LBL-32927
UC-000

Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

ENERGY & ENVIRONMENT DIVISION

Presented at the Western States Section/The Combustion Institute/
1992 Fall Meeting, Berkeley, CA, October 12–13, 1992,
and to be published in the Proceedings

The Effects of Gravity on Wrinkled Laminar Flames

L.W. Kostiuk, L. Zhou, and R.K. Cheng

September 1992

ENERGY & ENVIRONMENT DIVISION

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

LBL--32927

DE93 002572

The Effects of Gravity on Wrinkled Laminar Flames

L.W. Kostiuk, L. Zhou, and R.K. Cheng

Energy and Environment Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

September 1992

This work was supported by NASA Microgravity Sciences and Applications Division and NASA Lewis Research Center under contract No. C-32000-R through the U.S. Department of Energy Contract No. DE-AC03-76SF00098.

The Effects of Gravity on Wrinkled Laminar Flames

L. W. Kostiuk, L. Zhou and R. K. Cheng

Combustion Group
Energy & Environment Division
Lawrence Berkeley Laboratory
Berkeley, CA 94720

Introduction

The effects of gravity are significant to the dynamics of idealized unconfined premixed flames. Moderate to low turbulence Reynolds number flames, i.e. wrinkled laminar flames, of various unconfined geometries have been used extensively for investigating fundamental processes of turbulent flame propagation and to validate theoretical models. Without the wall constraints, the flames are free to expand and interact with surrounding ambient air. The flow field in which the flame exists is determined by a coupling of burner geometry, flame orientation and the gravity field. These complex interactions raise serious questions regarding the validity of comparing the experimental data of open flames with current theoretical and numerical models that do not include the effects of gravity nor effects of the larger aerodynamic flow field. Therefore, studies of wrinkled laminar flame in microgravity (μg) are needed for a better understanding of the role of gravity on flame characteristics such as flame orientation, mean aerodynamics stretch, flame wrinkle size and burning rate.

To date, most studies of microgravity combustion have concentrated on investigating laminar flames. The primary diagnostic used is high speed movies of flame luminosity to observe gross flame properties changes. For example, Durox et al. [1] reported flame tip motion of rich laminar Bunsen flames under microgravity and analyzed the motion by a flame instability model. However, the study of premixed turbulent flames under microgravity requires more sophisticated diagnostics. But there are also many experimental constraints. The short duration of microgravity experiments in drop towers or onboard parabolic flights precludes detailed statistical investigation of velocity and scalar fluctuations. The lack of a high power laser source prohibits the use of many established techniques to measure parameters such as flame crossing frequencies and mean scalar length scales suitable for direct comparison with theoretical models such as the one developed by Bray et al. [2].

Our approach to characterize and quantify wrinkled laminar flame structures under microgravity is to exploit qualitative and quantitative flow visualization techniques coupled with video recording and computer controlled image analysis technologies. The microgravity experiments have been carried out in the 2.2 second drop tower at the NASA Lewis Research Center. The longest time scales of typical wrinkled laminar flames in the geometries considered here are in the order of 10 msec. Hence, the duration of the drop is sufficient to obtain the amount of statistical data necessary for characterize the flame structures.

Diagnostics and apparatus

Schlieren visualization was widely used in early studies of premixed turbulent combustion. Since schlieren is a line-of-sight technique, it has been superseded by laser planar imaging techniques in recent years. Schlieren's most appealing aspects for microgravity work are that it require relatively low power light source, the optics are relatively simple, easy to align and does not require seeding of the flow. When using a laser source coupled with modern CCD cameras with high shutter speeds (up to 1/10000 sec), new video recording and analysis technologies, laser schlieren can provide qualitative information of the flame and quantitative information such as flame angles and perhaps the scale of the flame wrinkle size.

The schlieren system developed for the microgravity experiments uses a 0.5 mW He-Ne laser light source and two 75 mm diameter schlieren lenses. The lenses' diameter is also the effective field-of-view of the system. Due to the constraints of the drop package size, (3' x 3' x 1.5') the two lenses are of different focal length. The transmitting lens has a shorter focal length of 300 mm and the converging lens has a focal length of 1000 mm to maintain a sensitive system. An opaque 1mm diameter spot etched on a glass plate is used as the schlieren stop. This arrangement produces a reverse field image (i.e., dark background), and regions of high density gradients appear bright. The use of reverse field schlieren has advantages for computer controlled image analysis. By choosing an elevated intensity for the background during image processing the dynamic range of the image can be improved.

