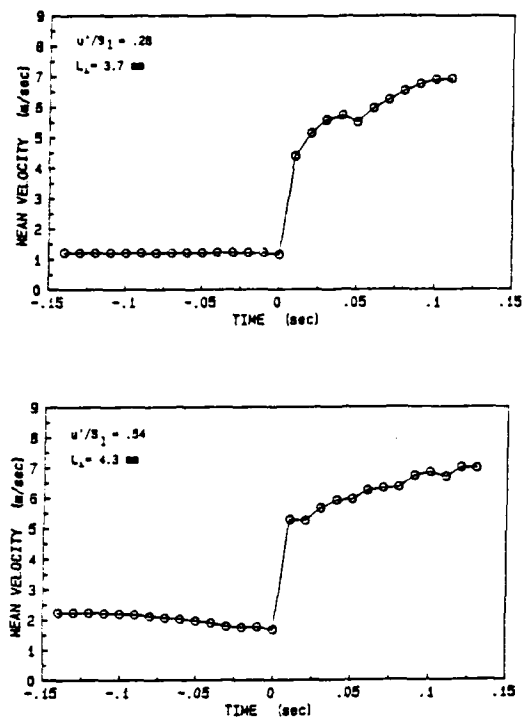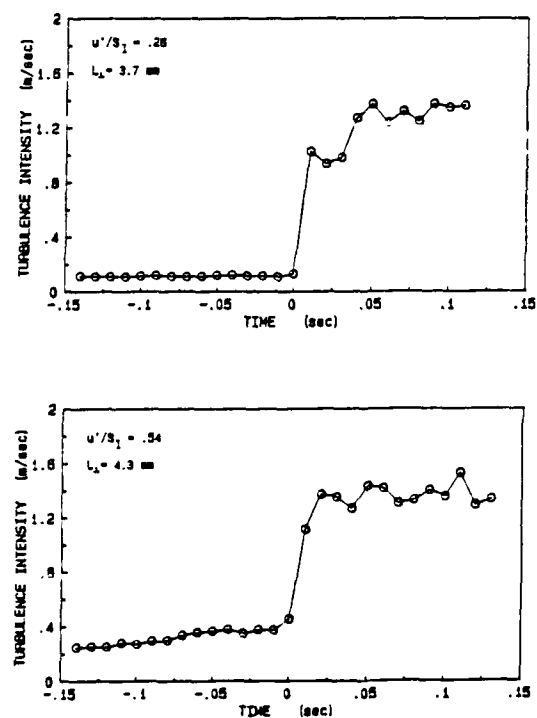FIGURE 6. Ensemble Averaged Velocity Measured Through Propagating Flame

FIGURE 7. Ensemble Averaged Turbulence Measured Through Propagating Flame

than one would expect due to the unconfined nature of the flame. Also, note that both flames show a slight decrease in the velocity ahead of the flame, where again this can be attributed to the fact that this is an unconfined flame. That the velocity decrease appears to start much earlier or further ahead of the higher turbulence intensity case flame is primarily due to the difference in the laboratory flame of reference propagation rates of the two flames. The higher turbulence intensity case flame propagated much more slowly which serves to "stretch" to time axis on these plots. Once the propagation velocity is accurately measured, it will be possible to convert this data from temporal to spatial profiles.

The ensemble averaged turbulence intensity results are shown in Figure 7. Again, the higher turbulence intensity case result can be thought of as having an expanded time axis due to its slower propagation velocity. Both flames show clear evidence of an increase in turbulence intensity ahead of the flame. This is more clearly resolved in the higher turbulence intensity case, where nearly a factor of two increase is observed. Flame arrival is indicated by the sudden increase in turbulence intensity. With respect to the upstream turbulence intensity, there is a tenfold and a fivefold increase in the low and high turbulence intensity cases, respectively. It is perhaps more relevant to note that the absolute change in turbulence intensity is approximately the same, i.e., 1 m/sec, in both cases. This is consistent with the limited amount of similar data which is available from other experiments [5,6].

The velocity-time data is also used to calculate the ensemble averaged temporal autocorrelation coefficient. A typical temporal autocorrelation curve is shown in Figure 8, where the area under the autocorrelation curve is equal to the integral time scale. In Figure 9, the integral time scale is plotted versus time through the propagating flame for both turbulence cases. In both cases, there is a decrease in the integral time scale immediately ahead of the flame, while behind the flame the time scale is observed to increase in one case and decrease in the other. Whether or not these results, particularly behind the flame, are meaningful will require additional measurements. Assuming that Taylor's hypothesis is valid in this flow, one can calculate the integral length scale from the integral time scale. The

