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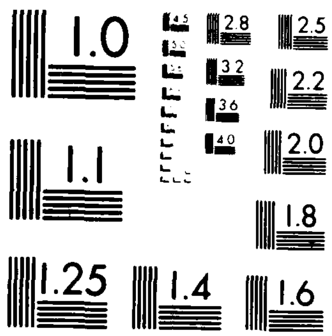
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A comprehensive investigation has been carried out of the structure and statistical properties of unconfined turbulent flames, both V-shaped and conical. Measurement techniques included conditioned velocity measurements using two component LDV, flow visualization techniques, and Rayleigh scattering. Additionally, a new time-resolved technique, LARS (Linear Array for Rayleigh Scattering) was developed which makes possible the determination of the instantaneous location of the flame sheet within the turbulent flame brush. A major objective of these flame studies was to assess the appropriateness of models such as the Bray-Moss-Libby (BLM) model for describing the structure of planar turbulent combustion zones.

The results of these investigations have revealed that many of the predictions of the BML model accord reasonably well with experimental observations, although some of the constants chosen in the theory are not verified experimentally. Agreement is better for

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the V-shaped planar flame than for the conical flame, particularly in the vicinity of the flame tip. Flamelet passage frequencies, which are directly related to the spatial distribution of heat release in the turbulent flame brush, are better described by a gamma-two probability density distribution than by an exponential one, both of which have been employed in the BML analysis. Conditioned LDV and LARS measurements of Reynolds stresses and flame fluctuation amplitudes reveal that much of the apparent increase in velocity fluctuations ascribed to flame generated turbulence is due to flame motion, which itself seems to be controlled by the incident turbulence in the oncoming flow. Increase in heat release for a given inlet turbulence level results in an increase in the amplitude of the flame fluctuations without modifying their spectral characteristics, although dilatation effects in the products downshift the frequencies of the most energetic eddies.

Studies of the flame stabilization region in the wake of flameholders showed evidence of vortex shedding in the wake and of diminished fluctuation intensity with increased heat release. It was also observed that reaction in the shear layer bounding the recirculating products does not occur until a finite distance downstream of the flameholder. This observation is confirmed by CH fluorescence imaging of the flame region.

AFOSR-TR- 88-0270

FINAL REPORT

AFOSR GRANT 84-0124

Application of Rayleigh Scattering to Turbulent Flow with Heat Transfer and Combustion

Principal Investigator: L. Talbot

University of California, Berkeley

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RESEARCH OBJECTIVE

The objective of this research program has been to investigate experimentally the fluid-mechanical properties of premixed turbulent flames, by means of detailed local measurements of velocity and density and by flow visualization techniques, with the goal of determining the detailed structure of what in the large is described as a turbulent flame brush, and to what extent this structure can be described theoretically by models such as the Bray-Moss-Libby (BML) model. The combustion configurations investigated have been an unconfined V-shaped rod-stabilized flame propagating into a turbulent, essentially uniform flowfield, and a premixed conical flame produced by a Bunsen-type burner. For the most part, ethylene-air flames were chosen for the investigations.

RESEARCH RESULTS

The results of the investigations carried out under the subject grant are described in the following papers.

1. Hertzberg, J.R., Namazian, M., and Talbot, L., "A Laser Tomographic Study of a Laminar Flame in a Karman Vortex Street". Combustion Science and Technology 38, 205-216, 1984.

   Abstract - An optical study of the interaction of a laminar, premixed, rod stabilized flame and a Karman vortex street has been performed. The technique used was laser tomography, in which the unburned gases are seeded with a silicone oil spray and then illuminated with a sheet of laser light. The oil spray evaporates and disappears in passing through the flame, making possible the high speed cinematography of the structure of the flame sheet.

   The wavelength and frequency of the perturbed flame motion is found to correspond closely to that of the vortex street, allowing a simple phenomenological explanation of the cyclic behavior of the flame.

