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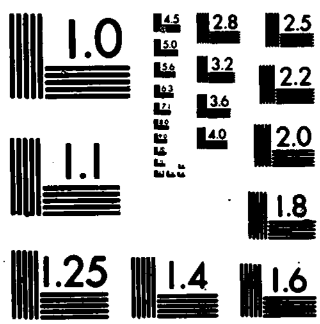

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COHERENT STRUCTURES IN TURBULENT FLAMES, II

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18. Supplementary Notes

19. Key Words

Combustion, Turbulence, Instrumentation, Coherent Structures, Eddies, Fuel Sprays, Laser Anemometry

20. Abstract

The aim of this investigation is to obtain increased understanding of turbulent combustion in flows related to propulsion systems. Simultaneous measurements of fluctuating velocity, temperature and local ionization level, have been made with arrays of probes, with variation in probe separations and flame initial conditions. The stored data are processed in a variety of ways, including the use of novel conditional sampling techniques. Information is thus derived on turbulent structure, eddy structure, eddy convection, eddy-reaction interaction, reaction zone structure and mixing. It is demonstrated that individually eddies can exist in flames for substantially longer distances than is apparent from classical space-time cross correlations. Similar techniques are also used in turbulent sprays and in a flame impinging on a flat plate.

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(b) Research Objectives and Work Statement

The principal objective is to obtain increased understanding of turbulent combustion in flows related to propulsion systems. The specific approach of this study is to quantify the roles of large eddies (coherent structures) in these flows and establish their relation to interface burning regions, residence times, macro- and micro-mixing and droplet vaporisation and burning in fuel sprays. This requires precise measurement techniques with good temporal and spatial resolution and advanced data analysis techniques for processing time histories simultaneously acquired from several probes in a flame. In the initial part of this investigation emphasis was placed on the development of these measurement techniques: laser anemometry, light scattering, miniature thermocouples, ionization probes and high-speed cine photography using laser schlieren or interferometry. The experiments concentrate on axisymmetric gas flames. The techniques are also applied to turbulent fuel sprays, in work jointly funded by NASA and SRC (UK).

This investigation is designed to provide data which can be utilised by modellers of turbulent combustion.

These data include the essential initial and boundary conditions of the flows, length and velocity scales of the turbulence, eddy convection velocities and life times, spreading rates and the statistical properties of fluctuating velocity, temperature and ionization level (related to the local reaction rate). The most original aim of this investigation is the application of new data analysis techniques to process time histories of the various fluctuating quantities, to educe detailed measurements of eddy and reaction zone structure, variation and interaction with movement downstream. To achieve this, the research program uses modified forms of novel conditional sampling and flow visualization techniques which were previously developed to measure large eddies (coherent structures) in cold non-reacting turbulent flow. We summarise below statements of the proposed work during this investigation:

(i) To develop high resolution measurement techniques for turbulent flames and sprays and to develop data acquisition, logging and processing techniques for the simultaneous acquisition of data from several probes, measuring the same or different quantities. Specific techniques are, laser anemometry (velocity), miniature thermocouples (temperature), ionization probes (local reaction rate), light scattering (conserved scalar or droplet sizes and velocities), beam deflection (gas density) and high speed cine (eddy characteristics).

(ii) To apply conditional sampling and cross-correlation techniques to measure coherent structures (large eddies) in turbulent flames by analysing data from the probes above. To conduct these measurements in a range of positions and in a range of flames with systematic variation in initial conditions.

(iii) To map mean quantities and the statistics of fluctuating quantities in the same flames.

(iv) To relate high speed flow visualisations with the results of probe measurements to thus aid understanding of the 'physics' of the flows.

(v) To apply these techniques to turbulent sprays, in addition to gaseous flames, and thus deduce information on eddy-droplet interaction.

(vi) To relate this measurement program to computer modelling investigations by the interaction with modelling groups.

(c) Status of Research Effort

1. Turbulent Flame Structure

The laser anemometer, thermocouple, ionization probe, beam deflection and flow visualization techniques have been developed, tested and are now in use. An LSI-11 minicomputer system, with floppy discs, teletype and xy plotter, has been built up. A wide range of preamplifiers, multiplexes and analogue/digital converters and other electronic modules, has now been built. During the latter part of this reporting period, the complete probes-interfaces-data acquisition/processing system has been fully commissioned. There has thus been an intensive period of data acquisition in the gas flames with a wide range of probe combinations, positions and flames studied. This period is being followed by a period of data analysis. Each digitally stored time history can be processed in several ways and various conditional sampling criteria can be applied to select different features of the flows for investigation. A further program of measurements will then follow, planned in the light of the first set of data.