A CCD camera and a S-VHS video recorder are used to record the schlieren images with the shutter speed varied from 1/60 to 1/10000 sec. The system has an effective framing rate of 60 Hz even though standard play-back speed is 30 Hz. Each frame is made up of two interlaced fields (i.e., separate images) recorded 1/60 sec. apart. Individual fields can be displayed by the S-VHS recorder during freeze-frame operation or the images can be digitized and the fields separated using a computer controlled image processing system. The digitized images can be stored and analyzed by standard image processing software.

A conical Bunsen type burner is used for the first set of experiments. The burner is made of aluminum and has a 25 mm diameter outlet supplied by a converging nozzle mounted on a cylindrical settling chamber. The converging nozzle is designed to produced laminar flows with uniform velocity distribution across the exit. The flame is stabilized by a ring fitted to the exit of the burner to enable stabilization of lean flames. Turbulence is generated by a perforated plate placed 20 mm upstream of the exit. The entire experiment is contained within the standard drop package frame for the NASA Lewis Research Center 2.2 second drop tower facility. The schlieren system is located on the upper level of the package. The laser, optics and camera are mounted on a reinforced 0.5 inch thick aluminum plate to act as a stable optical platform. The central level of the drop package contains all of the electronics which includes a computer, control box, ignition system and a fiber optic transmitter to send the video signal to a recorder at the top of the drop tower. The bottom level of the package is for the fuel and air supplies, valves and regulators to control the flow rates and two battery packs to supply power to all the electrical equipment.

The package is placed in an outer shield which feels the aerodynamic drag during the drop and the package the free falling within this shield. The package and shield are hoisted to the top of the drop tower where the flame is manually ignited and several seconds of the schlieren images in normal gravity are recorded as a reference for the μ g portion of the experiment. The flame is shut-off, the drop package is then sealed and the onboard computer proceeds with the drop sequence governed by externally switched TTL signal used as inputs. The computer and control box can open and closed solenoid valves for the fuel and air, turn on and off any of the electrical equipment, position or retract the spark electrode, and trigger the ignition spark. Ignition can be done in normal gravity and the transition to μg can be observed, or the ignition can be done in μg. At the bottom of the drop tower, just prior to impacting the sand pit, the computer turns everything off except the air to purge the system .

Results

Normal gravity

As a necessary prerequisite to the microgravity experiments, a parametric study to determine the mixture and flow conditions at which the effects of gravity on flame characteristics are most prominent had been conducted. Schlieren images of laminar and turbulent conical flames subjected to +g (upwards) and -g (downward) forces on the product gases are compared. The -g experiments were done by inverting the burner. In addition to schlieren visualization, selected flames are investigated in detail by the use of two-component laser Doppler anemometry (LDA) to determine the coupling between the flow field (reactants, flame, products and surrounding air) and the flame characteristics.

Figure 1 shows a typical schlieren image of a +g laminar conical flame. The flame is shown by the triangular silhouette above the burner exit. In addition, the interfaces formed between the hot products and the ambient air are also visible. This product/air interface is unstable and is characterized by the formation of bulges reminiscent of the roll-up of torroidal vortices. A comparison of two time sequences of +g and -g schlieren images of a laminar methane/air flame ($\phi = 0.6$ and incident flow velocity $U = 0.7$ m/s) is shown in Fig. 2. The development of the roll-up vortex like structure in the unstable product/air shear interface is apparent. The video also shows that the flame tip moves up and down synchronously with this shear layer disturbance. When subjected to -g the flames shown in Fig. 2 has its tip flattened and the product/air interface in the vicinity of the flame has become much more stable than the +g case. As a consequence there is very little movement of a laminar flame in -g. At higher flow rates the flame tip is not flattened and has the same general appearance to the +g flame but with no flame tip motion.

