N96-15600

# EFFECTS OF ENERGY RELEASE ON NEAR FIELD FLOW STRUCTURE OF GAS JETS[1]

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## Introduction

The interaction of flames and flow structures in combustion systems has been the subject of several investigations in recent years [1-6]. The phenomena occurring in the near-field of a gas jet determine the burning characteristics and pollutant generation from its diffusion flame. The diffusion of the oxidizer near the nozzle exit governs the flame stability and flame lift-off. Entrainment of the oxidizer into the fuel jet is controlled by the Kelvin-Helmholtz instabilities in the shear layer between the fuel jet and ambient fluid, and by the buoyancy driven instabilities outside the flame. The jet growth and fuel-air mixing rates depend upon these near-field fluid dynamics which could be modified to alter the energy release and pollutant emission characteristics of diffusion flames. Thus, an understanding of the near-field structures of jet flames and physico-chemical factors affecting them is important for improving the combustion characteristics of diffusion flames.

Figure 1. taken from Savas and Gollahalli [3] shows the schlieren photographs of nonburning and burning propane jets at the same nozzle exit Reynolds number of approximately 13,000. These photographs clearly show that the flame inhibits coalescence of small scale coherent structures and hence, suppresses the radial growth of the shear layer. The lengthening of the coherent structures has been attributed to the changes in the jet fluid viscosity [1], volummetric expansion [7], and the stretching effect of buoyancy [8]. The buoyancy associated with ground experiments has prevented a clear identification of the mechanisms responsible for this effect. The buoyancy also generates vortical structures outside the flame resulting in the flame flicker [9].

The primary objective of this research is to understand how buoyancy affects the structure of the shear layer, the development of fluid dynamic instabilities, and formation of the coherent structures in the near-nozzle regions of gas jets. The secondary objectives are to study the role of buoyancy in lifting and reattachment process of diffusion flames, to evaluate the scaling behavior of diffusion flames, and to aid development and/or validation of theoretical models by providing quantitative data in the absence of buoyancy. Fast reacting hydrogen or hydrogen-inert fuels are used in this study to isolate the effects of buoyancy on fluid dynamics without masking the flame behavior by soot and radiative heat transfer. This choice of fuel also permits an evaluation of simulating low gravity in low pressure ground experiments because the similarity constraints are relaxed for the fast reacting, nonsooting diffusion flames. The diagnostics consists primarily of a color schlieren system coupled with computer generated rainbow filters, video recording and image analysis.

The project involves (i) drop tower experiments (ii) ground experiments, and (iii) theoretical analysis. The following sections describe the work accomplished to-date and the plans for future work of this project.

[1] This project was started in June 1994

Drop Tower Experiments

The apparatus for this series of experiments, shown in Figure 2, was developed by Griffin and Greenberg [10]. This consists of a color schlieren system mounted on a drop module for studies in the 2.2 second drop-tower at NASA Lewis Research Center. The schlieren system is based on 75 mm diameter, off-axis parabolic mirror optics. The white light is provided by a fiber-optics cable connected to the light source either within the module or outside at the control platform. The light emerging from a 50 micron slit is collimated by a 300 mm focal length lens and decollimated by a 3000 mm focal length lens combination. A computer generated rainbow filter is used at the light source image to color code the ray deflections. The schlieren image is captured by a CCD color camera and transmitted fiber optically to a S-VHS video recorder and a TV monitor at the control platform.

The fuel supply system consists of a 75 ml fuel tank at 5 bar, a flow meter, a solenoid activated flow control valve, associated tubing, and an interchangeable fuel-tube. The fuel was ignited prior to the drop by a retractable hot-wire. The apparatus was controlled either manually or by an inboard computer. Prior to the drops a pre-burn was done to ensure proper functioning of the system. The schlieren images were recorded during the main run at both the normal and low gravity conditions.

Ground Experiments

The ground tests consist of experiments at atmospheric and sub-atmospheric pressures. Penner [11] found that no practical combustion process can be exactly modeled in a strict sense of similarity. This prompted Spalding [12] to suggest partial modeling where only a select few of the similarity restrictions are followed. Mortzavi et al [13] used scaling approach to obtain weakly-buoyant flames simulating low-gravity by exploiting the fact that the buoyancy scales with $p^2g$ in laminar flames where p=pressure and g=gravitational acceleration. The finite rate reactions, soot formation and radiative heat transfer in hydrocarbon flames studied by these authors impose severe similarity constraints. Because of the fast reactions, the absence of soot and the lack of significant radiation in hydrogen flames, similarity constraints are considerably relaxed in the present study.