FIGURE 8. Typical Ensemble Averaged Temporal Autocorrelation Coefficient Ahead of Flame
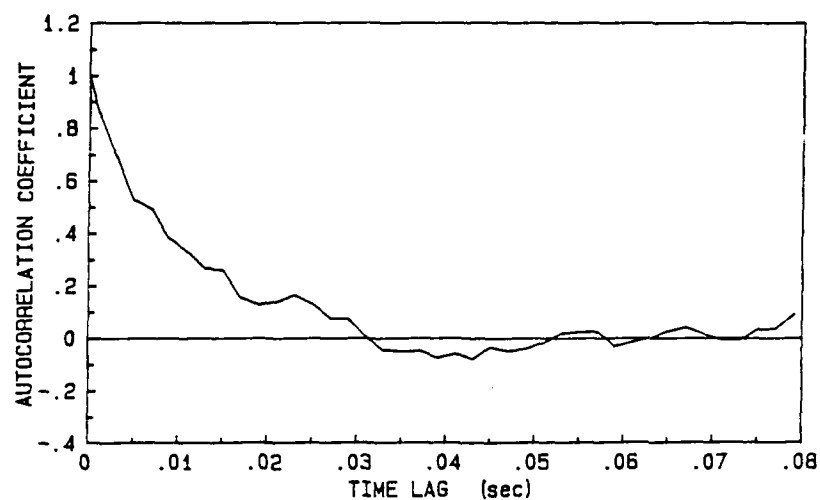

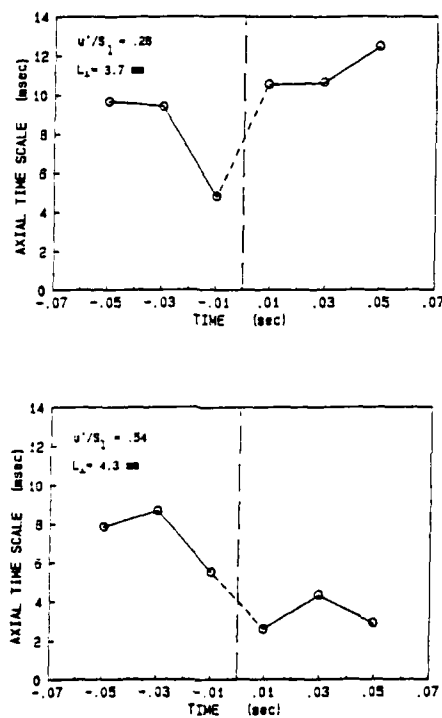FIGURE 9. Ensemble Averaged Integral Time Scale Measured Through Propagating Flame
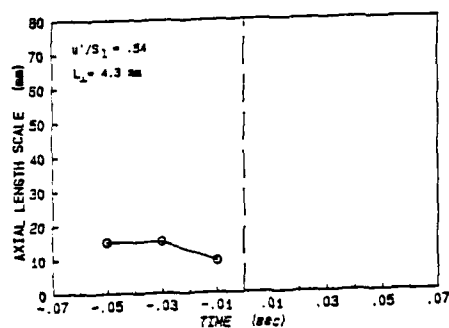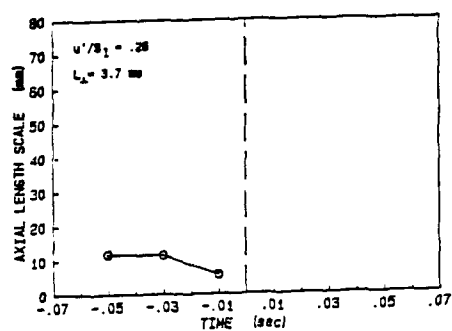
FIGURE 10. Ensemble Averaged Integral Length Scale Ahead of Flame Obtained
Using Taylor's Hypothesis

results obtained ahead of the flame are shown in Figure 10. If these are compared to the length scale measurements obtained from the two-part spatial correlation measurements, one finds that they differ by a factor of approximately three, which is not unexpected since the isotropic, homogeneous, equilibrium turbulence assumptions required for Taylor's hypothesis are not valid in this flow.

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3. Mandelbrot, B. B., J. Fluid Mech., 72:401-416, 1975.

4. Gouldin, F. C., Comb. and Flame, 68:249-266, 1987.

5. Driscoll, J. F. and Gulati, A. (1987), to appear in Comb. and Flame.

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PUBLICATIONS

The following publications are in preparation for submission to <u>Combustion and Flame</u>. It is expected that they will be submitted before April 1, 1988.

"Fractal Analysis of Premixed Turbulent Flame Structure," by G. L. North and D. A. Santavicca.

"Propagation of an Unconfined Premixed Turbulent Flame," by B. D. Videto and D. A. Santavicca.

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B. D. Videto, Graduate Student
C. A. Wilson, Graduate Student (M.S. Degree expected 6/88)
J. G. Zoeckler, Graduate Student (M.S. Degree expected 6/88)

INTERACTIONS

Results from this research were presented at the following meetings and workshops:

"Turbulence-Flame Interactions in an Unconfined, Premixed Turbulent Flame," B. D. Videto and D. A. Santavicca, presented at the Fall Meeting of the ESSCI, December 1987.

"Turbulent Flame Propagation," D. A. Santavicca, presented at the AFOSR Air-Breathing Propulsion Contractors Meeting, June 1987.

"Premixed Turbulent Flame Propagation," B. D. Videto, G. L. North, and D. A. Santavicca, presented at DOE sponsored DHC Meeting, April 1987.

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