Measurements which have been accomplished in the past year include:

1.1 Single Probe measurements of mean, r.m.s., spectra, autocorrelations and probability density functions of velocity, temperature and ionization levels in flames with systematic variation in flow rates and mixture ratios. Parts of this work have been reported by the authors in Ref. 5. Other parts are reported in Ref. 3 and a separate paper, including measurement of flame length and transition distance as a function of initial conditions, is in preparation for submission to a scientific journal.

1.2 High Speed Cine Films have been analysed to measure eddy sizes, passing frequencies and convection velocities. Initial results were reported in Ref. 5.

1.3 Multiple Probe Data: these measurements form the most original feature of this investigation and reveal the most important information on eddy structure and eddy-combustion interaction. Listed below are measurements which have been made, often in a range of different flames and also, in some cases, in non-burning flows for comparison. At the time of writing, analysis of all of these data has not been completed. The data are stored digitally on 'floppy discs' and also in analogue form on half-inch magnetic tapes. Certain measurements of cross-correlations were also made in real time by using a Hewlett Packard correlator.

(a) Two Ionization Probes. For variation in positions and separations in different flames, signals have been analysed to give space-time cross-correlations and conditional sampling techniques are being used to educe the structures and movements of the reaction zones. Figure 1 shows cross-correlation data with streamwise probe separation (Ref. 3).

(b) 'Single Point" Simultaneous Measurements by L.D.A., Thermocouple and Ionization Probe. Three probes have been positioned within 1 mm of each other and data have been acquired for radial traverses of two flames.

(c) Simultaneous 'Single Point ' L.D.A. and Thermocouple Measurements. The thermocouple was positioned within 200 microns of the L.D.A. measurement volume and traverses have been made in a range of flames. As can be seen from Figure 2, a clear correlation between velocity and temperature is seen in many positions.

(d) Simultaneous Thermocouple and Ionization Probe Measurements. Data have been acquired for radial traverses of various flames.

(e) Thermocouple Arrays. Temperature time histories have been acquired simultaneously from eight thermocouples equally separated in the streamwise direction. This array has been used in several positions in four different flames. As can be seen in Figure 3, the signals clearly show the retention of eddy coherence. This coherence is not obvious from cross-correlations, which have low amplitudes. Measurements are in progress with radial probe arrays.

(f) Resistance Probe Arrays. In collaboration with Dr. John LaRue (San Diego) "cold" jets, from the same burner, have been investigated by temperature 'tagging' the primary flow to give a temperature difference of approximately 10°C. Intermittency-type conditional sampling analyses are being applied to stored data from resistance probe arrays with azimuthal, radial and streamwise probe separations.

2. Turbulent Sprays

Work has continued in the measurements of spray vaporization and burning (Refs. 4, 7 and 8). A novel 'laser tomographic' technique has been developed to transform line-of-sight integrated light scattering data from laser beam scans to give point measurements of droplet size distributions and volume concentrations (jointly with SRC and NASA).

3. Impinging Flames

The techniques which have been developed in the AFOSR supported flame experiment are also being applied to study the structures of flames impinging on a flat plate (Ref. 9). This work is supported by the U.S. Army European Office.

4. Computer Model

A time-stepping computer model has been further developed to predict the transitional flame near the burner nozzle. The model has been improved by using a triangular grid and a finite element approach. Cold flow predictions show agreement with stability analyses for the initial vortex roll-up. Combustion is now being included.

(d) List of Publications

Refereed Papers

1. Yule, A. J., Laser Doppler technology. *Proceedings of Analytical Division of the Chemical Society (London)*, 16, 3, 105-6 (1979).

2. Yule, A. J., Phase scrambling effects and turbulence data analysis. Volume of selected papers from *2nd Int. Symp. on Turbulent Shear Flows* (F. Durst *et al.*, Eds.), 263-281, Springer-Verlag, Heidelberg (1980).

3. Ventura, J. M. P., Suzuki, T., Yule, A. J., Ralph, S. and Chigier, N. A., The investigation of time dependent flame structure by ionisation probes. *18th Symp. (Int.) on Combustion*, University of Waterloo, Canada, August 1980. Proceedings to be published by Combustion Institute, Pittsburgh.

