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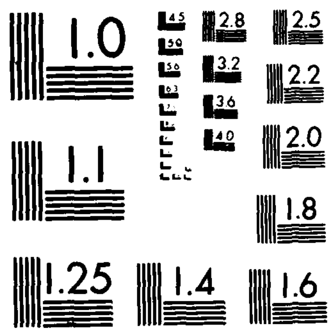

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AN INVESTIGATION OF FLOW STRUCTURE, MIXING AND CHEMICAL REACTION IN COMBUSTING TURBULENT FLOWS

Annual Technical Report

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An experimental investigation of the relationship between flow structure and chemical reaction structure in a combusting turbulent flow has been initiated. The objective is to study the spatial structure of the unsteady reaction process as it relates to the unsteady velocity field. The configuration chosen for study is a co-flowing, non-premixed jet flame, with methane in the core flow and air in the surrounding flow. Initial experiments show that under suitable forcing conditions a very periodic and controllable flow suitable for conditional sampling can be produced. Preliminary results from single component velocity measurements indicate that when the jet is forced at a particular frequency the flame breaks up into a periodic series of flamelets and the flow acceleration and turbulence intensity on the jet axis is substantially reduced. Significant progress has been made in the development of a planar laser-induced fluorescence technique for radical species visualization in the flame. Single-shot images of both CH and C2 fluorescence have been obtained in hydrocarbon-air flames.

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SUMMARY

An experimental investigation of the relationship between flow structure and chemical reaction structure in a combusting turbulent flow has been initiated. The objective is to study the spatial structure of the unsteady reaction process as it relates to the unsteady velocity field. The configuration chosen for study is a co-flowing, non-premixed jet flame, with methane in the core flow and air in the surrounding flow. Initial experiments show that under suitable forcing conditions a very periodic and controllable flow suitable for conditional sampling can be produced. Preliminary results from single component velocity measurements indicate that when the jet is forced at a particular frequency the flame breaks up into a periodic series of flamelets and the flow acceleration and turbulence intensity on the jet axis is substantially reduced. Significant progress has been made in the development of a planar laser-induced fluorescence technique for radical species visualization in the flame. Single-shot images of both CH and C2 fluorescence have been obtained in hydrocarbon-air flames.

BACKGROUND AND RESEARCH OBJECTIVES

Recent research in turbulent combustion has focused on establishing appropriate models for the interaction between turbulence structure and flame chemistry. Although there has been a considerable increase in our understanding of the physics of mixing and combustion, there are as yet no data which directly reveal the coupling between the unsteady velocity field and the unsteady reaction field in a combusting flow. The objective of the present work is to combine time-resolved field measurements of velocity and of the concentration of short lived species in a time-dependent hydrocarbon-air flame. Interpretation of the results will employ topological methods which have been used to characterize the structure of non-reacting flows. This methodology provides a unified approach for characterizing various strain and rotation fields which can occur in turbulent flows. The results from this study can be used to address the following important question: how much detail of the physics of the flame-turbulence interaction is required for the development of models for a given level of prediction?

STATUS OF THE RESEARCH

The research makes use of a variable pressure facility designed to permit the study of chemically reacting flows for pressures in the range from 0.1 to 10.0 atmospheres and free stream velocities up to 10.0 meters per second. The variable pressure feature of the facility allows the flow Reynolds number and Grashof number to be varied while overall velocities and length scales are held fixed. The test section is equipped with Schlieren quality windows on all four sides to provide access for a variety of optical measurements. The configuration investigated in this study is a co-flowing non-premixed jet flame, with methane in the core flow and air in the surrounding flow. The methane passes through a small chamber containing a loudspeaker which can be used to add a velocity perturbation to the core flow at various frequencies and amplitudes.