The height of the flame tip above the burner exit is shown in Fig. 3 for +g and -g condition as a function of the total flow rate and for two equivalence ratios. At low flow rates the -g flames have flattened tips and are as a result shorter than the +g flames. As the flow rate is increased the -g flames appear conical and become longer than the +g flames at the same flow rate. Both +g and -g flames increase in length almost linearly with flow rate, but the rate of increase in -g condition is greater. As a result, the higher the flow rate the greater the difference between the flame tip heights, and by implication the effects of gravity on the flame height does not diminish with increased flow momentum. This is a counter-intuitive result and may be explained by subtle differences in the flame shape between +g and -g.

The flame tip motion being fully synchronous with the unsteady product/air interface is also observed in the +g turbulent flames. Figure 4 shows a typical sequence. The flame wrinkles are either stretched larger or compressed smaller during the cycle. This implies a direct flow field effect on the turbulent burning rate.

Durox et al. [1] also reported and analyzed flame tip motion in their rich laminar flames under normal and microgravity. By only observing flame luminosity, they were not aware of the significance of the product/air interface. The flame tip motion in their study was attributed to flame instability developed at the burner rim. To estimate if their results are consistent with the present data, the schlieren videos are analyzed to determine the fluctuation frequencies of the product/air interface. The width of the product/air interface silhouette at the mean height of the flame tip are determined for 60 fields (1 sec total time). The results are fitted with a cubic spline and analyze by Fast-Fourier-Transform. All flames show primary fluctuation frequencies between 8 to 13 Hz (Fig. 5). These frequencies are about the same as those reported by Durox et al. Therefore, it seems that the flame tip motion observed by Durox et al. are also induced by the instability of the product/air interface.

The unstable product/air interface also induces flow fluctuations in the approach flow. The velocity spectra obtained at the centerline about 4 mm upstream of a laminar flame tip clearly show a dominant fluctuation frequency (Fig. 6) and higher harmonics of this primary frequency also exist. This is a strong evidence of the coupling between the flow field and flame front dynamics. Velocity spectra obtained in a turbulent flame also show the dominant fluctuation frequency (Fig. 7) though the relative energy containing in this frequency is diminished by the turbulent kinetic energy associated with the grid turbulence. This observation strongly suggests that the unstable product/air interface has a significant influence on flame propagation and is the avenue through which gravity affects turbulent flame characteristics.

Microgravity

The μg experiments were conducted at NASA Lewis Research Center in September, 1992. The μg data set includes methane/air laminar flames with flow rates ranging from 0.26 to 0.46 litres/s all at an equivalence ratio of 0.9 and turbulent flame at a flow rate of 0.45 litres/s and equivalence ratio between 0.7 and 0.75.

Initial experiments were done by igniting the flame in normal gravity and then begin the drop. Only flames well away from blow-off conditions were able to withstand the transition to μg. Most flames, both laminar and turbulent, found the transition into μg in the 2.2 second drop tower facility to be too disruptive to remain stabilized to the burner. Therefore, most μg results come from flames ignited after the drop. The only problem with ignition in μg is that the 0.5 seconds to ignite and stabilize the flame is a significant portion of the total drop time thus reducing the amount of data available for statistical analysis.

In μg the product/air interface leaves the field of view as a stable large pocket of products surrounds the burner exit. The instability of this interface no longer has a dominant role in pumping the flame tip motion. In the laminar flames there still exists an instability of the flame. The amplitude of this instability is small compared to the normal gravity disturbance to the flame. Durox [1] also noted an instability in their low gravity flights and was thought to come from "g-jitter" (the inability of the aircraft to maintain constant acceleration to oppose gravity). Yet the flame continues to show instabilities despite the fact that there is no "g-jitter' in the drop tower. In the turbulent flames due to the random nature of the wrinkled flamelets, it is difficult to identify any difference between normal and μg flames without a detailed analysis of the video image. Many image analysis and display software are available from the LBL Image Analysis Group for characterizing the schlieren images. The analysis is in progress and the results will be forthcoming.

Summary

A detailed study of the effects of gravity on laminar and turbulent conical Bunsen type flames has been undertaken. The study compares results from normal gravity with the burner in an up-right orientation (+g), the burner inverted (-g), and in microgravity (μg) by using the NASA Lewis drop tower facility. The primary diagnostic is a laser schlieren system and some LDA measurements were taken for the +g condition to measure the flow field.

