Title

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EXPERIMENTAL STUDY OF COMBUSTION IN A TURBULENT BOUNDARY LAYER

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ABSTRACT

The effect of H_2-Air combustion on induced turbulence in a heated boundary layer has been studied through time and space resolved measurements of velocity (laser Doppler anemometry) and density (Rayleigh scattering). From these measurements mean, rms fluctuations, probability density functions and auto-correlations were obtained by digital processing. The experimental conditions covered equivalence ratio from 0 to 0.3, wall temperature between 1100 to 1300 K and free stream velocity from 14 to 22 m/sec. A typical Reynolds number based on the free stream velocity was 3×10^5. Three modes of combustion were indicated: 1) surface reaction, 2) surface reaction combined with gas phase reaction in the boundary layer, 3) flame-like structure situated at the edge of the boundary layer. Velocity fluctuations of about 4% in the non-heated boundary layer were reduced to 2% by wall heating. Density fluctuations of 8 to 10% were observed in the heated boundary layer both with and without combustion. The maximum density gradient region of the flame-like structure was found to fluctuate at a fairly regular rate of 0.5 to 1.25 Khz depending on various conditions.

NOMENCLATURE

x	distance along the wall
y	distance normal to the wall
u	stream-wise velocity component
v	cross-stream velocity component
ρ	density
T	temperature K
rms	root mean square
pdf	probability density function
$R_\rho(\tau)$	density auto-correlation function
τ	auto-correlation variable
w	wall condition
∞	free stream condition
'	fluctuation quantity
$\overline{}$	time averaged fluctuation quantity
ϕ	equivalence ratio

INTRODUCTION

The interaction of fluid mechanical turbulence with the combustion process is an important element of almost all practical combustion systems. The combustion intensity, the degree of completion of combustion, and the generation of gaseous pollutants are profoundly affected by the nature and degree of turbulence. Considerable progress has been recently made in numerically modelling turbulence, and the results have been applied to turbulent combustion with varying degrees of success. In order to assist in the formulation of suitable approximations for turbulent combustion, and to critically evaluate the results of these numerical models, laboratory scale experiments on suitable turbulent combustion geometries capable of detailed diagnostic studies are required. In the present work a heated flat plate boundary layer with induced turbulence in which premixed combustion can occur is being studied.

This classical geometry was chosen because of the extent of theoretical and experimental work dealing with laminar and turbulent boundary layers. A heated boundary layer is well suited for the study of combustion for it can support combustion under a wide range of equivalence ratios ranging from stoichiometric to very lean by proper control of the wall temperature and free stream velocity. The change in the scale and intensity of turbulence as a result of combustion heat release can be investigated over a much wider range of conditions than in conventional combustion systems such as flames. Furthermore, the combustion heat release can be adjusted to occur throughout the boundary layer permitting detailed study of the evolution of turbulence through each stage of the exothermic process.

Previously, a series of experimental and numerical studies have been carried out to determine the general features of combustion in a heated laminar boundary layer [1,2]. In these studies density and velocity profiles for H_2-Air combustion in a laminar boundary layer over a heated catalytic platinum surface for various wall and flow conditions were measured. The experimental results were compared with numerical results which solved the governing equations for these flows. These results have provided insights into the control of boundary layer combustion, thus establishing the necessary background to determine the boundary conditions for turbulent flow in this work.

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EXPERIMENTAL SYSTEM

The experimental configuration consists of a vertical, 2.5 cm square channel 7.5 cm in length, shown schematically in Fig. 1. The optical measurements are carried out in an open flow section beyond the end of the three unheated channel walls. One of the walls is lined with five heating elements, made of 125 μ thick Kanthal A-1 strips of various widths, to provide the heated boundary layer. These are mounted on a ceramic block and the current supplied to each heating element is controlled individually to give a uniform wall temperature along the channel. This heater arrangement provides wall temperatures approaching 1500 K. The surface temperature is measured using a disappearing filament optical pyrometer, assuming a surface emissivity of 0.75. The premixed fuel air mixture is supplied by a cylindrical stagnation chamber 20 cm in diameter with internal screens to suppress turbulence. The flow channel and the stagnation chamber are mounted on a three-dimensional stepping motor driven traverse mechanism with a 0.001 cm positioning sensitivity.

