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THREE-DIMENSIONAL FLOW IN A MICROGRAVITY DIFFUSION FLAME

Jean Hertzberg
Center for Combustion Research
Department of Mechanical Engineering
University of Colorado at Boulder

Mark Linne
Division of Engineering
Colorado School of Mines

Science Objectives

The objective of this work is to understand the fluid dynamics in the interaction of large scale, three-dimensional vortex structures and transitional diffusion flames in a microgravity environment. The vortex structures are used to provide a known perturbation of the type used in passive and active shear layer control techniques.

'Passive techniques' refers to manipulation of the system geometry to influence the three dimensional dynamics of vortex structures, and 'active' refers to any technique which adds energy (acoustic or kinetic) to the flow to influence the shear layer vortex dynamics. In this work the passive forcing is provided by an elliptic jet cross-section, and the active forcing is incorporated by perturbing the jet velocity.

Relevance and Applications

The study of transitional diffusion flames in a microgravity environment is important for several applications: fire safety in spacecraft environments, practical applications of flames in low earth orbit (such as welding and cutting torches for space construction and heating for industrial processes), but most importantly for better understanding and control of all turbulent diffusion flames.

Recent fundamental investigations of transitional, forced axisymmetric diffusion flames have led to increased understanding of the role of shear layer dynamics in the transition to turbulence of these flames. (refs. 1, 2) Experimental studies of the stabilization process of fully turbulent lifted jet flames (ref. 3) have illustrated the importance of large scale shear layer structures and their three-dimensional evolution in time. These results have important consequences for the control of efficiency and pollutant formation in turbulent jet flames via passive and active shear layer control techniques.

Passive shear layer control can be achieved through the use of asymmetric jets, i.e. not plane- or axi-symmetric jets. For instance, nonreacting small aspect ratio elliptic jets have been found to have entrainment ratios several times larger than either plane symmetric or axisymmetric jets (ref. 4). This high entrainment has been attributed to the dynamics of the noncircular vortex rings which form as coherent structures in the jet shear layers. These dynamics are governed by self induction, the effect of one portion of the vortex ring on another. The regions of an elliptic vortex ring with higher curvature convect ahead of the rest of the ring, which in turn increases the curvature of the lagging portions. These portions then overtake and decrease the curvature of the initial high curvature sections (ref. 5). As a result, the elliptical shape is restored, but the axis which was initially the minor axis has become the major axis, and the motion then begins again. This behavior is also seen in the vortex rings formed in the shear layers of elliptic and rectangular jets, and is responsible for the increased entrainment and axis switching observed.

On a fundamental level, the application of passive techniques involves some form of three-dimensional perturbation to a shear layer, which may be separating burned and unburned reactants, or fuel and air. For instance, Grinstein and Kailasanath (ref. 6) demonstrate the effect of 3-d perturbations numerically in a square non-premixed flame, while Lasheras et al. (ref. 7) are studying high-order azimuthal perturbations to free jet diffusion flames. Lower order perturbations to premixed and annular diffusion flames (with an air core), corresponding to triangular, or elliptic configurations have been studied in some detail by Gutmark et al. (ref. 8). Increased mixing and higher centerline temperatures were found, confirming the utility of these configurations.

Active forcing in the form of periodic flow perturbations has been found to be effective in controlling many types of free shear layers by encouraging (or discouraging) pairing of the large scale structures which are responsible for much of the entrainment. Active forcing is also useful for the analysis of periodic flows since it organizes the flow by reducing the phase jitter of the large structures, and thus allows ensemble averaging based on the phase angle. In combustion, active forcing can be used to either suppress large scale flame/vortex interactions and enhance small scale mixing, as is useful in the control of combustion instabilities in ramjets, or it can be used to enhance the large scale vortex structures, as has been used to such advantage in pulse combustor technology.

The ultimate applications of these shear layer control techniques are at fully turbulent Reynolds numbers, however, study of a transitional flow allows clearer determination of the effect of the shear layer controls at a Reynolds number where mechanisms of the transition to turbulence can be traced. The major drawback to this approach is that buoyancy effects dominate the flow field under these conditions. In fully turbulent flames, buoyancy plays a much smaller role. In order to examine the transitional flow in the absence of buoyancy effects, the flame must be studied in a microgravity environment.