Figures 3 and 4 show, respectively, the schematic and a photograph of the test chamber. This 0.75m high stainless steel combustion chamber has a square cross-section (0.3m x 0.3m). The hydrogen or hydrogen/inert mixture is supplied to a fuel-tube at the center of the chamber. Because of the large chamber volume, the influence of side walls on the jet flow characteristics is expected to be negligible. Optical access is provided by glass windows (0.2m x 0.60m and 10 mm thick) on two parallel side walls. An access door to facilitate changing of the burner and a retractable spark-igniter are provided on other side walls. Upstream and downstream ends of the chamber connect, respectively, to a diffuser and a nozzle with flow smoothening honeycombs. The downstream end is connected to a vacuum pump rated to provide 0.055 $m^3/s$ (117 cfm) at up to 0.0033 bar absolute pressure. The vacuum pump is driven by a 3-phase 7.5 HP electric motor. The entire chamber is mounted on a swiveling bracket to facilitate orienting the flow direction at any angle with the gravity vector.

The burner is mounted in the collimated optical path of a color schlieren system set up on an optical rail. The schlieren system consists of a halogen light source with fiber-optics, a 50 micron aperture, and 63 mm diameter, 490mm focal length collimating and decollimating lenses. A computer generated rainbow filter is used at the light source image. The schlieren images are captured by a 3-chip CCD color video-camera connected to a microcomputer through a frame grabber. The real time schlieren images can be viewed on the computer screen and the frame sequences can be digitized and stored for post processing.

Theoretical Analysis

The analysis follows the recent investigations to simulates effects of heat release on flow structures [6,8,14-15] by solving time-dependent conservation equations of the mixture mass, species mass fraction, momentum and energy. These equations in cylindrical polar coordinates have the following general form:

$$\frac{\partial}{\partial t}(\rho\phi) + \nabla\cdot(\rho\vec{v}\phi - \Gamma_\phi \nabla\phi) = S_\phi \qquad (1)$$

where $\phi$ stands for the dependent variable. $\Gamma_\phi$ and $S_\phi$ are, respectively, the diffusion coefficient and generation rate of the variable $\phi$. $\rho$ is the density and $\vec{v}$ is the velocity vector. The dependent variables are pressure, radial and axial velocities, sensible enthalpy, and species mass fractions. The transport equations are solved by a commercial computational fluid dynamics code, PHOENICS modified to include chemical kinetics and transport properties computed by the chemical kinetics code CHEMKIN.

## Results and Discussion on the Work Completed

The first series of drop tower experiments were conducted at low fuel flow rates because of the safety concerns with releasing hydrogen in an unconfined environment. Figures 5 and 6 show schlieren pictures obtained from video recordings at a cold jet Reynolds number of 90 for two different fuel-tubes. Figure 5 pertains to the tube inside diameter of 0.58 mm, tube wall thickness of 0.15mm and the average exit velocity of 16m/s while the corresponding values in figure 6 are 1.19mm, 0.23mm, and 8m/s. The rainbow filter was one-half of the symmetric filter shown in figure 7. Figures 5 and 6 indicate that the flame widens in the absence of gravity. Video recordings also indicated low gravity flames were more stable compared to their normal gravity counterparts. These results agree with previous experiments with diffusion flames, for example, by Bahadori et al [16]. Figures 5 and 6 also show that the difference in flame width at normal and low gravity depended upon the fuel flow rate. At the same cold jet Reynolds number, the normal gravity flame was 12% wider at the higher fuel flow rate while the corresponding low gravity flame was 55% wider. The flame anchored upstream of the fuel tube exit at both normal and low gravity. This upstream distance of 2 OD at normal gravity increased to approximately 6 OD at low gravity. Similar observations were made by Haggard and Cochran [17] who used black and white infrared film to photograph the low gravity flames.