Three well developed laser diagnostic techniques are used. Differential interferometry provides a convenient means to display and study the density gradient patterns in the boundary layer, while the intensity of Rayleigh scattering gives the local gas density (and temperature since the pressure is constant throughout the boundary layer) and Laser Doppler Anemometry (LDA) gives the local velocity.

A Spectra Physics 4 watt argon-ion laser is used as the light source for all of the diagnostics. The setup of the interferometer is described in Ref. 3. An 18 mm focal length lens is used to expand the laser beam and a microscope slide is placed near the focus to generate interferometric fringes in the expanding beam. The beam is passed through the open flow section of the channel and the resulting interferogram can either be projected on a screen or recorded on Polaroid film.

For measuring Rayleigh scattering the laser beam is focused to 40 micron waist diameter by two lenses and the scattering is collected at 90° from the beam direction by an f/1.2, 55 mm focal length camera lens. A 10 nm band pass filter centered at 488 nm and an RCA 981A type photomultiplier are used to detect the light. The photomultiplier current is amplified by an electrometer with a bandpass of about 3 kHz.

The LDA system is of the intersecting dual-beam type with real fringes. An equal path length beam splitter with fixed separation of 5 cm is used, and the two laser beams are focussed by a 250 mm focal length lens to form the scattering volume. Seed particles are generated by a blast atomizer using silicone oil and are introduced into the air supply prior to the stagnation chamber. Scattering bursts from the particles are collected at 45° from the forward scattering direction by a lens, filter and photomultiplier assembly and the frequency of the bursts are obtained using a Thermal Systems 1090 frequency tracker.

A computerized data acquisition system based on a Digital Equipment Corporation PDP 11/10 computer has been developed to record the Rayleigh scattering signals from the electrometer and the processed LDA signals from the frequency tracker. The stepping motors and the three-axis traverse are computer controlled and thus scan flow field positions for Rayleigh and LDA measurements automatically. In a typical measurement sequence the diagnostics scan the boundary layer, calculate the mean and rms fluctuation values and display the results graphically on the terminal for monitoring the experiments. The Rayleigh signal was sampled at a constant rate of $5x10^3$ Hz, and 5000 samples were recorded at each flow field position. In the case of LDA the measurements were initiated by the signal validation pulses from the frequency tracker and the time intervals between measurements were obtained from a programmable clock. At each position 1000 samples of validated signals and time intervals were recorded. All the raw data were stored on disc memory files for post-processing. Fortran computer codes were written to read the stored data and to calculate probability and autocorrelation functions.

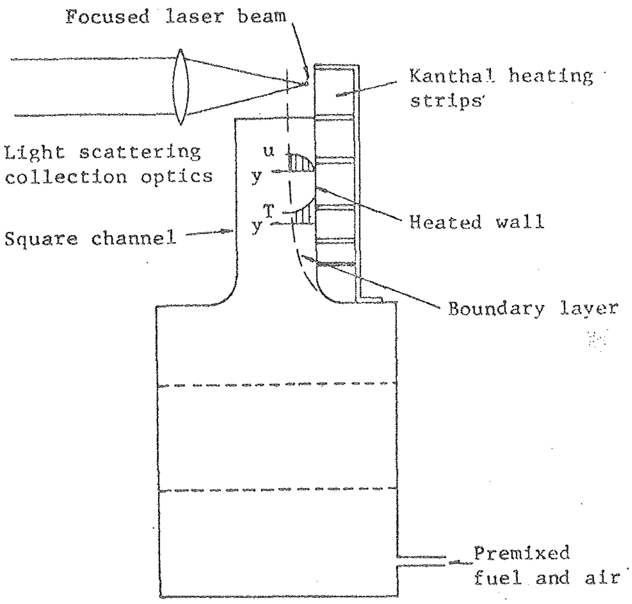

Fig. 1 Schematic of the 2.5 cm square channel

RESULTS AND DISCUSSION

The maximum free stream velocity obtained in the channel is about 20 m/sec, giving a Reynolds number at the exit of the channel of $3x10^5$, about the minimum necessary to sustain turbulent fluctuations in the boundary layer. Some preliminary studies of the flow field at the channel exit were carried out using hot wire anemometry, and indicated that the flow was quite uniform and had free stream rms velocity fluctuations less than 0.5%. Measurements within the boundary layer along the surface lined with the heating strips indicated rms velocity fluctuations of about 3%, normalized by the free stream velocity. These fluctuations were induced by the relatively uneven surface provided by the Kanthal heating strips.