Research Approach

Experimental studies of the acoustically forced, elliptic jet diffusion flame will be made under normal gravity, inverted, and microgravity conditions. The flow field and the flame-flow interactions will be examined using a variety of flow visualization techniques. Particle Image Velocimetry (PIV) will be used in the stationary experiments, and a particle tracking technique will be developed for the 2.2 second drop tower experiments. A schematic of the system is shown in Figure 1. Ideally, full velocity field information would be determined for the microgravity case as well, however, appropriate diagnostics are not yet available. Knowledge of the velocity field under normal and inverted gravity conditions should provide insight into the microgravity flow field when coupled with the flow visualization and particle tracking measurements from the drop tower tests. The flow is expected to retain bilateral symmetry, so laser sheet techniques (including PIV) will provide useful information in the planes of symmetry.

The combustor consists of a 2:1 aspect ratio elliptic cross-sectioned nozzle (0.5 X 1.0 mm). The nozzle is connected to a plenum chamber which contains a 6.5 inch diameter loudspeaker. The fuel flow (methane) enters the plenum via a flow controller and a seeder device. The flame orientation will be horizontal, to provide the greatest possible length within the drop rig. The flow will be impulsively started and the flame ignited after drop to avoid buoyancy induced currents. The flow will be sinusiodally perturbed using the loudspeaker at the jet preferred mode and/or the plenum's resonant frequency, since high excitation levels will be required to affect the outer shear layer flow where the flame exists. All diagnostics will be phase-locked to the acoustic forcing signal.

Flow visualization techniques will focus on seeded flows, using both refractory particles which will survive the flame (for particle tracking) and oil droplet aerosols which can be used to mark the flame's thermal boundaries. Preliminary results have indicated that the flow rates to be used (10 to 80 ml/s) are insufficient to drive either conventional aspirated aerosol seeders or cyclone particle seeders. In addition, both types of seeders require gravity to operate properly. To avoid these problems, the plenum is of a sufficient size to be charged with seeded flow at a high rate prior to the experiment. An ultrasonic aerosol generator is also being developed which can provide densely seeded flows independent of flow rate.

The flows will be imaged using conventional video and photographic techniques, including macro stereo photography. Time resolution and phase-locking will be provided by strobing the light source. Both conventional strobe lights and modulated visible laser diodes are being investigated.

Results

This project has been underway since July 1994, although some preliminary experiments were performed prior to that date, using an early prototype combustor. Results from the early combustor are presented here. The early combustor consists of a cylindrical plenum chamber containing a 6.5 inch diameter bass-reflex speaker enclosure. The axisymmetric nozzle is an 8.3 cm length of 4.5 mm inner diameter stainless steel tubing. The burr from using a wheel-type tube cutter is retained.

An unusual flame phenomenon has been observed. At specific excitation frequencies the flame can be driven to bifurcate into a central jet and one or two side jets as shown in Figure 2. A perpendicular mirror view is also shown. The bifurcation is accompanied by a partial detachment of the flame from the nozzle exit, a shortening of the flame by a factor of two, and a change from the common yellow color of soot radiation to a clear blue flame. Under some conditions, a yellow region is observed on one or both flame tips. This phenomenon is of practical interest because the ability to control soot production or product species in a diffusion flame using an open loop forcing technique is potentially quite useful. In addition, this phenomenon illustrates the effectiveness of active forcing on this type of flame.