2. Cheng, R.K., and Shepherd, I.G., "Interpretation of Conditional Statistics in Open Oblique Premixed Turbulent Flames". Combustion

Science and Technology 49, 17-40, 1986.

Abstract - A consistent means to establish the flame coordinate for oblique premixed turbulent flames based on the use of conditioned statistics of two velocity components is described. The flame coordinate is used to transform the conditioned velocity data for comparison with the predictions of the Bray-Moss-Libby (BML) model of turbulent combustion, assess the modeling assumptions and calculate one of the empirical constants. The most significant change in the flame statistics after transformation is that the Reynolds stress is found to be at the same level as in the incident flow. The Favre averaged turbulence intensities and scalar transport derived from experimental measurements are in qualitative agreement with previously reported experimental and numerical results. The results also support the BML second order closure technique for the third order covariances. However, the values of the empirical constant computed from experimental data do not lend strong support to a sub-model for the change in the conditioned statistics.

3. Cheng, R.K., and Shepherd, I.G., "Intermittency and Conditional Velocities in Premixed Conical Turbulent Flames". Combustion Science and Technology 52, 353-375, 1987.

Abstract - A turbulent premixed ethylene/air conical flame in a large Bunsen type burner has been studied using a two-component laser Doppler anemometry (LDA) system. The unconditioned velocity statistics were measured using aluminium oxide particles. Conditioned reactant velocity statistics were measured using silicon oil aerosol, which evaporated and burned through the flame fronts, as the LDA seed. In addition, the intermittency was determined by monitoring the Mie scattering intensity from the aerosol. The intermittency data were the key to the generalized conditional analysis method which we have developed for deducing the conditioned product velocities. This method involves deconvolution of the intermittency weighted velocity probability density function (pdf). In the oblique flame region above the burner exit, the overall characteristics of the conditioned velocity statistics are similar to those observed previously in oblique V-flames. The relative velocity between product and reactant, ΔU , within the oblique region of the Bunsen flame is comparable to the velocity change across a laminar flame. The only difference is that peaks in the unconditioned rms velocity profiles are not found. Along the centerline, ΔU reduces to almost zero. The unconditioned and conditioned covariance (Reynolds stress) are negligibly small throughout the flame. Since the flame brush is almost parallel to the burner axis, this result is consistent with the covariances for the V-flames after the data was transformed with respect to the flame coordinate. The changes in the velocity statistics along the flame brush is in qualitatively agreement with a kinematic model of flame/turbulence interaction. Quantitative validation of this model

would require measurements of the instantaneous flame front orientations.

4. Shepherd, I.G., Hubbard, G.L., and Talbot, L., "The Dynamic Structure of Turbulent V-Shaped Premixed Flames". Proceedings 21st Symposium (International) on Combustion, Munich, 1986 (in press).

Abstract - A new technique, LARS (Linear Array for Rayleigh Scattering), for the investigation of the dynamic structure of premixed turbulent flames is described. The Rayleigh light scattered from a segment of a continuous laser beam is imaged, through an intensifier, onto a 512 element linear photo-diode array. The array is scanned at line rates up to 10 KHz and 2560 lines can be stored in a dual ported memory. The space-time images produced are manipulated by an image processor which normalizes the data and can perform a variety of image enhancement techniques.

Methane/air premixed turbulent v-shaped flames at an approach velocity of 2 m/s and a range of inlet turbulence levels and equivalence ratios from 5%-8% and 0.6-0.8 respectively were studied. The statistics of the flame front position were obtained by extracting the flame boundary from the images and generating a pdf of its distance from the mean. The standard deviation of these distributions varied from 0.31mm-1.38mm and show that increases in inlet turbulence and equivalence ratio thicken the turbulent flame zone by amplifying the flame motions. These results lend support to various modeling assumptions. Comparison of the spectra of the flame front oscillations and the cold flow velocity indicate that the incident turbulence controls flame motion at frequencies between 100 and 1000 Hz. Changes in heat release for a given inlet turbulence increase the amplitude of the flame fluctuations without modifying the spectral characteristics.