The first set of heated wall experiments were performed using the differential interferometer in order to determine the conditions, i.e. free stream velocity, wall temperature and equivalence ratios, necessary for combustion reactions to occur in the heated boundary layer. Changes in the fringe pattern of the interferograms and variations in wall temperature as fuel was added to the flow were studied. Using H_2 as fuel with the wall temperature initially maintained at 1220 K, the free stream velocity was varied from 14 to 20 m/sec with equivalence ratio ranging from 0 to 0.3. In Fig. 2 three interferograms

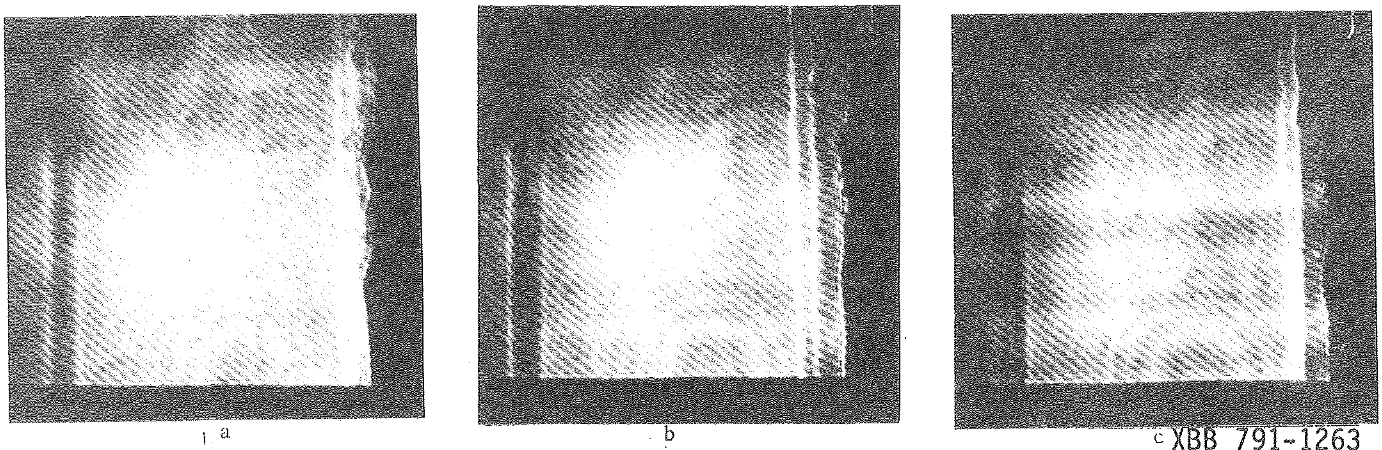

Fig. 2 Differential interferograms of heated boundary layer with or without combustion, $u_\infty = 18$ m/s (a) T = 1220 K, $\phi = 0.0$ (b) $T_W = 1300$ K, $\phi = 0.1$, (c) $T_W = 1335$ K, $\phi = 0.2$. Heated wall is shown at right.

of the heated boundary layer are shown, with and without combustion. In the case of no fuel, Fig. 2a, some eddies can be seen at the edge of the boundary layer. As fuel is added, 2b and 2c, the wall temperature and boundary layer thickness increased, indicating the occurrence of boundary layer combustion reactions, and it appears in both cases that the eddies in the boundary layer disappeared. What emerged in Fig. 2c seems to be two distinct regions of maximum gradient of index of refraction - the so-called schlieren positions. Since the fringes are discontinuous through the two schlieren positions, detailed analysis of the fringe displacements [2] could not be carried out. Further study of the boundary layer turbulence was carried out using Rayleigh scattering measurements.

Surface reactions, indicated by a slight increase in wall temperature without any significant change in the fringe pattern and boundary layer thickness, occurred at equivalence ratios as low as 0.05 for a free stream velocity of 18 m/sec. At higher equivalence ratios the wall temperature was increased by about 100 K and the thermal boundary layer significantly thickened due to more intense gas phase reactions in the boundary layer. Similar results were obtained at other free stream velocities; however, the equivalence ratio at which gas phase reactions would initiate seemed to vary with the flow velocity. This is in qualitative agreement with the results of similar studies [2] on combustion in a laminar boundary layer.