The +g laminar flame experiences a large amount of instabilities and results in an unsteady flame tip. The cause of this large instability are torroidal vortex rolling up between the products and the stagnate surrounding air. Comparison between the LDA measurements in the reactants and the schlieren images shows that velocity fluctuation are induced at the same frequency as the roll up vortices are formed. This pumping of the reactant stream by the product/air interface instability in the +g case is also observed in the turbulent flames.

In the -g arrangement the product/air interface is stable so there is no large pumping of the flame tip. At low flow rates the -g flames have flattened tips, but at higher flow rates they become conical in shape. Comparing the flame height between the +g and -g shows that when both flames appear conical the -g flames are longer for the same flow rate.

In μg the larger instabilities in the flame no longer exist as the product/air interface is believed to become stable. The laminar flames in μg still show small instabilities over the entire flame.

Acknowledgments

This work is supported by NASA Microgravity Sciences and Applications Division. Technical support is provided by NASA Lewis Research Center under contract No. C-32000-R. Project Scientist is Dr. Karen J. Weiland.

References

1. Durox, D., Baillot, B., Scoufflaire, P. and Prud'homme, R. "Some Effects of Gravity on the Behavior of Premixed Flames", Combustion and Flame, Vol. 82, 1990, p. 66.
2. Bray, K.N.C., Libby, P.A., and Moss, J.B., "Unified Modeling Approach for Premixed Turbulent Combustion - Part I: General Formulation", Combustion and Flame, Vol. 61, 1985, p. 87.

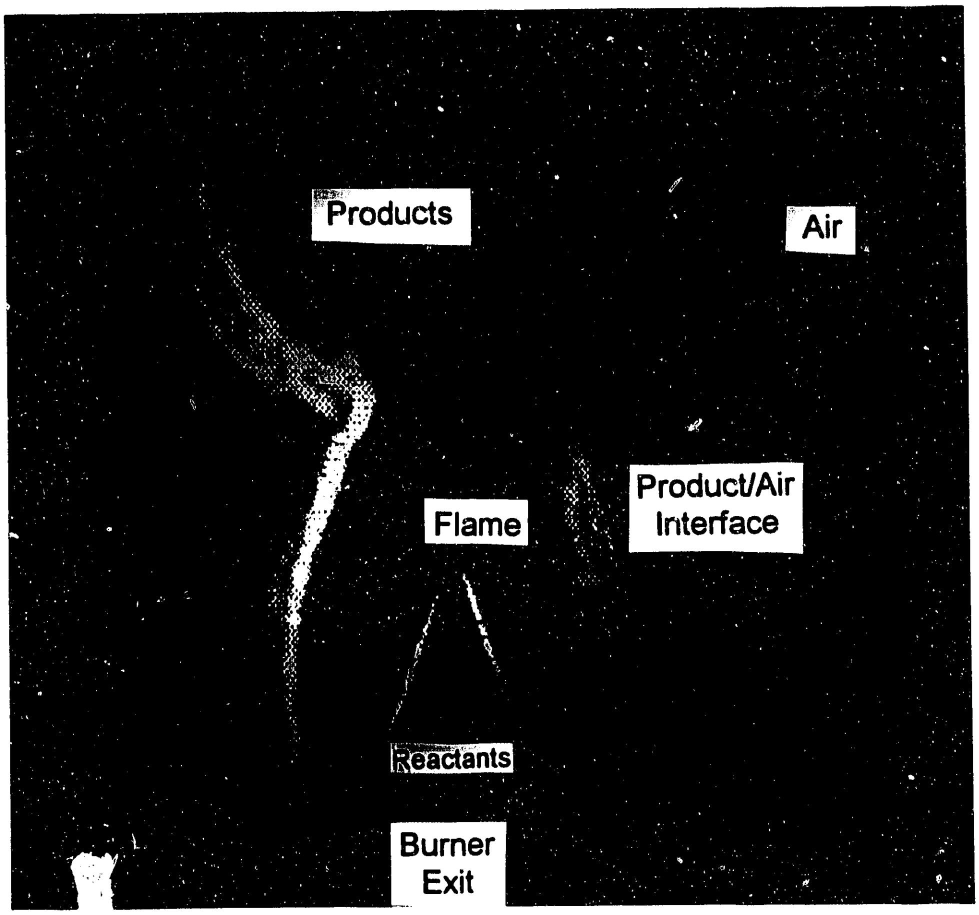


Figure 1: Typical Schlieren of +g Laminar Conical Flame.

