

STUDY OF BUOYANCY EFFECTS IN DIFFUSION FLAMES USING RAINBOW SCHLIEREN DEFLECTOMETRY*

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Introduction

Diffusion flames are extensively encountered in many domestic and industrial processes. Even after many decades of research, a complete understanding of the diffusion flame structure is not available. The structure and properties of the flames are governed by the mixing (laminar or turbulent), chemical kinetics, radiation and soot processes. Another important phenomenon that affects flame structure in normal gravity is buoyancy. The presence of buoyancy has long hindered the rational understanding of many combustion processes. In gas jet diffusion flames, buoyancy affects the structure of the shear layer, the development of fluid instabilities, and formation of the coherent structures in the near nozzle region of the gas jets. The buoyancy driven instabilities generate vortical structures outside the flame resulting in flame flicker. The vortices also strongly interact with the small-scale structures in the jet shear layer. This affects the transitional and turbulence characteristics of the flame. For a fundamental understanding of diffusion flames it is essential to isolate the effects of buoyancy. This is the primary goal of the experiments conducted in microgravity. Previous investigations, have shown dramatic differences between the jet flames in microgravity and normal gravity[1]. It has been observed that flames in microgravity are taller and more sooty than in normal gravity. The fuels used in these experiments were primarily hydrocarbons. In the absence of buoyancy the soot resides near the flame region, which adversely affects the entrainment of reactants. It is very important to eliminate the interference of soot on flame characteristics in microgravity. The present work, therefore, focuses on the changes in the flame structure due to buoyancy without the added complexities of heterogeneous reactions. Clean burning hydrogen is used as the fuel to avoid soot formation and minimize radiative losses. Because of the low luminosity of hydrogen flames, we use rainbow schlieren deflectometry for visualization. The visualized images are digitized for quantification.

The work reported here is divided into three sections; rainbow schlieren deflectometry (RSD), microgravity experiments and sub-atmospheric pressure experiments. The first section demonstrates the application of RSD for quantitative measurements in non-reacting and reacting flow systems. A computational effort to complement the experimental work is also included. In the second section, the experiments conducted at the 2.2s NASA Lewis Drop tower facility are described. The experiments were conducted to study the behavior of laminar, transitional and turbulent hydrogen flames in microgravity. The ability of RSD technique to provide quantitative data is highlighted. The final section deals with the sub-atmospheric pressure tests, which demonstrate that buoyancy in hydrogen diffusion flames can be scaled with pressure at normal gravity.

Rainbow Schlieren Deflectometry

The schlieren technique has been extensively used for qualitative flow visualization. Recently, Greenberg et. al. [2] developed the RSD technique for quantitative measurements. In the RSD technique, the knife edge used in the conventional schlieren apparatus is replaced by a continuously graded color filter. Quantitative measurements are made by the RSD technique utilizing computer imaging approach to create the color filter and to acquire/analyze color schlieren images. The color filters are calibrated to obtain the hue variation along the filter. The rainbow filter transmits a color uniquely represented by hue, according to the hue-saturation-intensity(HSI) model, from a given position on the filter plane. Thus, a color image of the test

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section revealing the ray displacements caused by refractive index gradients in the medium is formed on the CCD array. The camera output in the RGB format is digitized by a personal computer with 24-bit color frame grabber. The digitized schlieren image together with filter calibration curve, is used to obtain the angular deflections of the light rays by the medium. The refractive index distribution is obtained from the angular deflections using Abel inversion. The refractive index is then related to density and/or other scalar properties of the medium.