LDA measurements were made in non-heated as well as heated boundary layers at 1 cm above the open flow section with free stream velocities from 14 to 22 m/sec and wall temperatures of 300 K and 1220 K. Measurements in the heated boundary layer with H_2-Air combustion were also attempted. Under normal operating conditions the LDA system provided an average data validation rate of approximately 400 counts/sec in the free stream, decreasing to 100 counts/sec within the boundary layer. Even though the average count rate is rather low, a histogram of the sample time intervals at various positions indicated that over 30% of the sample time intervals were less than 10^{-3} sec. The LDA indicated about 3% rms velocity fluctuation in the free stream where the hot wire anemometer gave only about 0.5%. The LDA measurements apparently are affected by "instrumental noise" resulting from the imperfections of the Doppler bursts and the inability of the tracker to interpret these Doppler bursts as velocities. This "LDA instrumental noise" appeared to be uncorrelated with the mean velocity, and thus the LDA rms fluctuations were corrected by subtracting a constant mean square instrumental noise. This instrumental noise was determined by demanding agreement between hot wire and LDA turbulence measurements in the free stream.

LDA measurements near the heated wall could not be obtained due to the disappearance of the particles in this region. This was partially due to the thermophoretic force on the particles in a temperature gradient, resulting in significant motion of the particles towards the colder free stream. The behavior of this particle free region in a heated laminar boundary layer under various flow and wall conditions has been reported [4], and the thickness of the particle free region was found to scale with the hydrodynamic boundary layer thickness with a ratio of approximately 0.5. However, in the present situation the additional effect of evaporation of the silicon oil droplets is also responsible for the disappearance of the particles. Metal oxide particles will be used

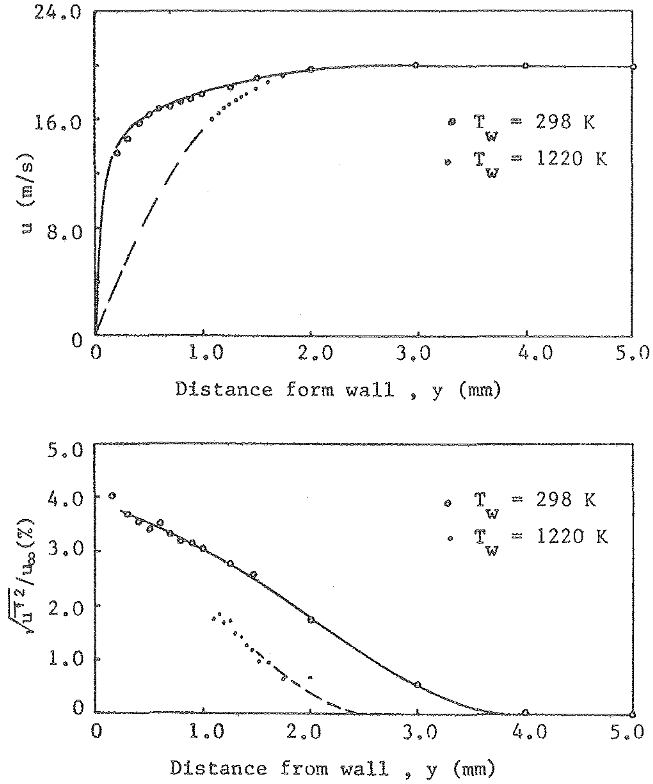

Fig. 3 Velocity, u, and rms fluctuation, $\sqrt{u'^2}$, profiles in non-heated and heated boundary layers.