Initial experiments were conducted at low Reynolds number with the aim of documenting the conditions under which we could generate a controlled flow. By forcing the jet in a range of frequencies encompassing its unforced natural frequency it was possible to produce a very periodic and controllable flow which was suitable for making conditionally sampled measurements of the unsteady velocity and reaction fields. (See the paper by Strawa and Cantwell included as Attachment A.) Figure 2 in Attachment A shows a visualization of the structure of these periodically driven flames. In these pictures the luminous image of the flame is superimposed on a Schlieren image. The jet exit velocity and freestream velocity are fixed while the excitation frequency is varied. The leftmost photograph depicts the unforced case. The rightmost photograph depicts the case where the forcing is at a relatively high frequency compared to the natural frequency of the flow. In these cases a double flame structure is observed with two distinct wavelengths. The luminous core exhibits an instability with a perturbation wavelength which is substantially longer than the wavelength of the outer hot gas envelope. The middle photograph depicts the case where the forcing is at a relatively low frequency. In this case the flow is excited at a frequency which causes the luminous core and surrounding outer flow to couple most favorably and the luminous core pinches off to form a series of flamelets with a single overall wavelength. The topology of the unsteady velocity field in these flames will be determined by means of conditionally sampled two velocity component Laser Doppler Anemometry. Conditionally sampled, single velocity component measurements at several different test section pressures currently are in progress. Flow visualization of the type depicted here has been carried out at several test section pressures of 15, 35 and 65 psia (maximum cold gas Reynolds numbers of approximately 2600). At the higher pressures the relative role of diffusion is decreased and the flame is quite three-dimensional. Nevertheless the flow continues to be very periodic even to the extent that much of the 3-D structure is quite repeatable from cycle to cycle. Preliminary results from the single component velocity measurements indicate that when the jet is forced at the low frequency, which corresponds to strong coupling, the acceleration of the flow along the jet axis is substantially reduced and turbulence levels also seem to be reduced.

While studies in the variable pressure facility were being carried out, a small, atmospheric pressure, flame facility was constructed. This facility allows us continue to study various flame configurations, excitation schemes and fluorescence detection methods while the main rig is occupied with the velocity measurements.

The topology of the reaction field will be determined by a two-dimensional time-resolved visualization of the regions of intense chemical activity in the flame. These measurements will be performed utilizing a laser induced fluorescence technique to detect hydrocarbon radical species (CH and C_2) which are present only in the reaction zone. Work is currently under way to develop an improved high speed Schlieren system based on a recently acquired Spin Physics video system and to evaluate laser sources and detection methods for intermediate species visualization.

FUTURE WORK

Significant progress has been made in the development of a planar laser-induced fluorescence technique for radical species visualization in flames. To date, single-shot two-dimensional images of both CH and C_2 fluorescence have been obtained in proof-of-concept experiments in hydrocarbon air flames. (This development has been jointly sponsored by AFOSR and ONR).

During the next reporting period work will continue on all aspects of the program. Specifically, laser induced fluorescence studies of transient radicals in small-scale laminar and turbulent laboratory flames will be initiated. We will determine flame conditions which will allow interference free measurement of these species and we will study the response of various candidate species to laser wavelength. In addition, we will extend the LDA measurements to include two velocity components and we will begin initial flow field surveys.

PUBLICATIONS

1) Strawa, Anthony W., and Brian J. Cantwell, 1985, Visualization of the Structure of a Pulsed Methane-Air Diffusion Flame. Physics of Fluids, Volume 28, Number 8 (August):2317-2320. Reprint included as attachement A.

PERSONNEL

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INTERACTIONS

1) Strawa, Anthony W., and Brian J. Cantwell, 1984, Breakup of a Forced Methane-Air Diffusion Flame, presented at the 37^{th} APS/DFD Meeting. Brown University.

ATTACHMENT A

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Visualization of the structure of a pulsed methane–air diffusion flame

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Visualization of the structure of a pulsed methane–air diffusion flame

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(Received 10 May 1985; accepted 20 May 1985)

Experiments have been carried out in a variable pressure flow facility with the objective of studying the structure of a co-flowing jet diffusion flame. The flow is visualized using an optical scheme which superimposes the luminous image of the flame on its Schlieren image. This gives a useful picture of the relationship between the bright, yellow-orange, soot-laden core flow and the edge of the surrounding hot gas envelope. A loudspeaker is used to force the central fuel jet at several frequencies. In the unforced flow and over most of the driving frequency range in the forced flow, a double structure is observed with two distinct wavelengths: a long wavelength associated with the luminous, buoyancy-driven core flow and a short wavelength associated with the shear-driven outer flow. Excitation at the proper frequency causes strong coupling to occur. In this case the core flow pinches off and the flame breaks up into a series of flamelets moving with a single wavelength.