The bifurcation behavior was observed at all flow rates ranging from the lowest measurable flow rate, 10 ml/s, to a flow rate just above that of lift-off, 95 ml/s. These conditions correspond to bulk velocities ranging from 0.5 m/s to 6 m/s and Reynolds numbers ranging from 240 to 1000. The behavior occurred at 246 +/- 20 Hz. This critical frequency range was found to be insensitive to the flow rate which indicates that the bifurcation is not strictly a shear layer or jet mode effect. The critical frequency was found to be independent of nozzle length, which suggests that it is not an effect of nozzle vibration. A plenum resonance is likely responsible for determining the critical frequency, and the bifurcation should appear whenever the forcing level is sufficient. In fact, the frequency is not sensitive to input forcing amplitude in that bifurcation would occur at low forcing amplitudes at the critical frequency, and not at higher amplitudes at other frequencies. The frequency response of the system must be measured to determine the actual velocity perturbation level at the nozzle. These measurements are in progress. Two possibilities for the resonance mechanism are the Helmholtz and a longitudinal standing wave pipe modes. The Helmholtz resonance mode for the nozzle and plenum combination was 4 Hz, well below any examined frequency. Like many such systems, there are many possible longitudinal modes. One is close to 240 Hz, a standing wave mode of the plenum calculated by using the speed of sound in pure methane and assuming 1.5 wavelengths in the plenum, that is, one closed and one open end. However, the plenum inlet tubing diameter is the same as the outlet, casting doubt on these end condition assumptions.

Outside of the critical frequency range the flame appeared to be an unremarkable transitional diffusion flame, although the flame height showed some sensitivity to the excitation frequency, particularly at low flow rates. The amplitude of forcing at 246 Hz required to cause bifurcation varied with flow rate, with the lower flow rates being more sensitive to forcing. Details of the bifurcation shape also varied with flow rate and forcing amplitude. For example, a splitting into three jets was observed under some conditions. At the highest levels of forcing (35 Vpp at the speaker) some form of bifurcation was always present. At lower levels of forcing the phenomenon was intermittent in time. Additional perturbations such as air currents could be used to induce transitions between the bifurcated and non-bifurcated (ordinary diffusion flame) states. Thus this phenomenon is a bifurcation both physically in space, and in time.

The nozzle lip condition is critical for the bifurcating behavior. A cleanly machined lip will not spontaneously produce a bifurcated flame. This is perhaps why this phenomenon is so rarely seen. While the study of perturbed jet diffusion flames is an active topic (refs. 7,9,10,11,12) few reports of any similar phenomenon have been made. Pfizenmaier (ref. 13) has observed a hydrogen jet flame to split when exposed to high amplitude transverse acoustic waves, and suggests that a helical jet mode instability is responsible. To our knowledge, the only other mention in the literature is a famous report by Tyndall (ref. 14) who studied the response of "naked" (unconfined) gas jet flames to sound, and observed "short, forked and brilliant" flames.

Flow visualization using alumina particles and a strobe light has been performed on a non-reacting air jet under the same Reynolds number and forcing conditions. The air jet was observed to bifurcate in what we assume to be a similar manner to the flame, shown in Figure 3. The phase-locked flow visualization in the air jet shows that a single vortex structure is formed each cycle. The base of the side jet remains fixed at an axial position, rather than convecting downstream with the primary vortex structure. This is consistent with a study of jets subject to high level axial velocity perturbations by Monkewitz and Pfizenmaier (ref. 15). They relate the formation of the side jets to a coupled effect of an azimuthal instability of the primary vortex ring structure with a strong braid structure. Other non-reacting jet bifurcations have been observed, but are due to specific transverse excitations.

Flow visualization experiments are underway to determine if an azimuthal instability mechanism can explain the bifurcated flame phenomenon. Presumably, the intense vortex structure premixes the fuel and air to some extent, resulting in the blue flame. The side jet may consist of more pure fuel, which would explain the yellow flame tip sometimes observed. The cause of the intermittent flame behavior has not been determined. However, the air jet responded to a much wider range of forcing conditions than the flame, was much less intermittent in time, and was insensitive to the nozzle lip condition. The air jet responded to frequencies from 60 to 260 Hz, at minimum amplitudes of approximately half of those required for the flame to bifurcate. These differences suggest that the flame is not passively following the fuel jet, but can intermittently 'overcome' a bifurcated fuel jet to burn in a normal (not bifurcated) manner. This point may be important for the successful application of active and passive forcing techniques to non-premixed flames.