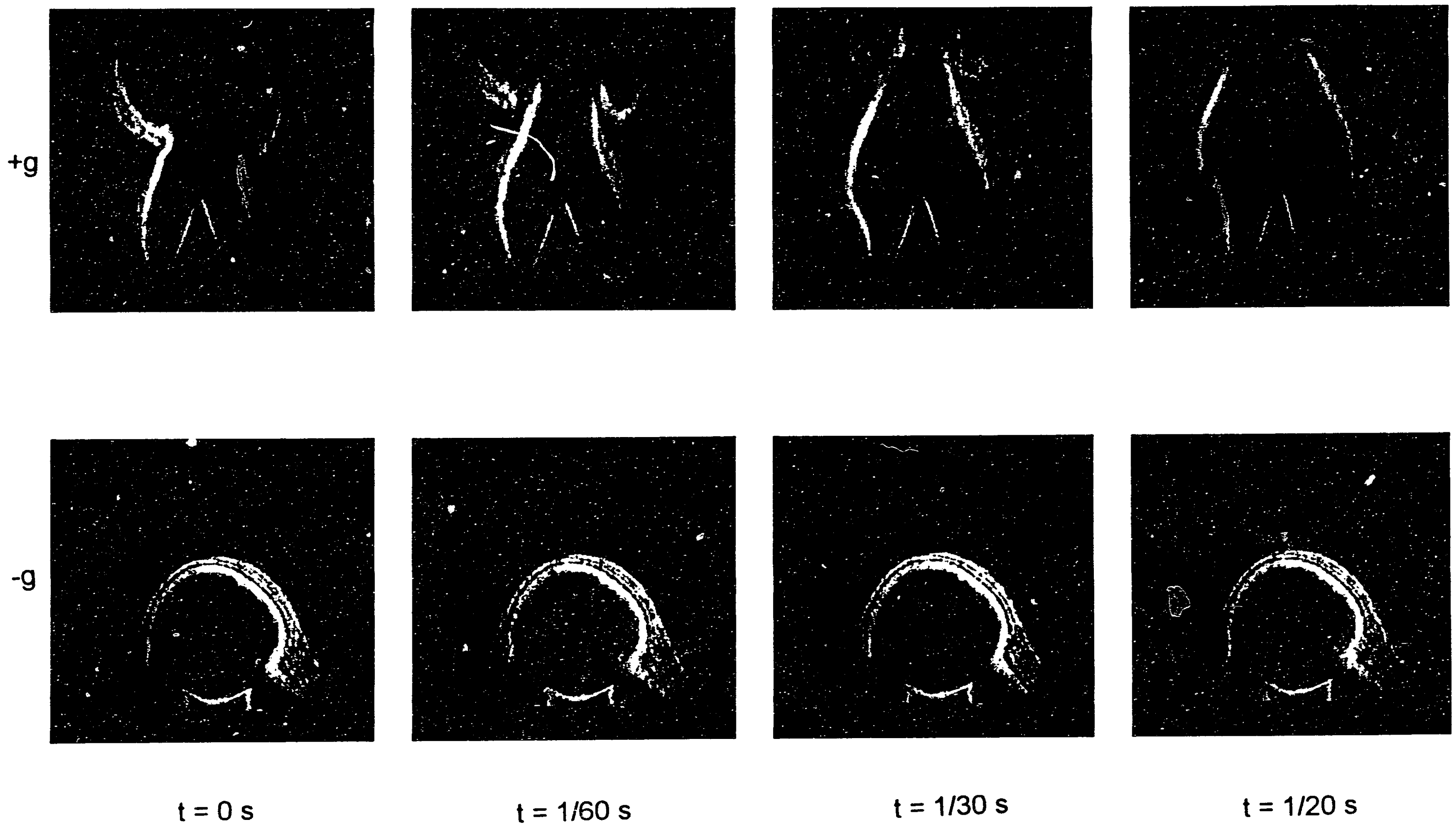


Figure 2: Time Sequence of +g and -g Laminar Conical Flame.