4. Yule, A. J., Ah Seng, C., Felton, P. G., Ungut, A. and Chigier, N. A., A laser tomographic investigation of liquid fuel sprays. *18th Symp. (Int.) on Combustion*, University of Waterloo, Canada, August 1980. Proceedings to be published by Combustion Institute, Pittsburgh.

Reports and Conference Papers

5. Yule, A. J., Chigier, N. A., Ralph, S., Boulderstone, R. and Ventura, J., Combustion-transition interaction in a jet flame. *Paper AIAA-80-0077*, presented at AIAA 18th Aerospace Sciences Meeting, Pasadena, California, January 1980. Also submitted to *AIAA J. Energy*.

6. Yule, A. J., Investigations of eddy coherence in jet flows. *Proceedings of Int. Conf. on the Role of Coherent Structures in Modelling Turbulence and Mixing*, Madrid, June 1980 (Jiminez, Ed.), Springer-Verlag (1980).

7. Yule, A. J., Ah Seng, C., Felton, P. G., Ungut, A. and Chigier, N. A., Measurement of fuel spray vaporisation by laser techniques. *Proceedings of Symposium on Long and Short Range Optical Velocity Measurements*, German-French Research Institute, ISL, Saint Louis, 15-18 September 1980 (H-J. Pfeifer, Ed.).

8. Yule, A. J., Ah Seng, C., Boulderstone, R., Ungut, A., Felton, P. G., and Chigier, N. A., Detailed investigation of a vaporising fuel spray. Part I: Experimental investigation of time averaged spray. *Internal memorandum CARL-IM-80-3*, Combustion Aerodynamics Research Laboratory, Department of Chemical Engineering and Fuel Technology, University of Sheffield (July 1980). (Submitted to NASA-Lewis as a Contractor's Report; also to be submitted to *Combustion and Flame*).

9. Yule, A. J. and Chigier, N. A., Break up of vortex rings in impinging turbulent jet flames. *Annual Technical Report to European Research Office of U.S. Army, Grant No. DA-ERO-79-0031.*

10. Heywood, J. B., Fay, J. A. and Chigier, N. A., Air pollution from aircraft. *NASA CR-159712*, NASA-Lewis Research Center, Cleveland (October 1979).

(e) List of the Professional Personnel Associated with the Research Effort

Dr. N. A. Chigier: Principal Investigator

Dr. A. J. Yule: Co-Investigator and Research Fellow supported by AFOSR contract

Contributions have been made by:

Dr. A. Ungut: Research Fellow
Mr. P. G. Felton: Research Fellow

In addition six graduate students are involved in the turbulent flame and turbulent spray experimental programs.

Mr. Takuji Suzuki of Ibaraki University in Japan made a 12 month visit to the Laboratory (August 1979 - August 1980). He co-operated in a program of ionisation probe measurements in the AFOSR-supported turbulent flame experiment.

Dr. John LaRue of the University of California, San Diego, spent three weeks in the Laboratory co-operating in a program of conditional sampling measurements in flames and cold jets.

(f) Interactions

(1) Spoken Papers Presented at Meetings and Seminars (8/1/79 - 8/1/80)

Dr. Chigier and Dr. Yule presented papers at meetings in Madrid (Spain), Waterloo (Canada), and Pasadena (California). These papers are also published (see attached publications list).

Dr. Chigier has given talks at the SQUID Contractors Meeting (Los Angeles, California), General Motors Research Laboratories (Warren, Michigan), the U.S. Army Combustion Workshop (Imperial College, London), the Royal Institute of Technology (Stockholm, Sweden), Volvo (Göteborg, Sweden), Renault (France), PSA-Peugeot Citroen (France) and Volkswagen (W. Germany).

Dr. Yule gave an invited talk on light scattering techniques at the University of Karlsruhe (W, Germany) on 3rd June, 1980.

(2) Consultative and Advisory Functions to Other Laboratories

During his visits to give talks at the SQUID Contractors Meeting and to the other bodies mentioned above, Dr. Chigier also acted in an advisory capacity.

Dr. Yule visited NASA Ames (AVRADCOM) in January (Dr. T. Leonard and Dr. McCrosky). Discussions were held regarding turbulence structure, instrument techniques and tomography.