One of the principal governing phenomena in non-premixed combusting flows is the interaction between flow structure and the reaction process. A better understanding of this interaction is central to the development of improved models of combustion and to the development of methods for eventually controlling combustion. As such, it has been the object of keen interest since the time of Rayleigh's[1] early experiments. Rayleigh and more recently Ballantyne and Bray[2] and Becker and Liang[3] as well as others have noted that regular instabilities exist in diffusion flames, and that these instabilities can lead to the breakup of the flame in a quasiperiodic fashion.

The experiments reported in this letter were carried out in a newly constructed facility capable of enclosing a combusting flow at elevated pressures. The test section is 10 cm × 15 cm × 35 cm and has Schlieren quality windows on all four sides to provide full optical access to the flow. The test section pressure range is from 0.1 to 10 atm and the maximum free stream velocity at maximum pressure is 10 m/sec. Air is supplied to the facility from a large high-pressure reservoir. Test section pressure and mass flow rate are regulated by upstream and downstream control valves. Exhaust gases can be either vented to the atmosphere or caught in a series of stainless steel storage tanks for later processing to remove noxious materials. The variable pressure feature of the facility allows the flow Reynolds number to be changed while overall velocities and length scales are held fixed.

Preliminary experiments at a test section pressure of one atmosphere were carried out in a co-flowing methane–air diffusion flame with the aim of generating a periodic flow. The immediate objective of these experiments was to generate flow fields which would be suitable for making conditionally sampled measurements of the unsteady velocity and reaction field. The purpose of this letter is to report some of the visual observations of the flow–flame interaction made during these experiments. The flow was excited by adding a periodic fluctuation to the central fuel jet exit velocity. By forcing the jet in a range of frequencies encompassing its unforced natural frequency, it was possible to produce a very periodic and controllable flow. The velocity perturbation amplitude required to achieve locking on of the flow was on the order of 5%–10% of the mean jet velocity. The flow structure did not appear to change with moderate increases in the amplitude. In the experiments reported here the amplitude of the excitation was not varied.

The experimental setup is shown in Fig. 1. The air stream passes through a series of perforated plates and screens and then through a 4:1 contraction prior to entering the test section at velocity U_{FS}. Methane gas passes first through a plenum and then is injected into the main air stream near the entrance to the test section at a mean exit velocity U_J. The jet is supported by a streamlined strut which spans the 10 cm width of the test section. The plenum houses a loudspeaker which is used to apply a relatively low-frequency (10–30 Hz), periodic fluctuation to the fuel flow. Hot-wire measurements taken near the jet exit confirm that the fluctuation is reasonably sinusoidal and apparently free of harmonic distortion over this frequency range, although detailed measurements of the spectrum of the fluctuations were not made. The jet is 2.2 cm in diameter and the flow direction is vertically upward. In the optical scheme depict-

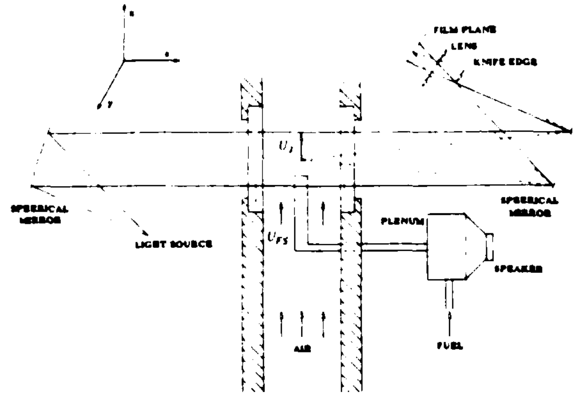

FIG. 1. A schematic of the experimental setup.