Three test cases were chosen to demonstrate the RSD technique, namely, temperature measurement in a heated air jet, oxygen concentration in an isothermal jet of helium, and temperature and oxygen concentration measurements in a hydrogen diffusion flame. In all the above cases the flow was laminar and axisymmetric and the jet issued into quiescent air. The heated jet issued from a 7.1mm nozzle with an exit Reynolds number of 400. In a heated jet, the refractive index is a function of only the temperature. The refractive index from RSD can be used to obtain the temperature distribution. The temperature measurements obtained from schlieren method were compared with thermocouple measurements (Fig. 1). The results agree well. In the second test case, oxygen concentration measurements were made in a helium jet issuing from a 7.1mm nozzle at a Reynolds number of 125. It was assumed that helium and air together behave as a binary mixture, with a fixed air composition. Hence, the gas properties are unique functions of the helium mass fraction. Thus the refractive index obtained by RSD could be directly related to oxygen concentration. The oxygen concentration was also measured using a diffusion based oxygen analyzer. The results (Fig. 2) indicate that the schlieren measurements show excellent agreement with the probe data. In the third test case measurements of temperature and oxygen concentration were made in a hydrogen flame. Laminar hydrogen flames have a large Damkohler number; hence it was assumed that the reactions reach chemical equilibrium instantly. This equilibrium chemistry model with unity Lewis number assumption was used to obtain the relation between refractive index and the scalar variables. The temperature and oxygen concentration were also independently obtained by probe measurement. The thermocouple measurements were not corrected for radiation losses. The temperature and oxygen concentration are compared in Figs. 3 and 4. The results in fuel rich region are not shown due to large uncertainties in that region, primarily attributed to instrument sensitivity, validity of the chemistry model, and unity Lewis number assumption. The schlieren measurements in the fuel lean region show good agreement with probe measurements.

RSD was used as a tool to evaluate CFD results. Numerical simulations of the hydrogen flames were performed with a mixture fraction approach and assuming equilibrium chemistry. Two diffusion models were used for the mixture fraction equation. The first model (Model 1) uses the thermal diffusivity and the second model (Model 2) uses the mass diffusivity in the mixture fraction equation. In Model 2, a two zone diffusion model [3] was used to account for non-unity Lewis number effects. The computed results of temperature and species concentration were used to generate a rainbow schlieren image which was then compared with the experimental image (Fig. 5). The computed images agree well with the experimental images near the nozzle. The computed image indicates higher upstream diffusion. The comparison of the computed temperature distribution with schlieren measurements is shown in Fig. 6. The figure shows that computations obtained from Model 2 agree well with the experiments in the fuel lean region. The discrepancy in the fuel rich region is due to reasons explained above.

Microgravity Experiments

Experiments were conducted in microgravity to study the behavior of hydrogen flames without buoyancy. The drop rig used was provided by NASA LeRC diagnostics group. While easily reconfigurable, this hardware was designed for use with rainbow schlieren optical systems. The flame data were collected during the 2.2 second drop using a Super-VHS tape recorder. The images from the video were digitized using a frame grabber. The study involved the visualization of laminar, flickering and transitional laminar flames. The schlieren image of a laminar flame obtained in microgravity is compared with that in normal gravity (Fig. 7). The jet issued from a tube of 0.3mm ID at an exit Reynolds number of 582. The figure indicates flame in microgravity with higher upstream diffusion. The images were used to obtain the refractive index distribution and temperature profiles at two axial locations, namely at 3.8D and 7.8D from the tube exit. The temperature distribution is shown in Fig. 8. The results in the fuel rich region are omitted, due to inaccuracies in recording and filter calibration. Reasonable values of the flame boundary location and the data in the fuel lean region were obtained. From the figure we observe that there is an increase in the flame width. Sharper temperature gradients near the flame at normal gravity were observed. This is caused by the convective motion of the heated gases from the flame surface. In normal gravity flickering of the flames is observed, which is induced by the outer vortices caused by buoyancy. The flames were observed in normal gravity (Figs. 9a-e); flickering frequency was ~13 Hz. In microgravity, the flickering disappears (Figs. 9f-j) as the flame grows. The flame was nearly at steady state, undergoing minor changes at the end of the drop. The transitional flames were studied to observe the effect of buoyancy on the structure of turbulence and mode of transition. The test were done using hydrogen jet issuing from a tube of 0.3mm ID and an exit Reynolds number of 1078. The images obtained in microgravity were compared with that in normal gravity (Fig. 10). The flames show a break point at both normal and microgravity. This indicates that microgravity and normal gravity

flames, have similar transition behavior, unlike the observation by Hegde et. al [4], whose results indicate that the entire flame becomes turbulent in microgravity without a break point.