In the U.K. Dr. Chigier and Dr. Yule have been consulted by many governmental and industrial concerns. In the area of sprays and particle laden flows there has been considerable interaction throughout the year with the U.K. Central Electricity Generating Board (Drs.J. Horrocks and C. J. Lawn), British Gas (Dr. Borrill), Pilkington Brothers Ltd. (Mr. J. S. Thomas).

(g) New Discoveries, Inventions and Specific Applications Stemming from the Research Effort

A completely new light scattering technique has been developed for characterising turbulent fuel sprays. This was reported at the 1980 Symposium of the Combustion Institute and has resulted in wide interest. This 'laser tomography' technique transforms line-of-sight light scattering data from laser beams into point measurements of fuel droplet sizes and concentration.

Our new multiprobe flame measurements have shown that individual eddies can exist from the burner nozzle up to at least halfway down the flame. Previously eddies were generally assumed to form and break up in distances comparable with the local flow length scale.

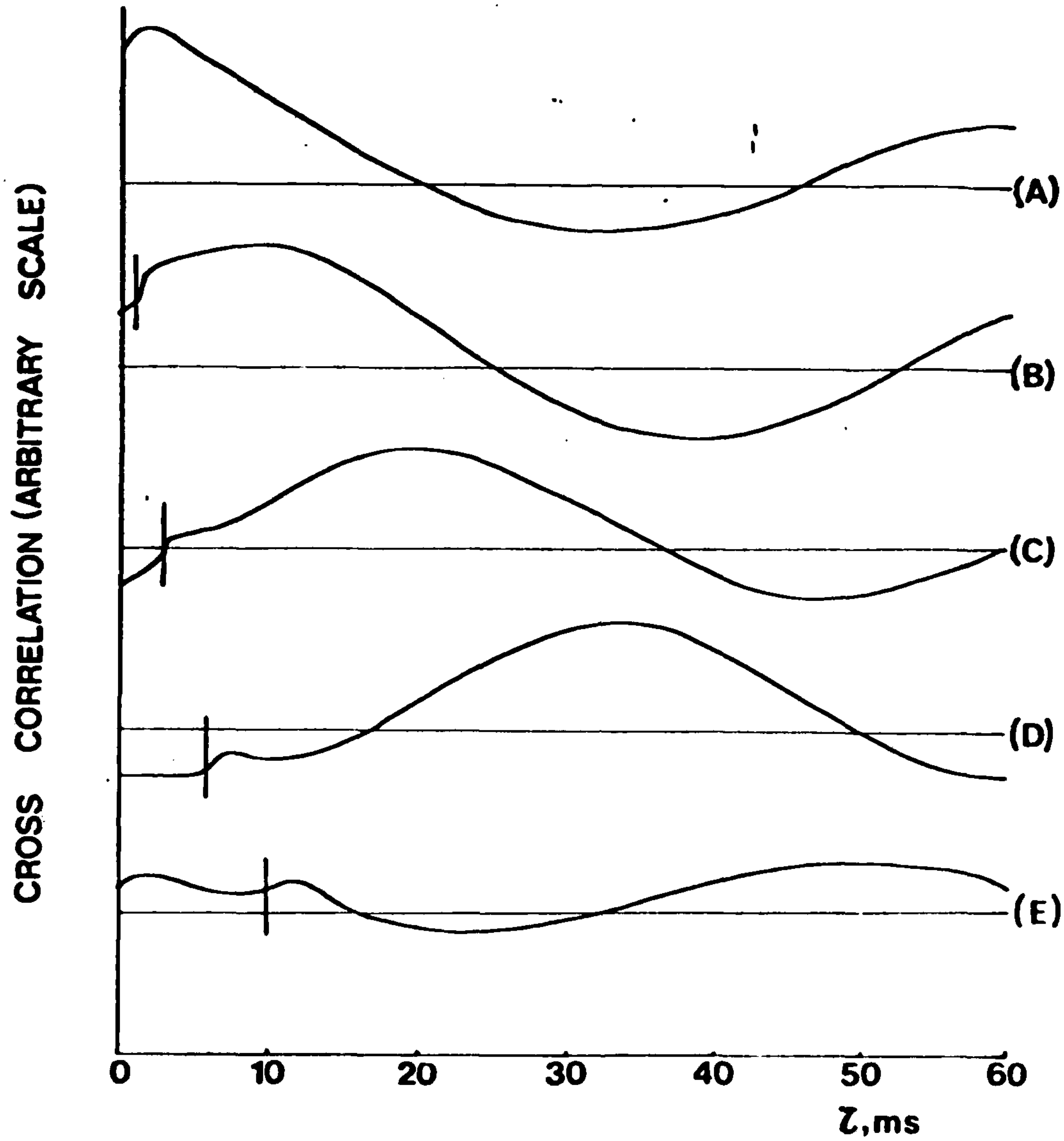

FIG. 1 Cross-correlations with variation in streamwise probe separation. $Re = 1.5 \times 10^4$; $\phi = 2.62$; $r/D = 0.5$; axial position (fixed probe) $x/D = 4$; probe separation: (A) 5 mm; (B) 15 mm; (C) 30 mm; (D) 50 mm; (E) 80 mm.

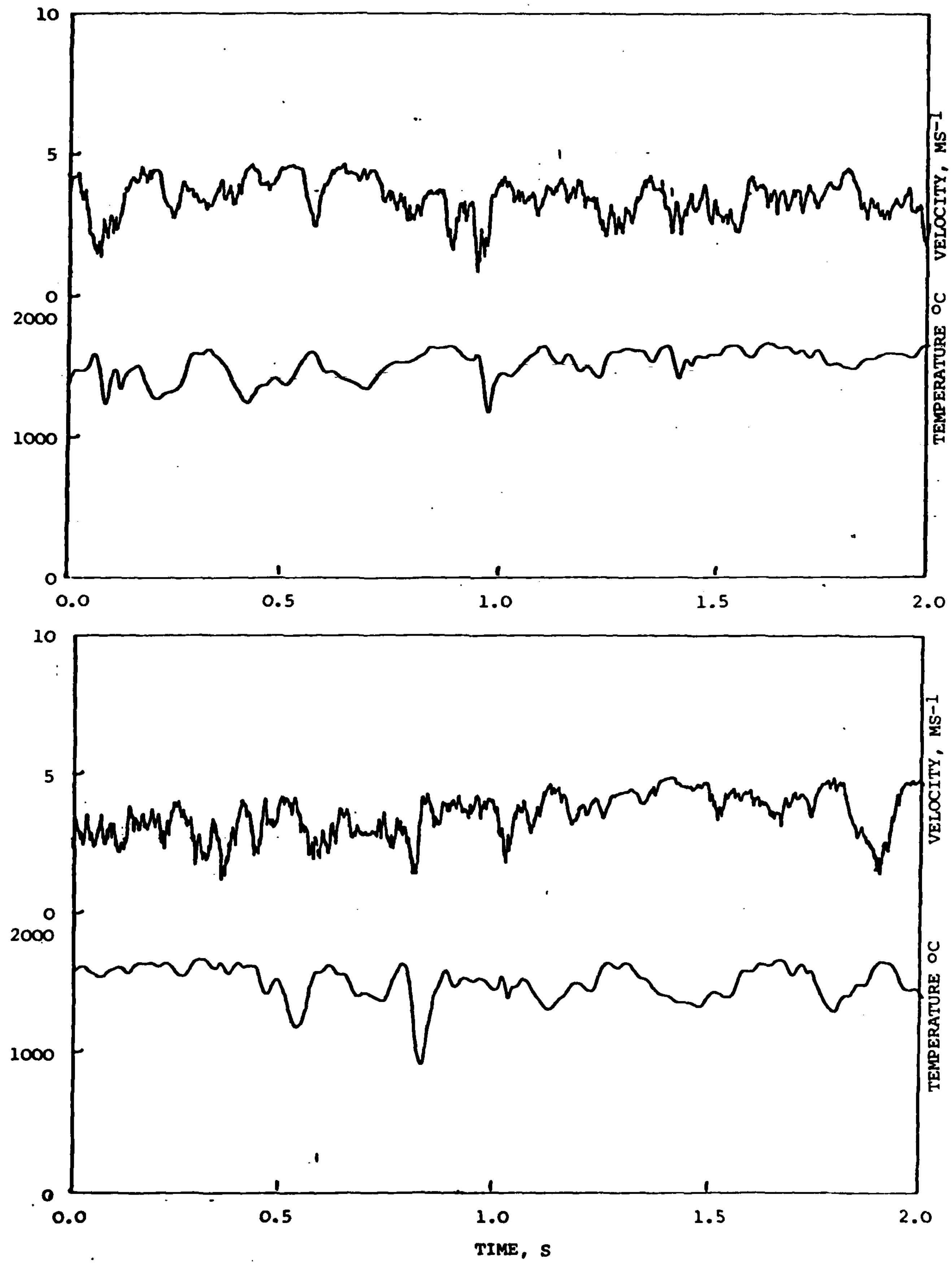

FIG. 2 Simultaneous time histories of velocity and temperature in propane flame, Re = 5000, Equivalence Ratio = 10.5, $x/D = 4$, $r/D = 0.63$.