The ground experiments were conducted at atmospheric pressure for various fuel tubes and flow rates. Figure 8 shows schlieren pictures at different Reynolds numbers for a 0.58mm ID tube. These pictures were obtained using a symmetric rainbow filter shown in figure 7. The flame appears laminar at a Reynolds number of 540 (figure 8a). At higher Reynolds numbers the laminar and turbulent zones are distinguished by the flame necking. The necking distance decreases with increasing Reynolds number as the flame becomes fully turbulent, lifts-off and eventually blows-off.

The experiments at low pressures will be conducted after the validation tests on the vacuum chamber facility are completed. The analytical procedure has been used for a different project to predict ignition of natural gas [18]. This procedure is currently undergoing validation for use in the present configuration.

## Future Plans

Future experiments in the drop tower will be conducted at higher Reynolds numbers. The ground experiments will be conducted for cold jets and flames at various pressures and Reynolds numbers. A high power strobing white light source will be used to capture details of the flow structures. The schlieren images will be processed to yield refractive index and temperature distributions. The analytical effort will focus on numerical simulations of the cold jets and flames studied experimentally.

Acknowledgments

This project is sponsored by the NASA Microgravity Science and Application Division grant NAG3-1594. We wish to acknowledge P.S. Greenberg and F. Miller for the helpful discussions on the rainbow schlieren system. We wish to thank R. Turley for his meticulous and hard work in fabricating and setting up the vacuum chamber facility.

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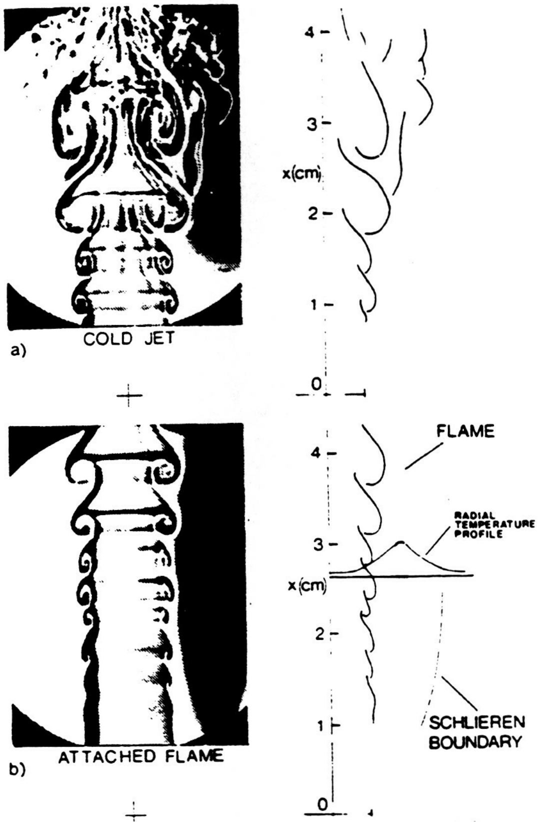