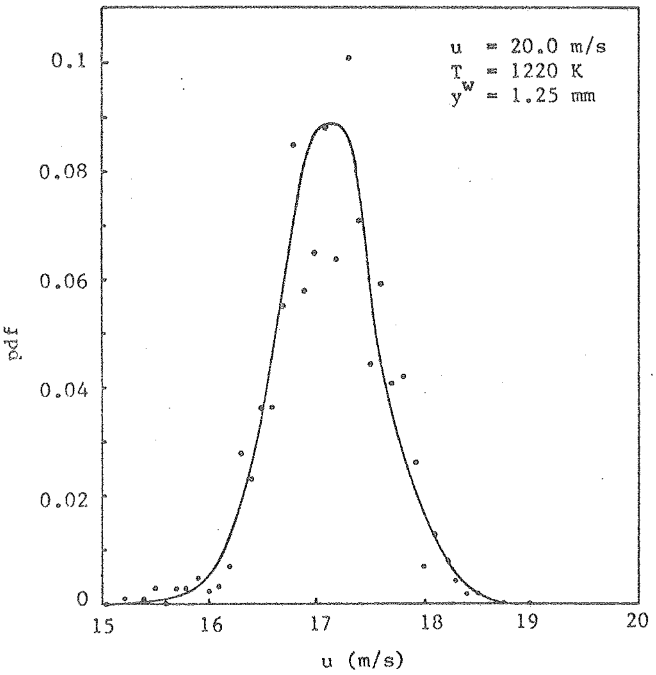

Fig. 4 Velocity probability density function, pdf, in a heated boundary layer, $y = 1.25$ mm.

in future experiments to eliminate the effect of evaporation, but the thermophoretic migration of particles will still remain as a major obstacle to turbulence measurements, near hot surfaces.

Mean and rms fluctuation profiles for boundary layers with and without wall heating are shown in Fig. 3. The non-heated mean boundary layer profiles obtained with various free stream velocities were compared with both a fully developed turbulent boundary layer profile as well as a Blasius laminar boundary profile. These profiles seem to be self-similar over the velocity range investigated and closely resemble that for a fully developed boundary layer. The distribution of fluctuation intensity within the boundary layer also appears to be in fairly good agreement with what has been observed in a turbulent boundary layer [5]. However, due to the low flow Reynolds number, the fluctuations are primarily driven by the flow over the uneven surface and cannot be regarded as typical for a turbulent boundary layer.

The effect of wall heating on the velocity boundary layer is quite apparent. For the purpose of comparison, the boundary layer profiles were arbitrarily extrapolated from the last data point obtained at the edge of the particle free region to the wall. These profiles appear to approach the shape of a laminar boundary layer; in addition, the thickness of the boundary layer is increased and the fluctuation level is decreased. The apparent stabilizing effect of the wall heating can be rationalized by the significant increase of the kinematic viscosity throughout most of the boundary layer.

Probability density functions of the velocity for various locations within non-heated and heated boundary layers were obtained. The example shown in Fig. 4 is the one for the heated boundary layer shown in Fig. 3 at $y = 1.25$ mm. All the velocity pdf's appeared to be quite symmetrical and uniform in shape. Unfortunately, measurements made in the heated boundary layer, especially with combustion, failed to produce data throughout the boundary layer due to thermophoretic motion and evaporation of the silicon oil droplets.

Rayleigh scattering measurements of density were carried out in a set of experiments with a constant free stream velocity of 20 m/sec. The heated wall temperatures were adjusted to 1120, 1220 and 1320 K while the equivalence ratio of the flow was varied from 0 to 0.2. The results obtained show that the existence of combustion in the boundary layer depends on mixture composition and wall temperature. Mean and rms fluctuation profiles obtained with $T_W = 1220$ K are shown in Fig. 5. For a heated boundary layer with no fuel, $\phi = 0$, the mean profiles are self similar. Under very lean conditions, $\phi \sim 0.05$, a slight increase of the boundary layer thickness occurs, indicating the presence of some surface reaction and gas phase reactions. However, the effect on the boundary layer profiles are small and the shape of the mean profile remains similar to that for $\phi = 0.0$. At higher equivalence ratio as shown in the results for $\phi = 0.1$, increased gas phase reactions are sufficient to significantly heat up and thicken the boundary layer. The boundary layer profile under this conditions is not similar to those of the previous cases. In the case of $\phi = 0.2$ more intense combustion takes place and the zone of heat release appears to move outside of the velocity boundary layer and rather resembles that of a flame front.