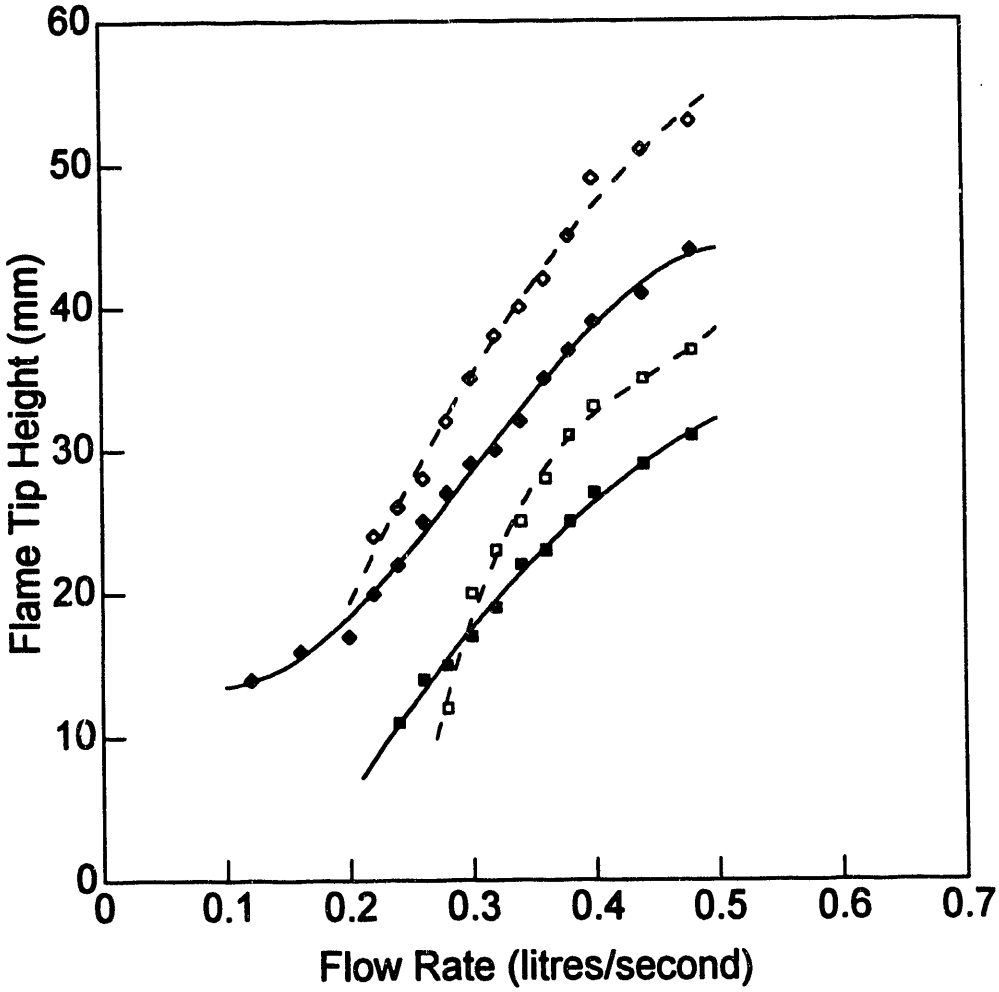
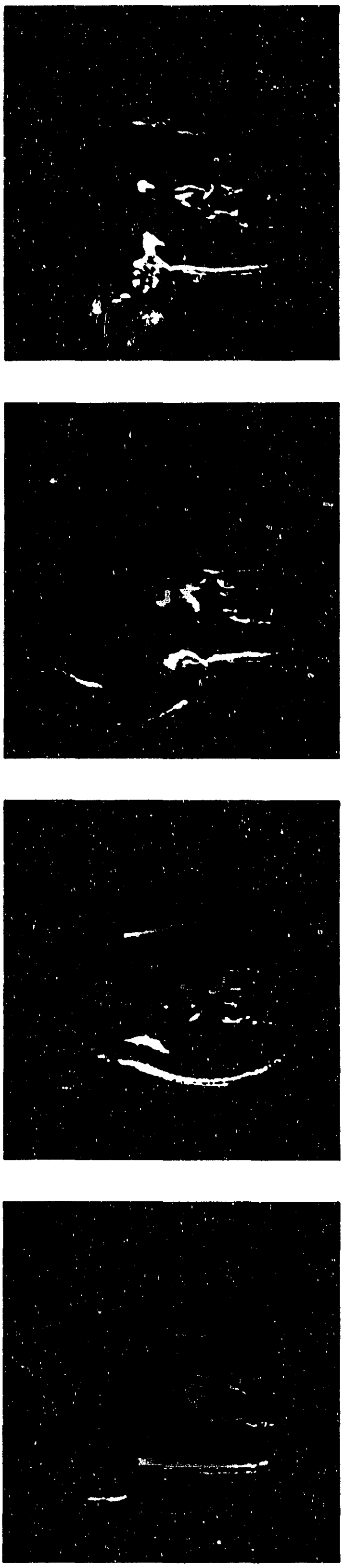