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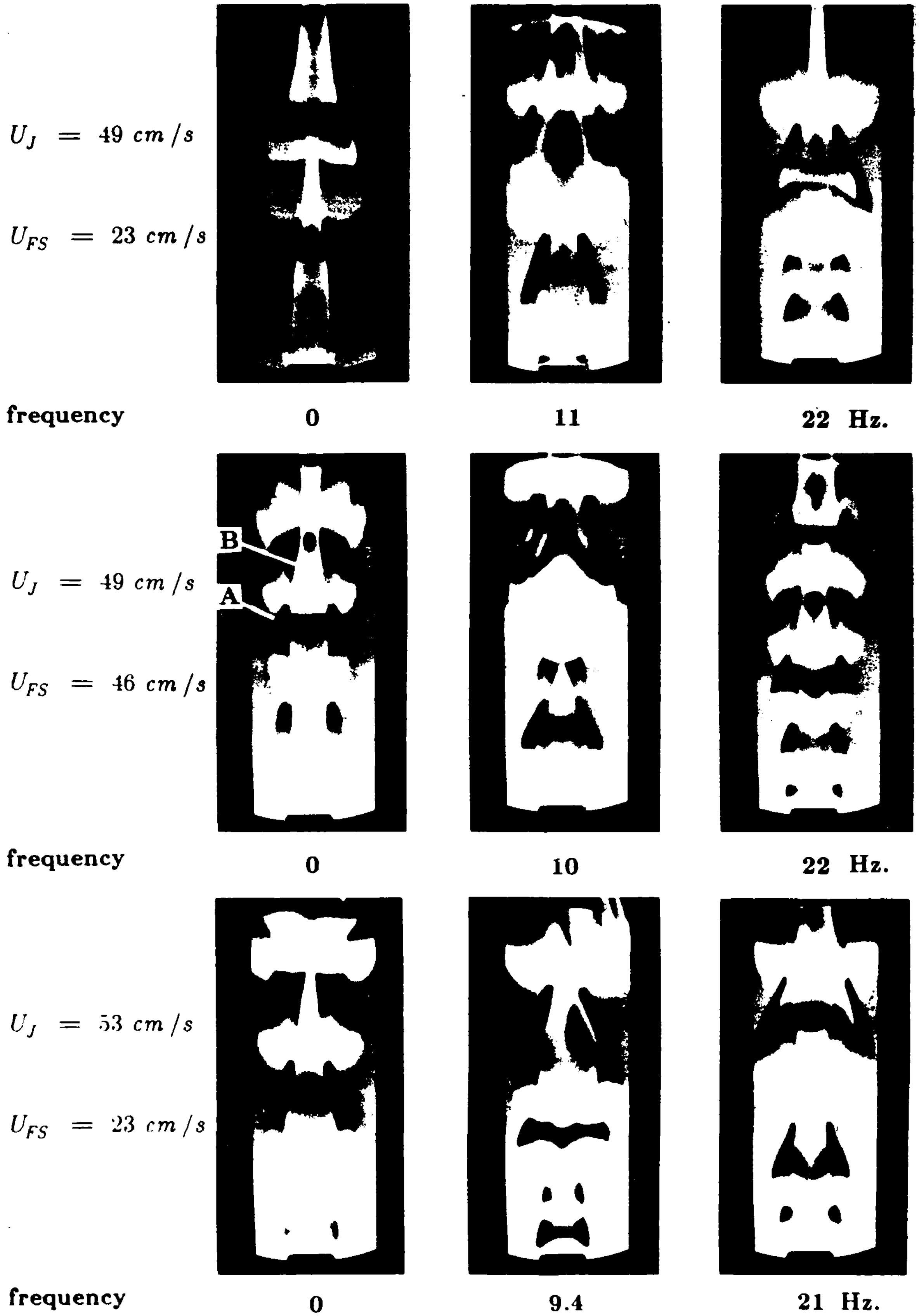
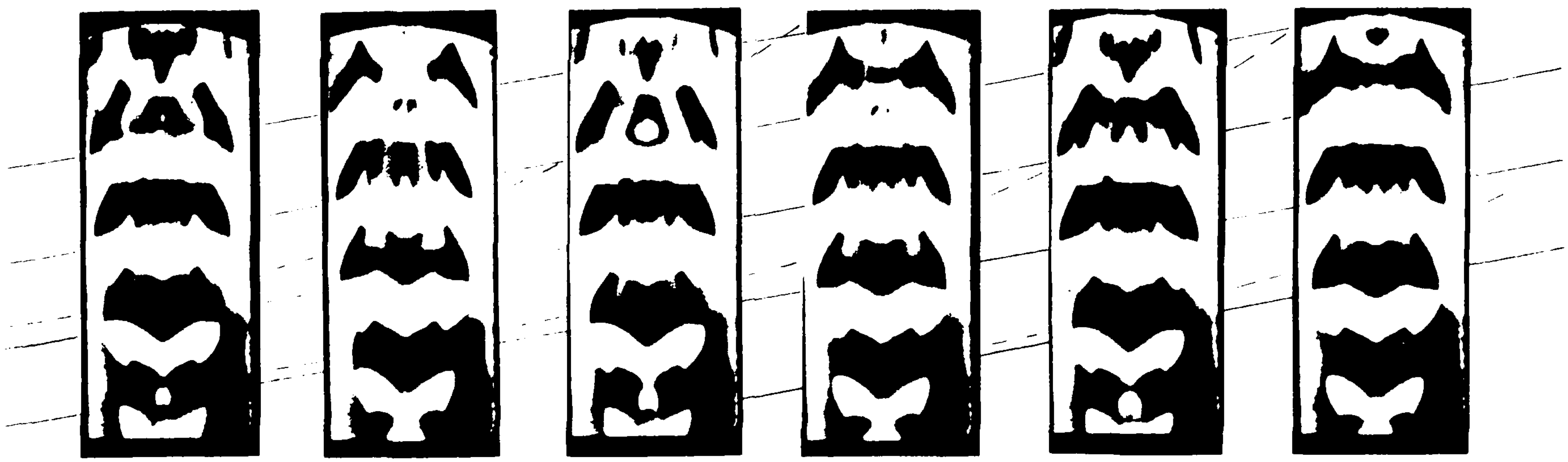