Fig. 1 Schlieren Photographs of propane cold jet and flame at Re=13000

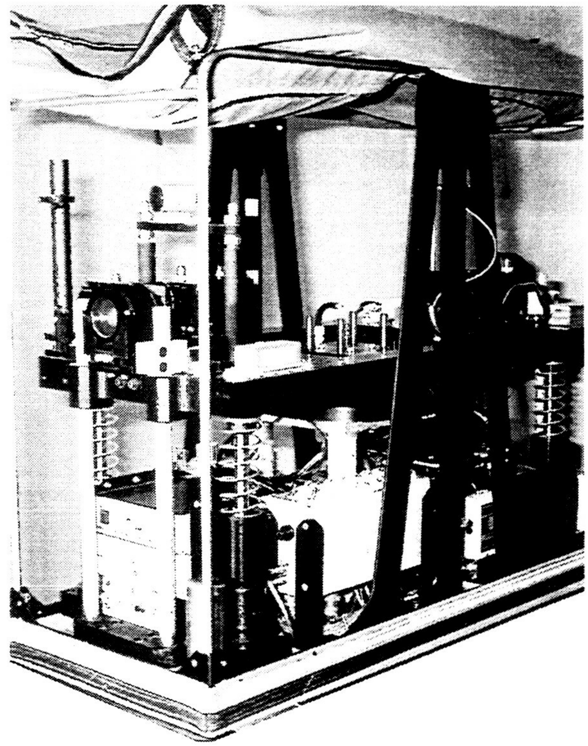


Fig. 2 The Drop Tower Test Rig

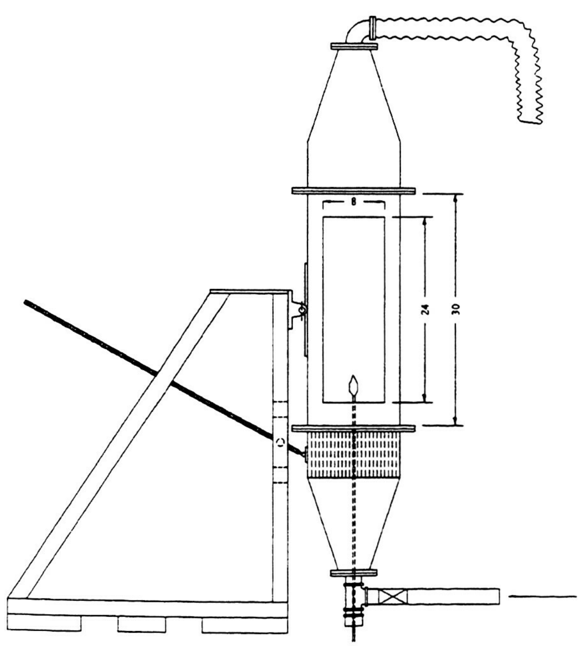



Fig. 3 Schematic of the Combustion Chamber

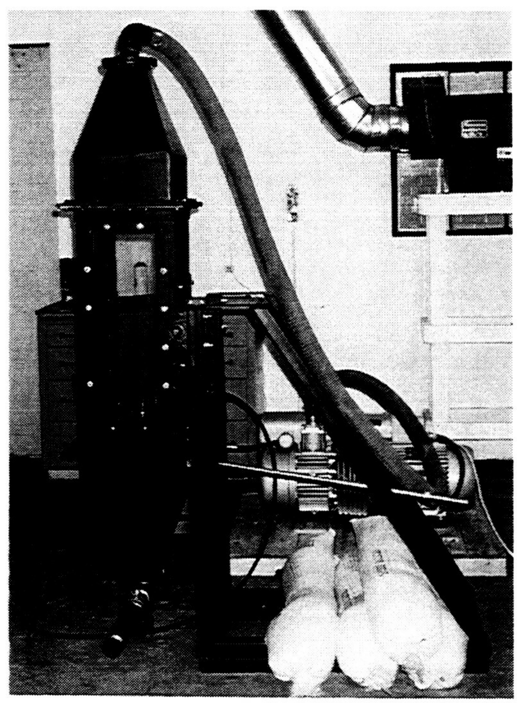


Fig. 4 A view of the Combustion Chamber

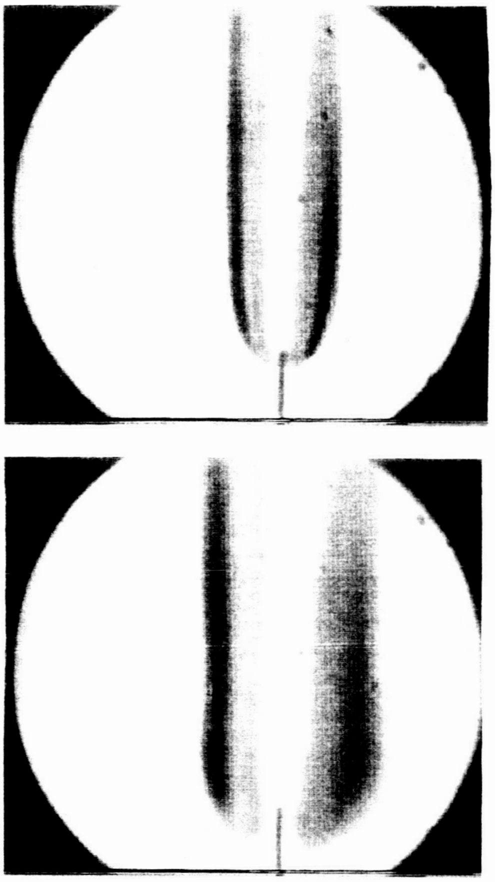


Fig. 5 Schlieren Photographs of Hydrogen Flame at Re=90, 0.58mm ID Fuel Tube; top) Normal Gravity, bottom) Low Gravity