Research Plans

Since this is a new project, the first year is being spent building the combustor at CU Boulder, and conducting vertical and inverted experiments in 1-G. A variety of flow and forcing conditions will be examined, and flow visualization techniques will be refined. The second year will begin with quantitative velocity measurements in a limited number of flow/forcing conditions, using the PIV system at the Colorado School of Mines. The combustor system will also be integrated into the drop package, and a trip to NASA Lewis is planned for preliminary drop tests. One week will be devoted to checkout of the drop package, and 20 drops are projected for this stage. The third year will involve final tests in the drop tower. Approximately 20 drops should be required. Supporting flow visualization and PIV tests will be made at CU Boulder and CSM.

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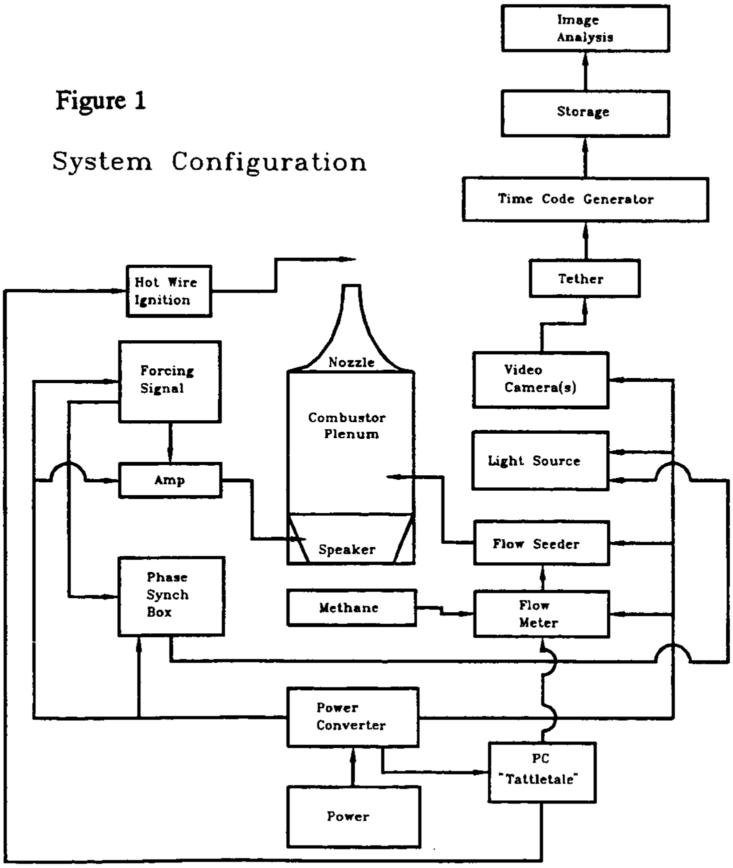