FIG. 2. Photographs of a pulsed co-flowing methane–air diffusion flame. The Schlieren effect marking the hot gas is labeled A and the luminous, yellow-orange, soot-laden core is labeled B.

sequence a



sequence b

FIG. 3 Sequence of pictures from a high-speed movie showing the evolution of a forced co-flowing methane diffusion flame. The mean jet velocity, U_J, and free-stream velocity, U_{FS}, are 60 cm/sec. In sequence a, the jet is forced at 10 Hz. In sequence b, the jet is forced at 20 Hz. Time between frames is 0.04 sec. The solid lines trace the trajectory of a bulge in the outer hot gas envelope. The broken lines trace the trajectory of the luminous soot-laden core gas.

ed in Fig. 1, light from a short-duration mercury arc is collimated, passed through the test section, focused onto a knife edge, and then imaged on the film plane of a camera. Light originating from the flame is also focused onto the image plane. The result is a color picture which combines the Schlieren effect with the image of the luminous portions of the flame. Typical results are shown in Figs. 2 and 3. The knife edge of the Schlieren system is oriented horizontally for all the photographs presented. The outer envelope of light and dark regions marks the hot gas surrounding the reaction zone of the flame. In Fig. 2 this region is indicated by pointer A. The central bright region associated with the luminous soot-laden core flow is indicated by pointer B.

The photographs in Fig. 2 were taken with a Canon FTb camera using Kodak Kodacolor VR ASA 400, 35 mm color film at a shutter speed of 1/500 sec. Figure 3 represents two sequences of frames taken from a high-speed motion picture of the flow. The movie was taken with a Photosonics high-speed camera using 16 mm Kodak VNX 7399 film at 400 frames per second. Every sixteenth frame is depicted so the time between frames in Fig. 3 is 0.04 sec.