Sub-atmospheric Pressure Experiments

Experiments were conducted in a subatmospheric pressure combustion chamber, to simulate low buoyancy conditions. By reducing the pressure in the combustion chamber the effect of buoyancy can be reduced. The primary aim was to verify that buoyancy can be scaled with pressure[5]. Previous experiments with hydrocarbon fuels faced problems at low pressure due to chemical kinetics and heterogeneous reactions in sooting flame. The present system with non-sooting, fast reacting hydrogen fuel significantly relaxes the scaling requirements. It was observed that by using hydrogen, the buoyancy effects may be scaled at sub-atmospheric pressures. The combustion chamber is shown in Fig. 11. The combustion chamber was constructed to provide sub-atmospheric pressure and to obtain continuous combustion with the chamber oriented at any desired inclination to the gravitational field. The images of hydrogen the flame were obtained using the rainbow schlieren technique. The experiments were performed with laminar and flickering laminar flames in a Reynolds number range of 100-500. The images of the hydrogen flame ($D = 0.58\text{mm}$, $Re = 300$) obtained at different pressure levels for zero inclination of the chamber are shown in Fig. 12. The images were compared with those obtained in microgravity. The characteristic schlieren width, defined as the peak-to-peak hue width divided by the jet diameter, for different pressures in normal gravity and at one atmosphere in microgravity is plotted versus the Froude number (The ratio of the Froude number to the Froude number at normal gravity and one atmosphere pressure) (Fig. 13). The figure indicates that the low atmospheric results tend asymptotically towards the microgravity results. The images of the flame were obtained with the chamber inclined at 60° ($D = 0.84\text{mm}$, $Re = 100$) for different pressures (Fig. 14). It can be observed that the flame becomes straighter with reduced pressure; further indicating that the buoyancy effects diminish with pressure. The amplitude of the flickering flames is affected by the buoyancy levels (Fig. 15). With reduced pressure the amplitude of the oscillations progressively diminishes, as seen in microgravity. From the above study, it was concluded that the buoyancy can be scaled with pressure.

Future Work

Currently, work is progressing on the development of a new drop tower rig with on board digital data acquisition, modified fuel and calibration system and precise imaging. The optimization of the schlieren setup is in progress for improved sensitivity. A parallel effort is in progress for the numerical simulation of hydrogen flames with non-unity Lewis number assumption and multi-component diffusion model.

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References

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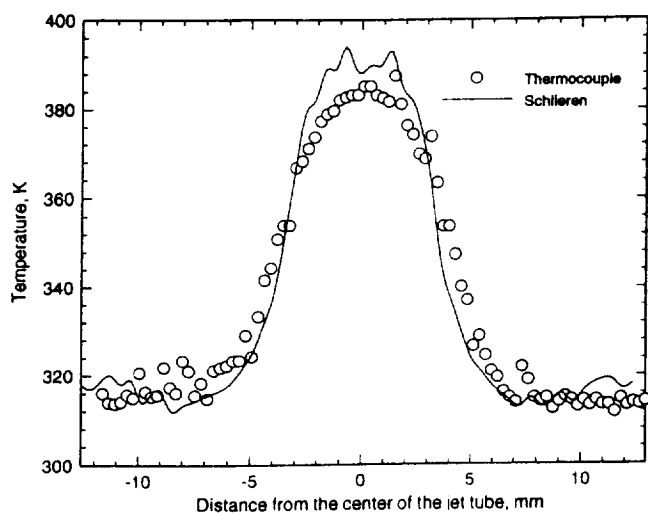