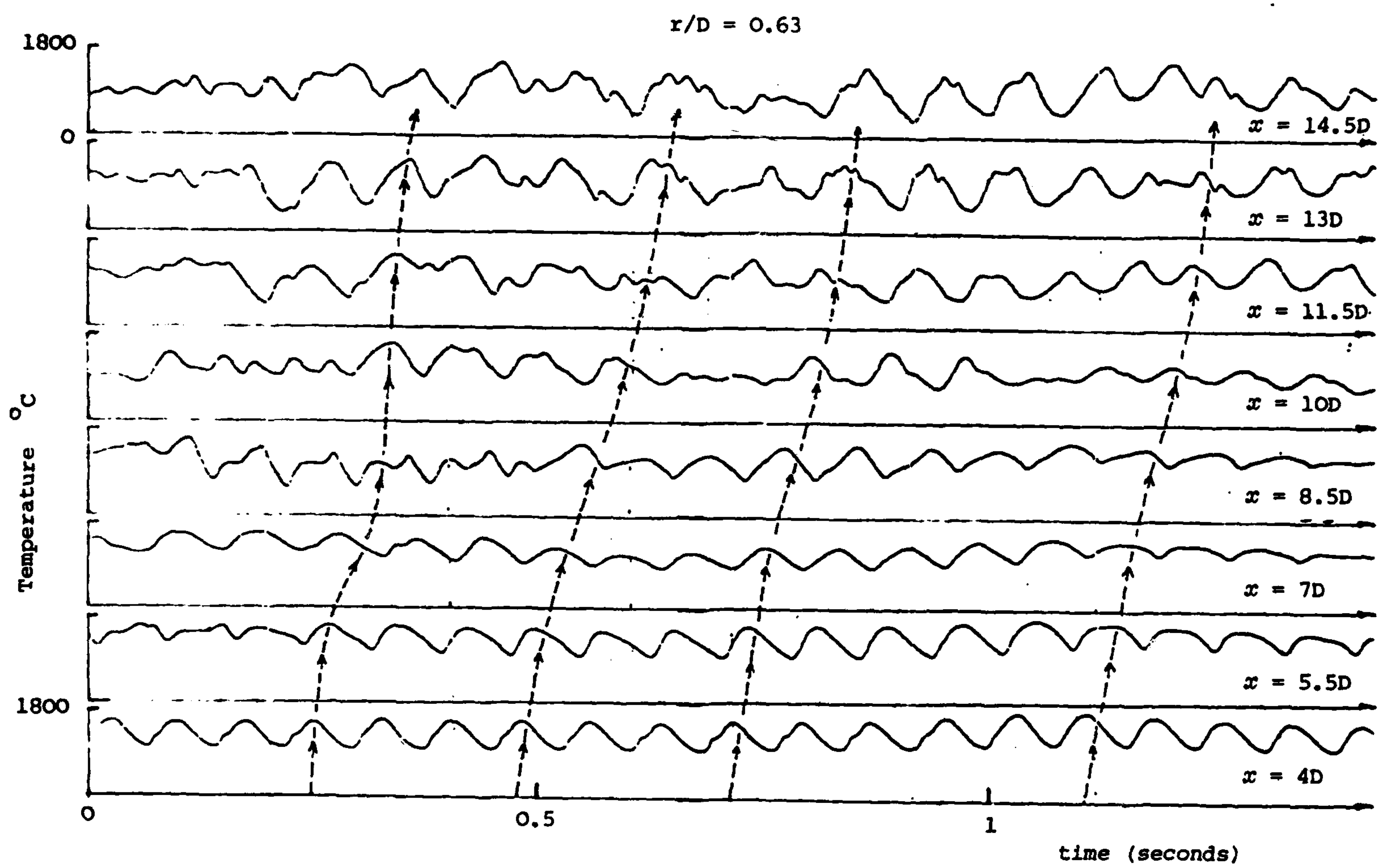

FIG. 3 *Simultaneous fluctuating temperature measurements in jet flame, r = 0.71D*