The peak rms fluctuation intensities were found to be around 10% for all cases. As shown in Fig. 5b, the maximum fluctuation intensity seems to occur near the point of maximum density gradient and does not appear to be strongly dependent on the thermodynamic or combustion parameters. Although the distribution of the fluctuation intensity is altered by the presence of combustion, no other apparent change was

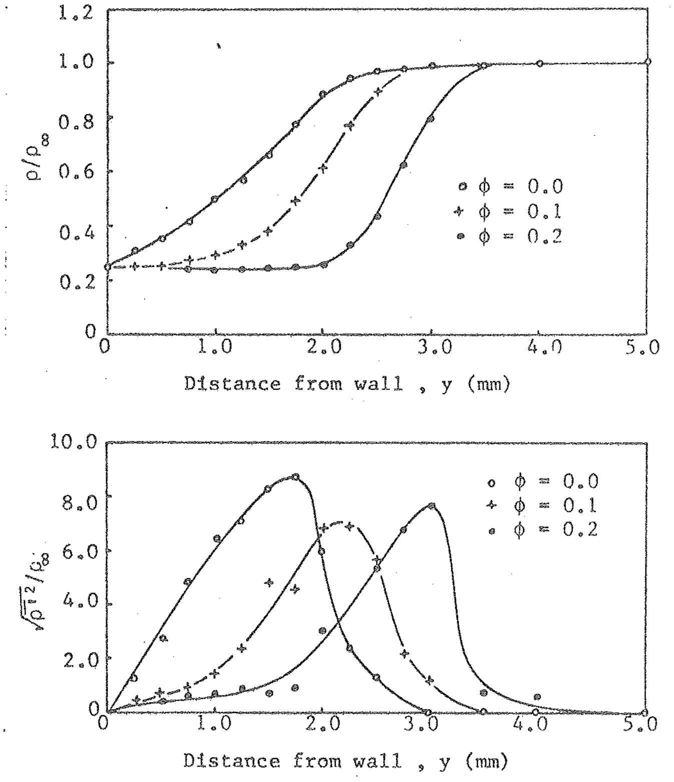

Fig. 5 Density, ρ, and rms fluctuation, $\sqrt{\overline{\rho'^2}}$, profiles in heated boundary layer with and without combustion, $T_w = 1220$ K, $u_\infty = 20.0$ m/s.

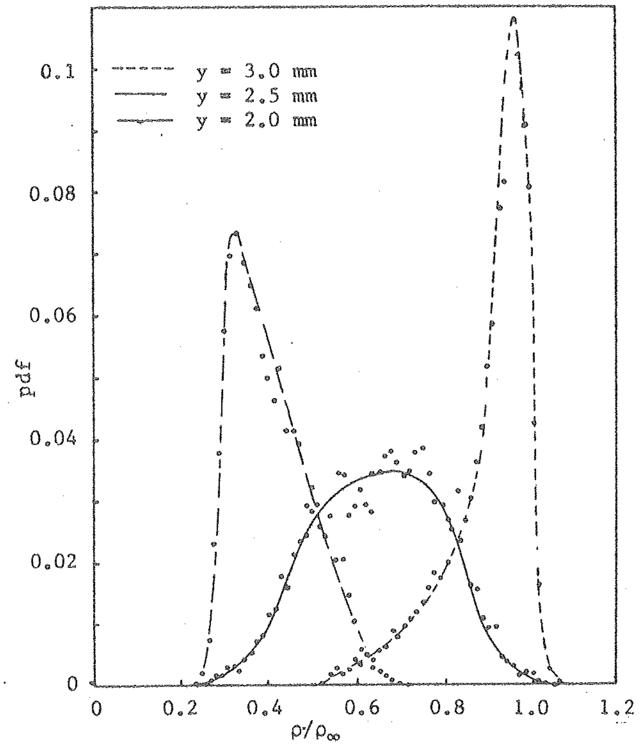

Fig. 6 Density probability density function at three positions in a heated boundary layer with combustion, T_W = 1120 K, u_∞ = 20.0 m/s.

observed.

Since satisfactory velocity measurements in combustion cases were not made, limited comparison of the density and velocity profiles could only be carried out for the heated boundary layer. Comparison of the velocity and density profiles shown in Figs. 3 and 5 shows that the corresponding velocity fluctuation level at the point of maximum density fluctuation is only about 1%, significantly less than the 8.5% density fluctuation. The large density fluctuations may be associated with velocity fluctuations in the y direction, for the density gradient in the heated boundary layer is primarily in the same direction.

The density pdf's for three points along the heat release zone of the flame-like structure of T_W = 1120 K, ϕ = 0.2, are shown in Fig. 6, where the location y = 2.5 mm corresponds to the point of maximum density gradient and the ones at 2.0 and 3.0 mm are located respectively at the edges of the hot and cold regions. The pdf for y = 2.5 mm is quite symmetrical and extends almost from the cold to the hot region. As to be expected, the density pdf at the other two locations are skewed. The high probability for hot and cold gases to penetrate into the y = 2.5 mm location seems to indicate that the whole reaction zone might be oscillating, if one assumes that the oscillation is primarily in the y-direction.