The Reynolds number based on cold jet exit conditions was approximately 600 for all of the flows presented in this paper. The Grashof number, based on an estimated nominal hot gas temperature of 1600 °C, jet exit diameter, and cold fuel gas kinematic viscosity ($\mu_j/\rho_j = 1.64\times10^{-5}$ m^2/sec) is

$$\mathrm{Gr} = [(T_j - T_\infty)/T_\infty](gd^3/\mu_j^2)\rho_j^2 = 2\times10^6. \quad (1)$$

An approximate value for the Richardson number is

$$\mathrm{Ri} = \mathrm{Gr}/\mathrm{Re}^2 = 5.7. \quad (2)$$

The Strouhal number at which strong coupling occurred was approximately 0.4 based on the jet diameter and mean jet exit velocity.

Figure 2 illustrates several interesting features of the flow. In these pictures the jet exit velocity, free-stream velocity, and excitation frequency are varied. The leftmost photograph in each horizontal group of three depicts the unforced (or self-forced) case. The rightmost photograph depicts the case where the forcing is at a relatively high frequency. In these two cases a double structure is observed with two distinct wavelengths. The luminous core exhibits a varicose instability with a perturbation wavelength which is substantially longer than the wavelength of the outer flow. High-speed movies clearly show that the hot core gas is strongly accelerated by buoyant forces and moves essentially independently of the slower moving, shear driven, outer flow. This acceleration of the luminous core is illustrated in sequence b of Fig. 3. Dashed lines in Fig. 3 trace the trajectory of a pronounced bulge in the luminous part of the flow. Solid lines trace the trajectory of a corresponding bulge in the outer flow. In the first three pictures of sequence b the luminous bulge passes through two outer flow bulges before exiting at the top edge of the picture.

The middle photographs in Fig. 2 depict the case where the forcing is at a relatively low frequency. In this case the flow is excited at a frequency which causes the luminous core flow and surrounding outer flow to couple most favorably. The strong coupling is evidenced by the fact that the luminous core pinches off to form a series of flamelets with a single overall wavelength. The pinching off of the luminous core is accompanied by a significant reduction in the acceleration of the core flow along the jet axis as can be seen by comparing the slopes of the dashed lines in sequences a and b in Fig. 3. As the excitation frequency is increased with the flow in the strongly coupled condition, a point is eventually reached when uncoupling occurs and the synchronization between the core flow and outer flow ceases as typified by the pictures in the right-hand column in Fig. 2.

Figures 2 and 3 also exhibit a wide variation in the brightness of the core flow in both space and time. Part of this variation is related to the fact that the depth of fields is of the order of the width of the flame, and therefore the film exposure is proportional to the depth of the radiating material as well as the intensity. This effect is responsible for the fact that the center of the flame is dark while the edges are bright; one is looking through a roughly axisymmetric luminous sheet. However, some of the variations in brightness appear to be caused by real effects. The pointer in sequence a of Fig. 3 indicates the evolution in brightness of a lobe of the luminous core which happens to be located in a region where the surrounding gas envelope is particularly thin. By the third and fourth figures from the left this region is glowing white, indicating a significant increase in temperature possibly related to increased oxygenation caused by entrainment and diffusion of the free-stream air.

Quantitative experiments using conditional sampling techniques are underway to elucidate some of the effects described above and to extend the range of observed Reynolds and Grashof numbers. Based on the visual results so far it seems clear that, when buoyancy and inertial effects are both important, the interaction between the flow structure and the reaction process may be dominated by several overall length scales, and that the degree to which one can accomplish control of combustion will depend on the degree to which one can control resonant coupling of buoyant and inertial forces.

ACKNOWLEDGMENTS

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[1] J. W. S. Rayleigh, *The Theory of Sound* (Dover, New York, 1977), Vol. II, pp. 227–228.

[2] A. Ballantyne and K. N. C. Bray, *16th International Symposium on Combustion* (The Combustion Institute, Pittsburgh, PA, 1977), p. 777.

[3] H. A. Becker and D. Liang, Combust. Flame **52**, 247 (1983).

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