Figure 1.- Temperature in a heated air jet

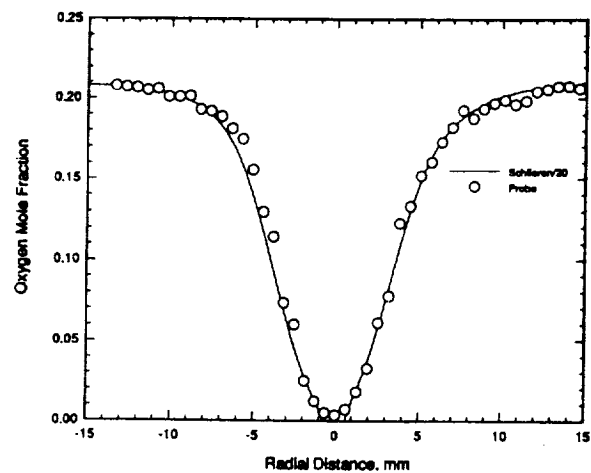


Figure 2.- Oxygen concentration in a helium jet

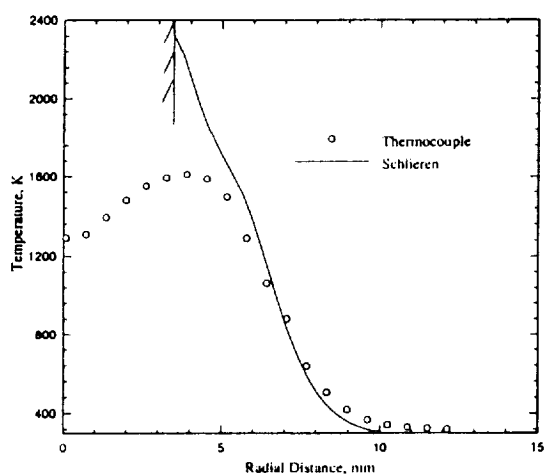


Figure 3.- Temperature in a hydrogen flame

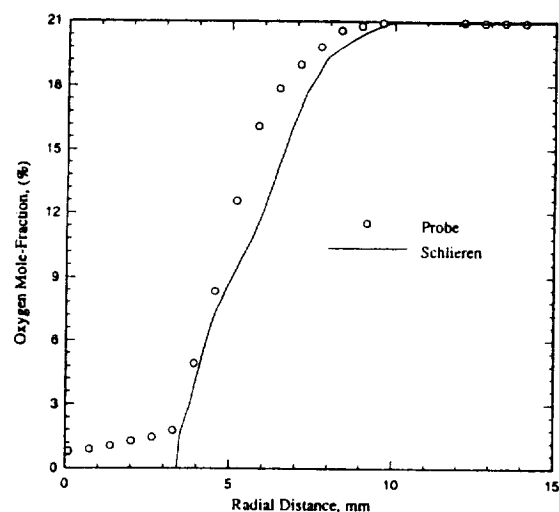


Figure 4.- Oxygen concentration in a hydrogen flame

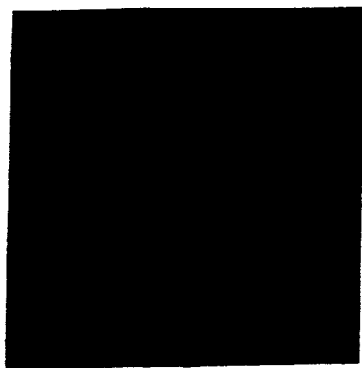


Figure 5.- Computed and experimental schlieren image of hydrogen flame

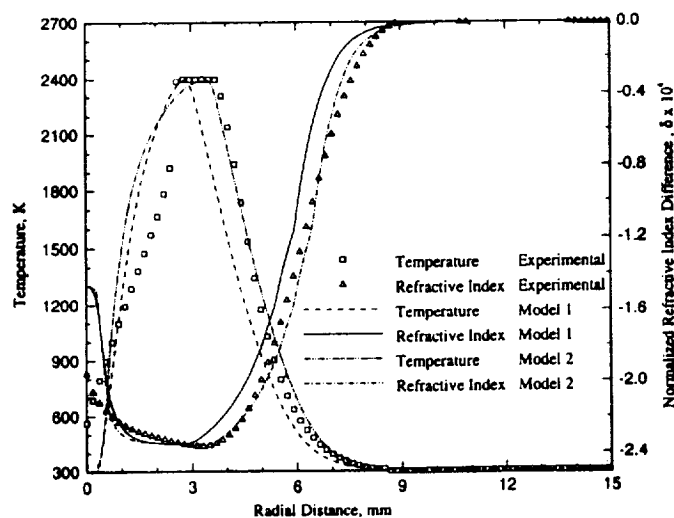