5. Gokalp, I., Shepherd, I.G., and Cheng, R.K., "Spectral Behavior of Velocity Fluctuations in Premixed Turbulent Flames". Accepted for publication in Combustion and Flame.

Abstract - Spectral characteristics of two ethylene/air premixed turbulent v-flames have been studied. The velocity measurements were made using a single component laser Doppler anemometry system, and the velocity spectra for the velocity components 30^{o} to the normal of the flame were deduced. Also deduced were the spectral distribution in wave-number space, the integral time and length scales. The spectra show that the influences of the turbulent flames on spectral behavior do not seem to correlate strongly with the turbulence Reynolds number. This lack of correlation suggests that the passage frequencies of the wrinkled turbulent flame front may be important for the interpretation of the velocity spectra. The wave-

number spectra show clearly the shifting of the energy containing eddies to lower frequencies in the product zone. This shifting to lower frequencies is consistent with the dilatation effect due to the increase in temperature and viscosity. The dilatation effects are apparent in the integral length scales profiles. However, the integral time scale is relatively constant within the flame brush.

6. Shepherd, I.G., and Cheng, R.K., "An Experimental Evaluation of the BML Model of the Scalar Field in Turbulent Premixed Flames". Accepted for publication in Combustion Science and Technology.

Abstract - An experimental evaluation of the BLM model of the scalar field in premixed turbulent flames is presented. Experimental measurements of probability density functions (pdfs) of the flame passage times, autocorrelations and spectra were made in open v-shaped and stagnation point flames by monitoring the Mie scattering of a laser beam by a dense oil aerosol which evaporates on passage through a flame front. These results are compared with predictions derived from the model using 'a priori' pdfs: the exponential and gamma two distributions. The product pdfs are self similar and well described by the gamma two distribution. The reactant pdfs are also self similar but are better represented by the exponential distribution except at small passage times. Comparisons between experimental and theoretical autocorrelations show the gamma two predictions to be more successful. The modeling of the low frequency region of the scalar spectra is also improved. Calculations of the integral time scale based on measured crossing frequencies using the gamma two model lead to significantly improved agreement with experimental values. The predicted distribution of the integral time scale which entailed further modeling is, however, in conflict with the experimental results. The two flame geometries give substantially the same results.

7. Hertzberg, J.R., "Stabilization of an Unconfined Flame by a Bluff Body", PhD Thesis, University of California, Berkeley, 1986.

Abstract - A detailed study of the velocity and density fields of an ethylene-air V-shaped flame in an open jet (50 mm diameter) wind tunnel with grid generated turbulence has been made. Two velocity components were measured simultaneously using Laser Doppler Anemometry. Point measurements of gas density were made non-intrusively using laser Rayleigh scattering. The development of the leading edge of the flame sheet was analyzed with an ionization probe. Two flameholders were used with different wake characteristics in order to investigate the effect of turbulence in the shear layer on the flame. A bar of rectangular cross section provided a fixed separation point and a highly turbulent wake. A rod stabilized flame was studied for comparison. Two equivalence ratios

were studied: a lean flame at equivalence ratio 0.63 and a very lean flame at 0.54 which is close to the blowoff limit. This allowed analysis of the change in fluid mechanics as blowoff was approached.

Only the richer flame stabilized on the bar showed evidence of vortices shed in the wake. These did not, however, perturb the flame. Near the flameholder the density and velocity probability density functions have monomodal distributions but further downstream these evolve into the bimodal shape characteristic of wrinkled laminar flames. This was found to be a useful stabilization criterion when comparing the various flames. The very lean flames have an increased recirculation zone length and higher turbulence in the wake compared to the richer flames implying that blowoff is related to these instabilities. In addition the leaner bar stabilized flame had a thicker ignition region indicating that the higher turbulence disrupted the initial flame formation region.