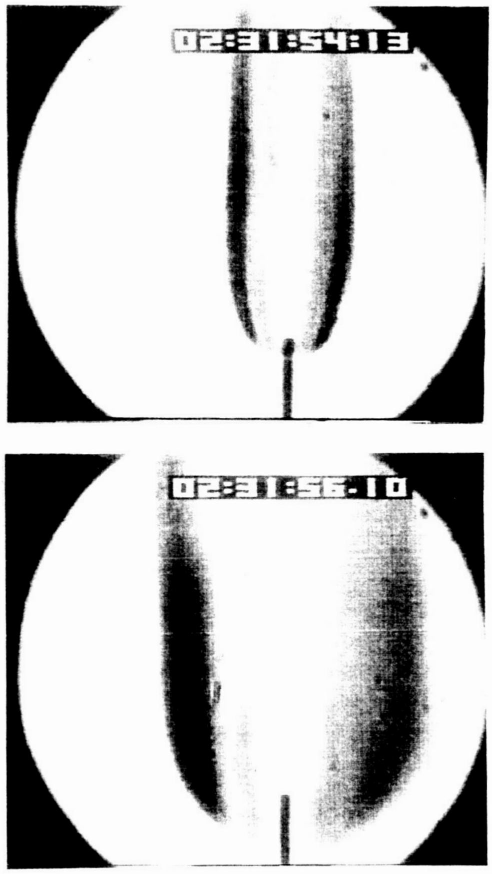



Fig. 6 Schlieren Photographs of Hydrogen Flame at Re=90, 1.19mm ID Fuel Tube; top) Normal Gravity, bottom) Low Gravity

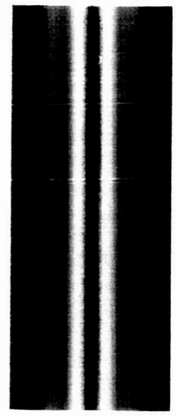
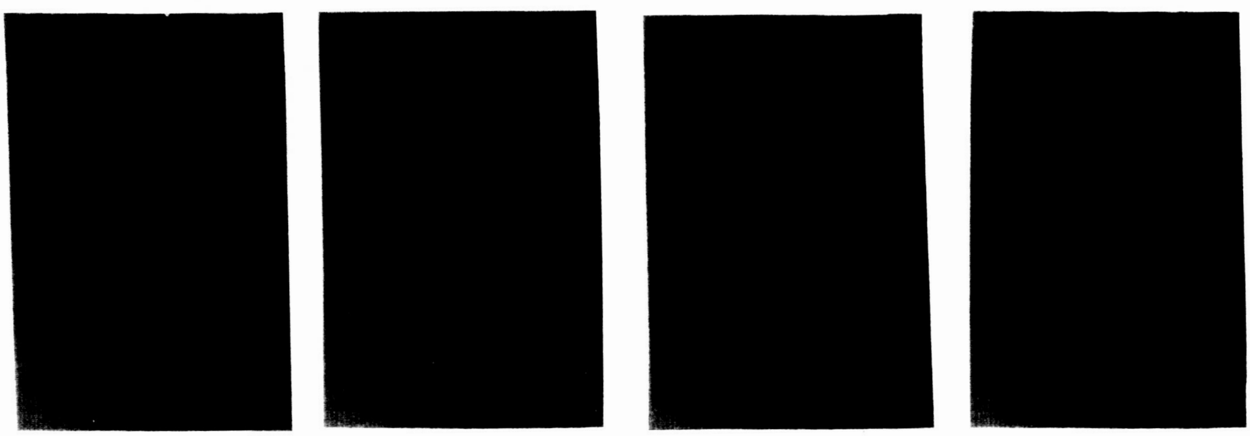


Fig. 7 Symmetric Rainbow Filter



a) Re=540 b) Re=1200 c) Re=1800 d) Re=2400

Fig. 8 Schlieren Photographs of Hydrogen Flame at Normal Gravity, 0.58mm ID Fuel Tube