Figure 6.- Computed and RSD temperature distribution of hydrogen flame



Figure 7.- Schlieren image of laminar hydrogen flame

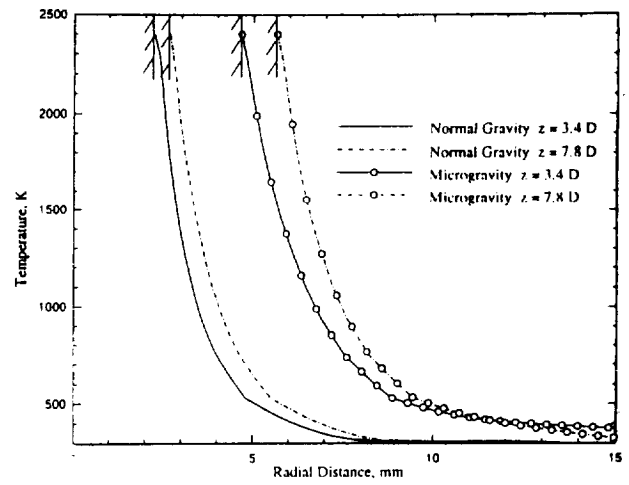


Figure 8.-RSD temperature distribution of hydrogen flame

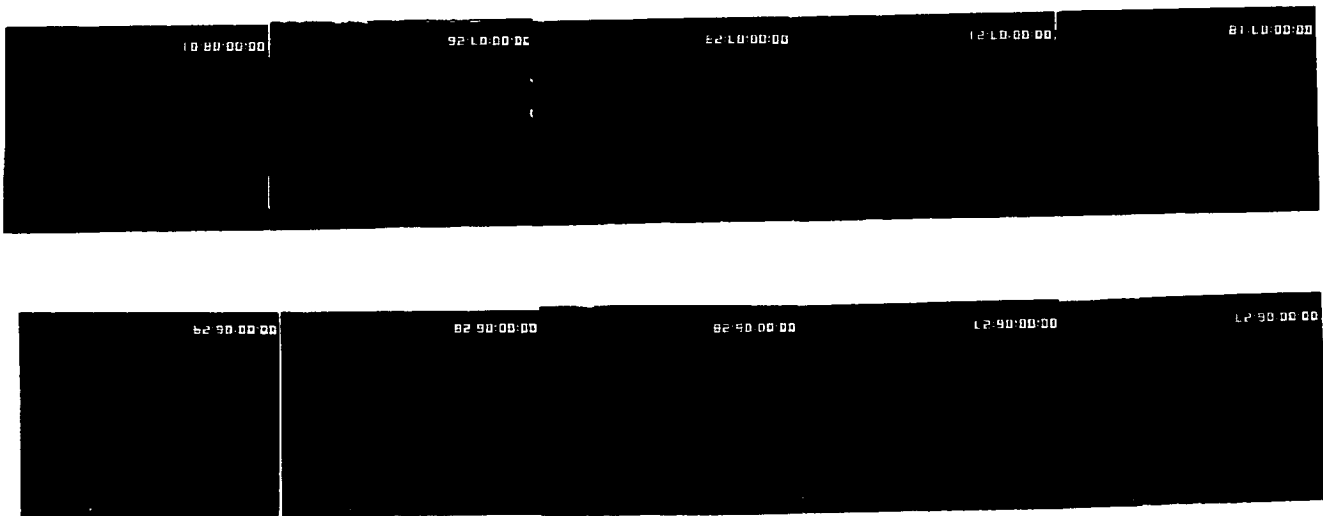


Figure 9.-Sequence of schlieren images of flickering hydrogen flames



Figure 10.- Schlieren image of transitional hydrogen flame

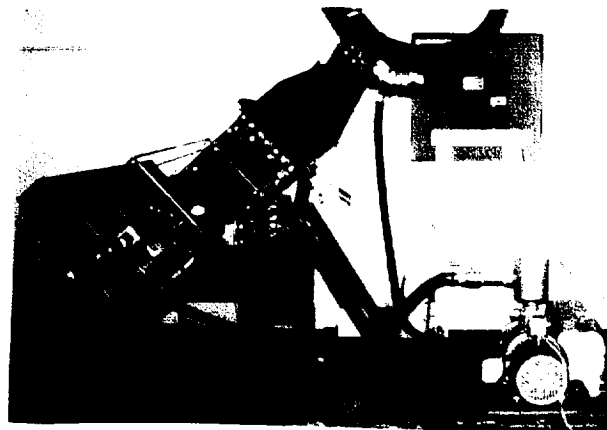


Figure 11.-Sub-atmospheric pressure setup