Figure 1

System Configuration

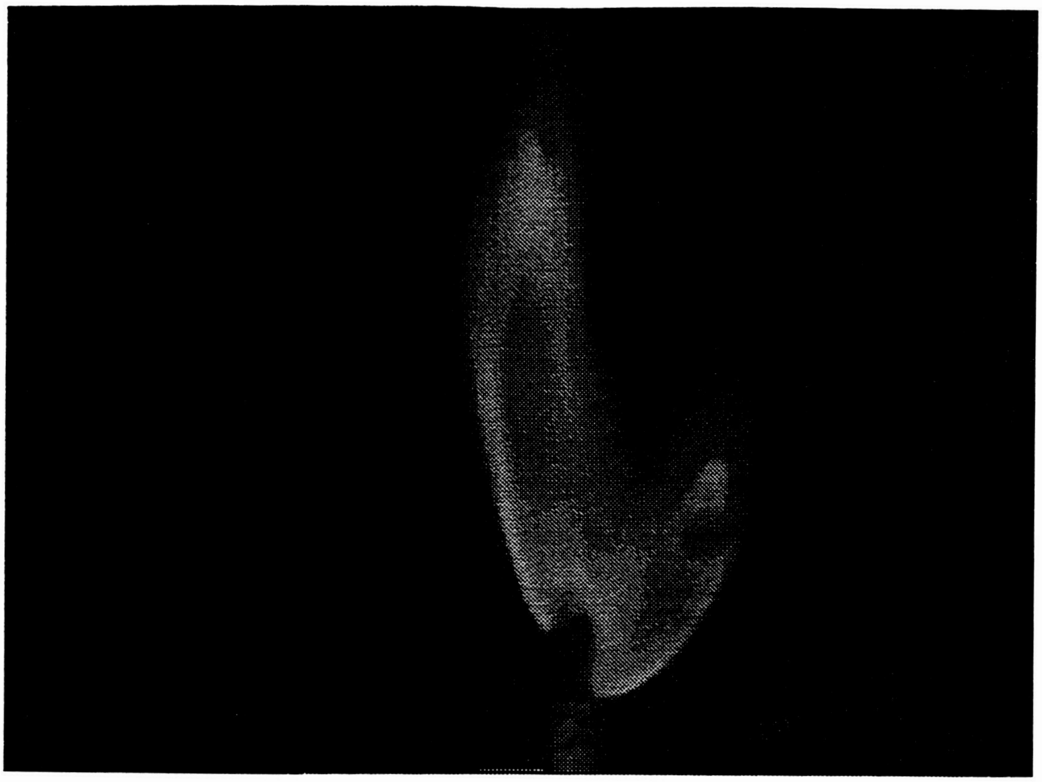

Figure 2: Bifurcated methane jet diffusion flame.

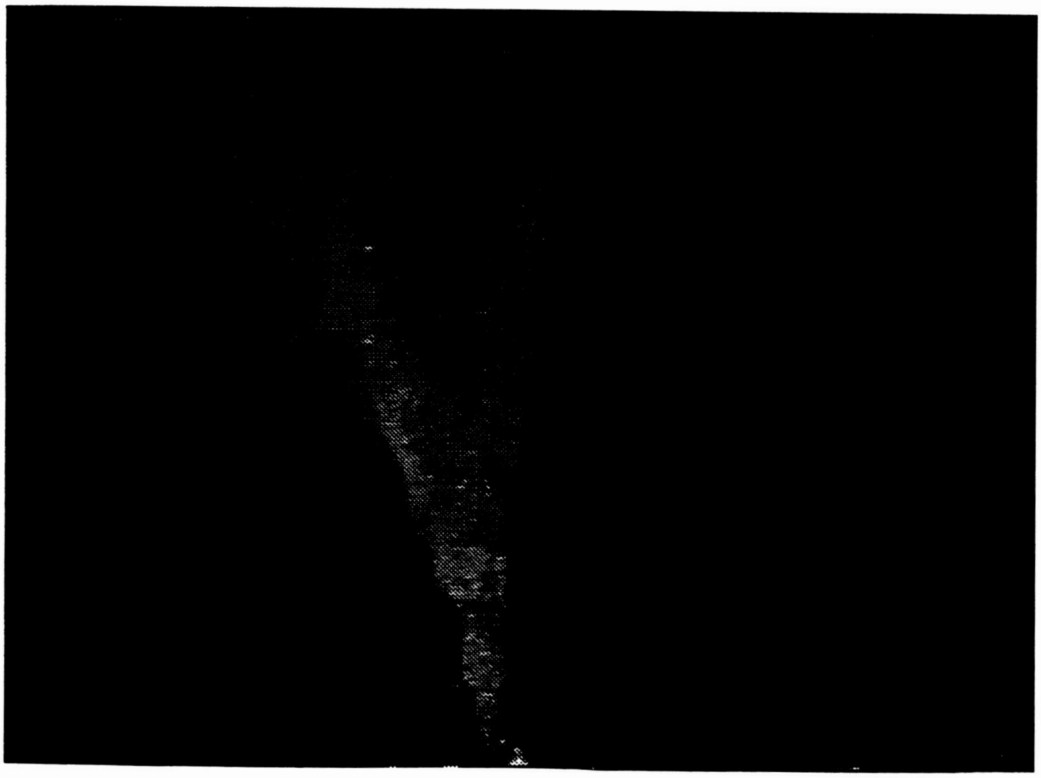

Figure 3: Strongly forced nonreacting jet.