In order to further understand the nature of the density fluctuations, the auto-correlation function $R_\rho(\tau) = \overline{\rho'(t)\rho'(t+\tau)}/\overline{\rho'^2}$ for the data obtained at 2.5 mm was evaluated. The result is shown in Fig. 7. The periodicity of the function is quite apparent and this indicates that the reaction zone oscillated at a fairly regular rate of about 500 Hz. This could explain the two well defined schlieren positions

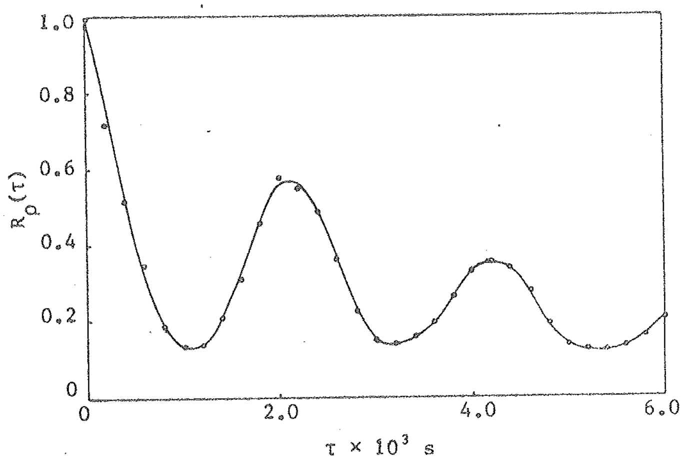

Fig. 7 Density auto-correlation function at the maximum fluctuation intensity point inside a heated boundary layer with combustion, T_W = 1120 K, u_∞ = 20.0 m/s.

shown in Fig. 1c, for within the exposure time 1/250 s, the reaction zone would have oscillated for several cycles forming the two schlieren positions on the record. The distance between the two schlieren positions is then indicative of the spatial variation of the reaction front position. Since two schlieren positions showed up on the interferograms taken at other conditions, several auto-correlation functions at the maximum fluctuation point for other conditions were evaluated. Periodicity was found in most of the auto-correlation functions, frequencies of which varied from 0.5 to 1.25 kHz. Whether the reaction zone fluctuates as a sheet or propagates at a characteristic velocity downstream is not known at this time.

SUMMARY AND CONCLUSIONS

Some features of combustion in a heated boundary layer with induced turbulence have been studied by the use of three laser diagnostic techniques. The convenience of using the differential interferometer as a tool for general survey of the gradient of density field was demonstrated, and the conditions where detailed velocity and density measurements were carried out were based on the results of the interferometric study. The use of LDV in the heated boundary layer has some serious complications due to the thermophoretic motion of the seed particles; however, measurements made at the edge of the heated boundary layer did provide some insight into the effect of wall heating on velocity fluctuations. The time and space resolved measurement of density using Rayleigh scattering was quite satisfactory. Besides giving detailed mean density profiles, statistical analysis of the data provided considerable insight into the nature of the density fluctuations.

The overall effect of combustion heat release on the boundary layer profiles was found to be similar to that observed in laminar boundary layers. The existence of combustion in the boundary layer depends on mixture composition, wall temperature and velocity, among other parameters. In the range of conditions studied, limited wall reaction was observed at an equivalence ratio of 0.05 and a flame-like structure occurred at an equivalence ratio of 0.2. Typically, velocity fluctuations were about 4% in the non-heated boundary layer and were reduced to about 2% when the wall was heated to 1200 K. Density fluctuations of

8-10% were observed in the heated boundary layer cases. The maximum fluctuation intensity appeared to be independent of the degree of combustion, and occurred near the position of maximum density gradient. Similarly, the probability density function did not show much dependence on the degree of combustion. However, the density auto-correlation function, obtained at the maximum fluctuation intensity point of the flame-like structure, showed fairly regular periodic structure in the range from 0.5 to 1.25 Khz. Such periodicity was not evident when there was no combustion.

ACKNOWLEDGEMENT

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