In addition to the above studies, an extensive series of flow visualization studies were carried out for the configurations and flow conditions employed in the investigations described in Ref. 7. These studies, carried out at the Livermore Combustion Research Facility of Sandia Corporation, exploited the laser-induced fluorescence of the CH radical within the flame sheet. As is known, the CH radical is extremely short-lived, and is present only within the reaction layer itself, and thus provides an excellent 'marker' for the reaction zone. Thus it is possible, using CH fluorescence, to distinguish the reaction zone from heated but as yet unreacted regions of the flow, both of which would appear essentially the same in Rayleigh scattering measurements. These CH fluorescence measurements are currently being analyzed, and first indications are that they are consistent with the conclusions reached in Ref. 7 concerning the extent of the ignition region preceding the formation in the flameholder wake of a well-defined flame sheet.

PRESENTATIONS

"Density Fluctuations in Premixed Turbulent Flames, by M. Namazian, L. Talbot and F. Robben. Presented at Twentieth Symposium (International) on Combustion, Ann Arbor, Michigan, August 1984.

"Characterization of Density Fluctuations in Turbulent Premixed Flames", by M. Namazian, I.G. Shepherd ad L. Talbot. Presented at the Western States Meeting, The Combustion Institute, Stanford, CA, October 22, 1984.

"Intermittency and Auditional Velocities in Premixed Conical Turbulent Flames", by R.K. Cheng and I.G. Shepherd. Presented at the Western State Spring Meeting of the Combustion Institute, April 21, 1985, San Antonio, Texas.

"Stabilization of an Unconfined Turbulent Flame by a Bluff Body", by J.R. Hertzberg and L. Talbot. Paper presented at the 21st International Symposium on Combustion, Munich, W. Germany, Aug. 3-8, 1986.

"The Dynamic Structure of Turbulent V-Shaped Premixed Flames", by I.G. Shepherd, G.L. Hubbard and L. Talbot. Paper presented at the 21st International Symposium on Combustion, Munich, West Germany, Aug. 3-8, 1986.

"Structure and Propagation of Turbulent Premixed Flames Stabilized in a Stagnation Flow", by P. Cho, C.K. Law, J.R. Hertzberg and R.K. Cheng. Presented at the 21st International Symposium on Combustion, Munich, W. Germany, Aug. 3-8, 1986.

COLLABORATIONS

Over the period of this grant, we have maintained an ongoing mutual working relationship with the Combustion Research Group of the University of California Lawrence Berkeley Laboratory directed by Dr. R.K. Cheng. This relationship has proved extremely beneficial to both the AFOSR program and the LBL-DOE program, in that the sharing of facilities and instrumentation has made possible the carrying out of experiments and the processing of data which neither group separately had the resources to accomplish. We have also collaborated with individuals at the Sandia Combustion Research Facility, Livermore, CA, in particular with Drs. M. Namazian and R. Schefer, with respect to the CH flame imaging work which has been described earlier. This work could not have been accomplished without the use of the unique, high power CO_2 laser system available at Sandia.

We have also collaborated with a number of individuals in respect to both our theoretical and experimental work. Chief among these collaborations has been that with Professor Paul Libby of U.C. San Diego and Professor K.N.C. Bray of Cambridge University, U.K. Our sharing of ideas and results has stimulated them to continue to refine their theoretical (BML) premixed flame model, and at the same time suggest to us new experiments which could test the predictions of their model. We also maintain close contact with the combustion group at U.C. Davis, in particular Professor C.K. Law, and have in part carried out a joint experiment on stagnation point flames designed to provide less ambiguous data on turbulent flame speed. We also have developed and maintained good working relationships with several combustion groups in France. Dr. I. Gokalp of CNRS, Orleans, has been a frequent visitor to our laboratory, and one of our papers (Ref.5) is the result of joint work by ourselves and Dr. Gokalp. This work was also presented as a poster session at Munich.

PERSONNEL

Personnel supported by the Grant during the period 4-1-84 through 9-30-87 were

Professor L. Talbot	Principal Investigator
Dr. Ian G. Shepherd	Research Engineer
Dr. Jean R. Hertzberg	Graduate Student

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