Figure 3: Flame Tip Height of Laminar Conical Flame.



+g

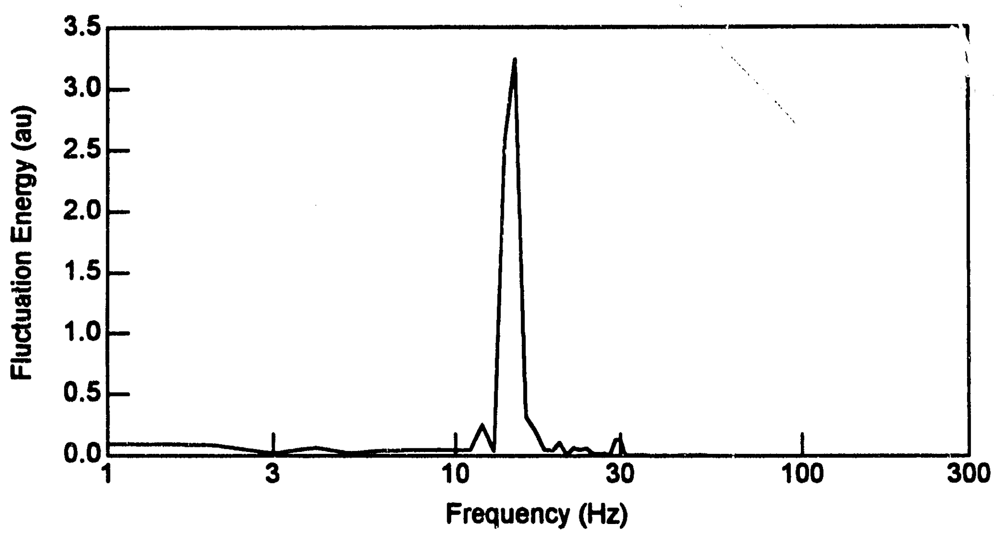


Figure 5:Spectra of Position of the Product/Air Interface for Laminar Conical Flame.