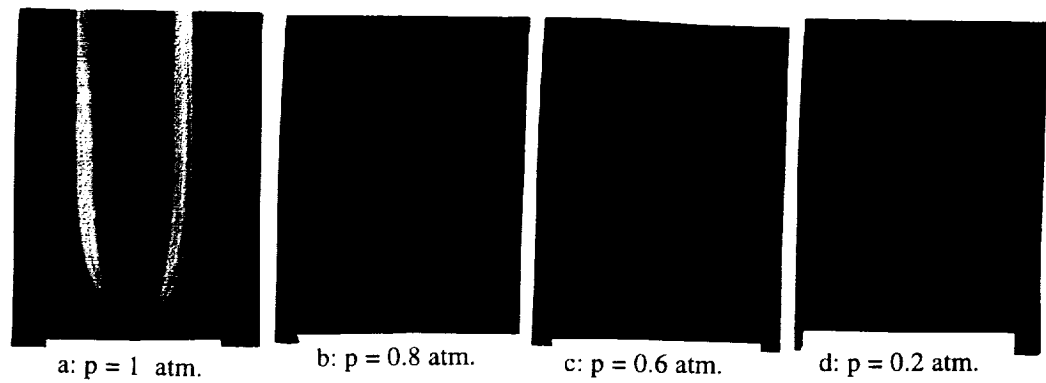


Figure 12.-Schlieren images of hydrogen flames at zero inclination to gravity vector

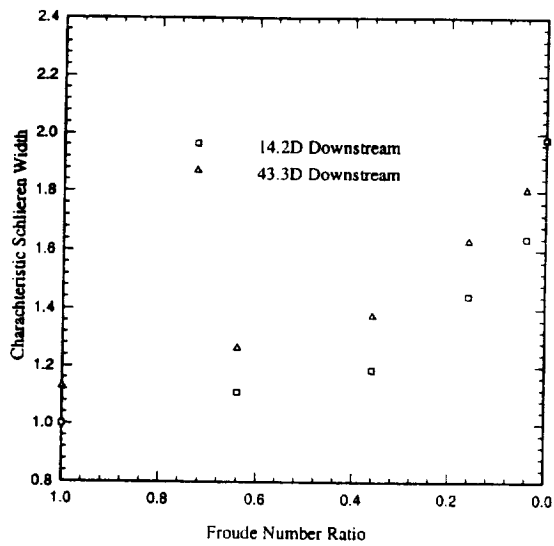


Figure 13.-Scaling of schlieren width with froude number ratio

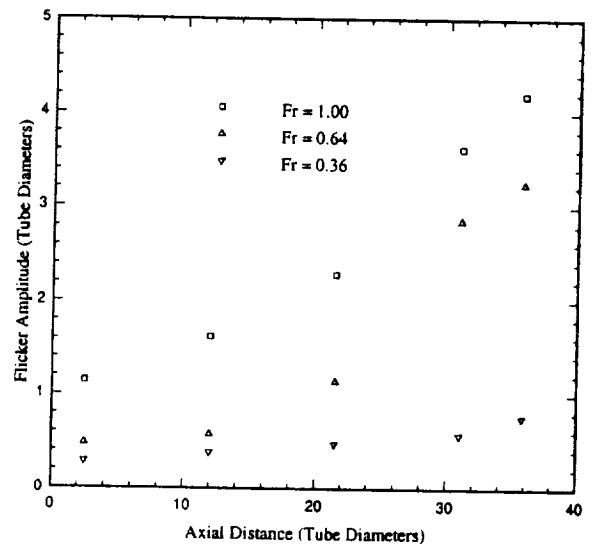


Figure 15.-Flicker amplitude variation with froude number

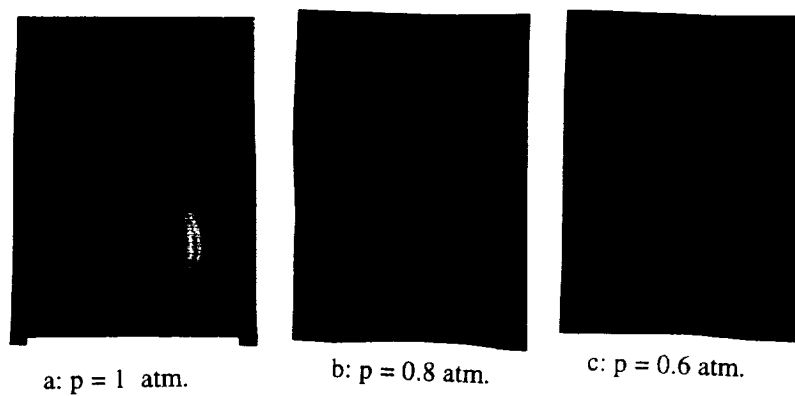


Figure 14.-Schlieren images of hydrogen flames at 60° inclination to gravity vector