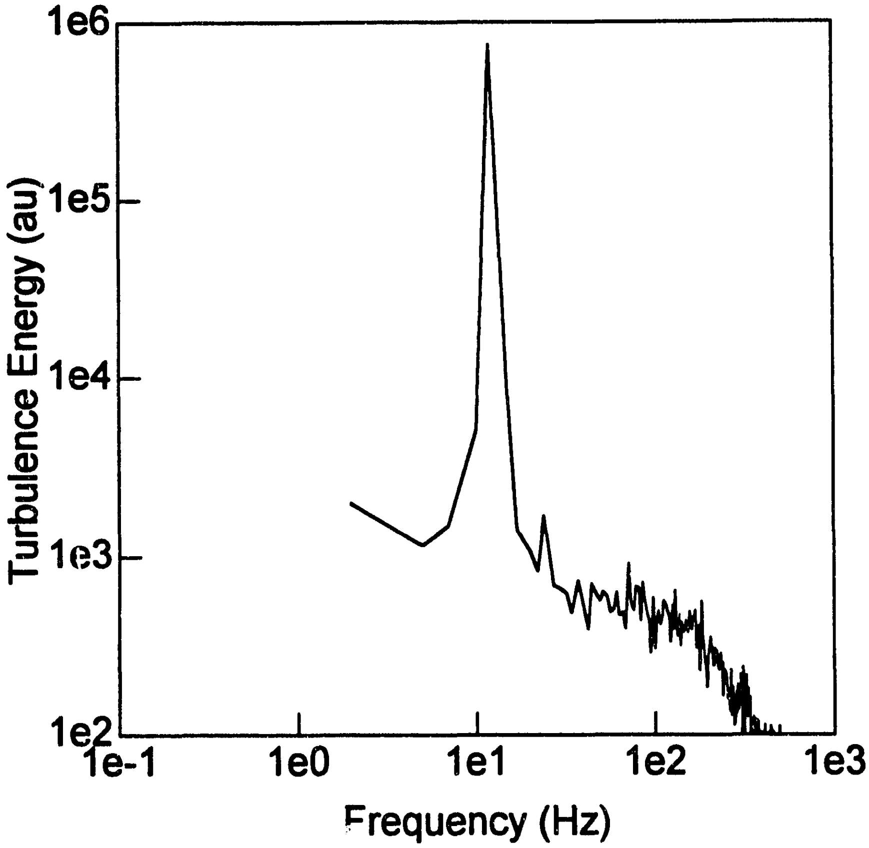


Figure 6:Axial Reactant Velocity Spectra for Laminar Conical Flame.

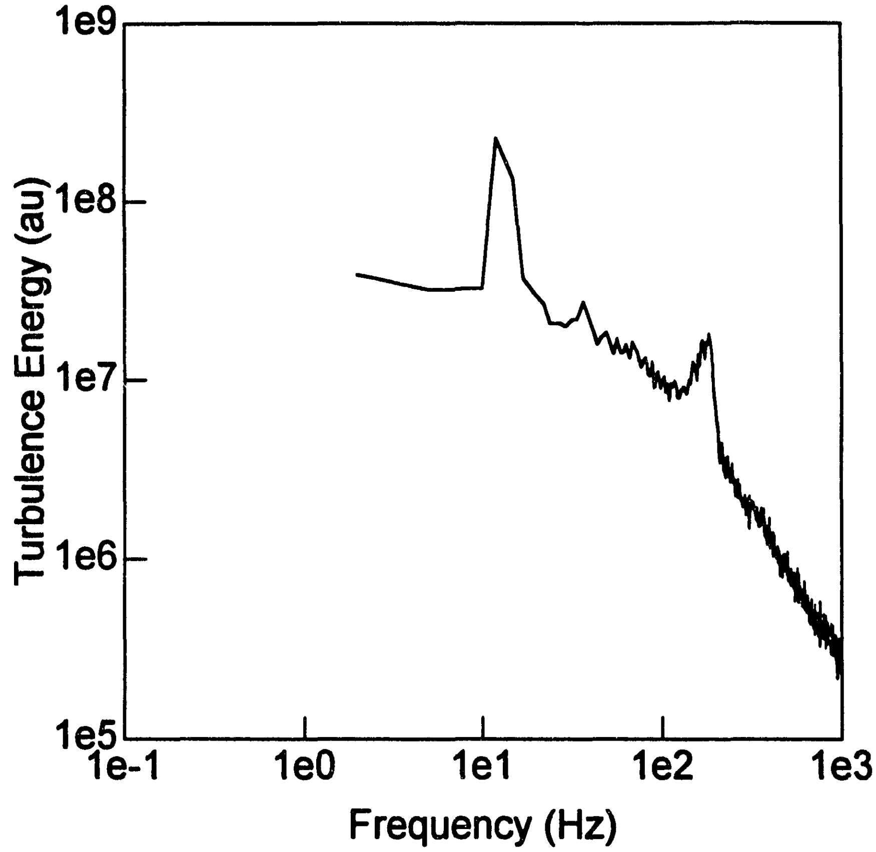


Figure 7: Axial Reactant Velocity Spectra for Turbulent Conical Flame.

DATE FILMED

01/21/93