

THE EFFECTS OF GRAVITY ON WRINKLED LAMINAR FLAMES

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N 93 - 20200

Introduction

The effects of gravity are significant to the dynamics of idealized unconfined open 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 flowfield 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 flowfield. Therefore, studies of wrinkled laminar flame in microgravity 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 turbulent flame structures under microgravity is to exploit qualitative and quantitative flow visualization techniques coupled with video recording and computer controlled image analysis technologies. The experiments will be 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 turbulent flame structures.

Diagnostics and apparatus

Schlieren visualization was widely used in early studies of premixed turbulent combustion. Because it 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 and it is easy to align. 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 flowfield and quantitative information such as flame angles and perhaps flame wrinkle size.

The schlieren system developed for our 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, the two lenses are of different focal length. The transmitting lens has

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.

a relatively short focal length of 300 mm and the converging lens has a focal length of 1000 mm to maintain a sensitive system. An opaque spot etched on a glass window 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.

A CCD camera and 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 on the S-VHS deck 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 produce 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 laser, optics, burner, flow control and supply systems, and onboard computer are mounted inside a standard 3' x 3' x 1.5' drop package frame for the NASA Lewis Research Center 2.2 second drop tower (Fig. 1).

Normal gravity studies

As a necessary prerequisite to the microgravity experiments, we have conducted a parametric study to determine the mixture and flow conditions at which the effects of gravity on flame characteristics are most prominent. Schlieren images of laminar and turbulent conical flames subjected to +g (upwards) and -g (downward) forces are compared. 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 flowfield (encompassing the reactants, flame, and surrounding gases) and the flame characteristics.

Figure 2 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. 3. 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. Subjecting the flame to -g changes the flame shape and turns the product/air interface into a stable envelope of hot gases, so the flame is much more stable than in the +g case.

The flame tip motion being fully synchronous with the unsteady product/air interface is also observed in the +g turbulent cases. Figure 4 shows a typical sequence. The flame wrinkles are either stretched larger or compressed smaller during the cycle. This implies a direct flowfield 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 flowfield 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. These results have been presented at the poster session of the 24th International Combustion Symposium [3].

Planned activities and diagnostic development

The microgravity work will be carried out at NASA Lewis Research Center in September, 1992. The experiments will be concentrated on methane/air laminar and turbulent flames with equivalent ratio from 0.5 to 1.0 and mean flow exit velocity from 0.5 to 1.0 m/s. These are the conditions found to be most affected by the change in the direction of the gravitation forces. Schlieren will be the primary diagnostic and the results will be analyzed as outlined above to obtain the changes in the flame shape, and the fluctuation frequencies of the flame tip and of the product/air interface. The videos will also provide qualitative information on the changes in the flame wrinkle sizes.

The second phase of the microgravity experiments will involve the use of other flame configurations such as rod-stabilized v-flames. The development of quantitative diagnostics for measuring flame wrinkle characteristics is also planned. The single beam schlieren technique will be exploited for measuring the flame crossing frequencies at a point. The deflection of a He-Ne laser beam traversing the flame zone can be quantified by the use of a diode. Fast Fourier transform of the diode output will produce a spectrum of the flame crossing frequency that is directly related to the flame wrinkle sizes. Refinement of the technique will rely on comparing the results with those obtained from the Mie scattering from oil droplet method that is normally used in laboratory experiments. The comparison will also help to establish the proper data interpretation method.

References

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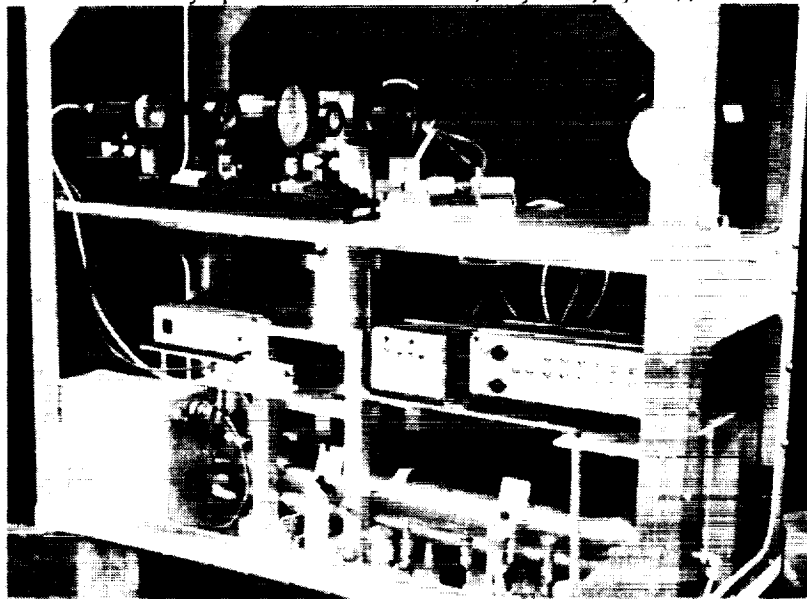


Figure 1: Photograph of Drop Package.

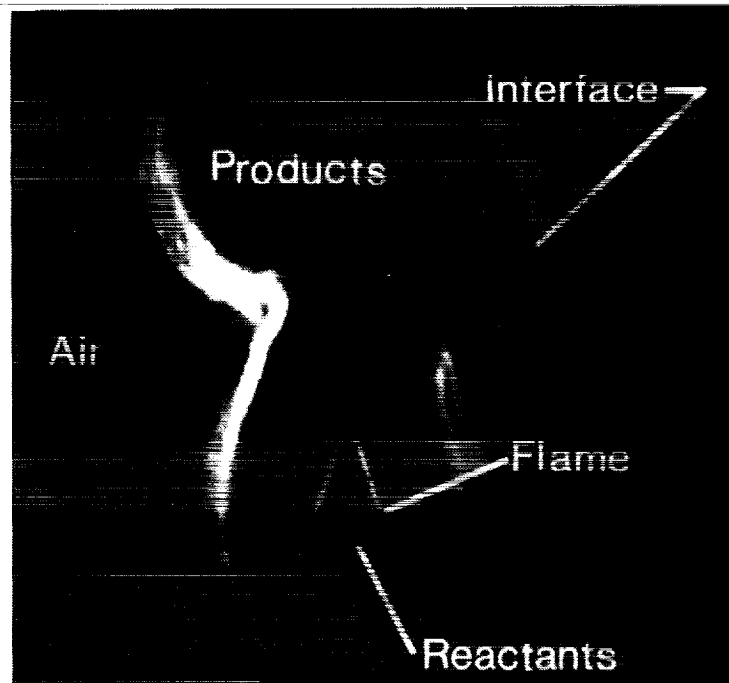


Figure 2: Typical Schlieren Image of Premixed Laminar Bunsen Flame.

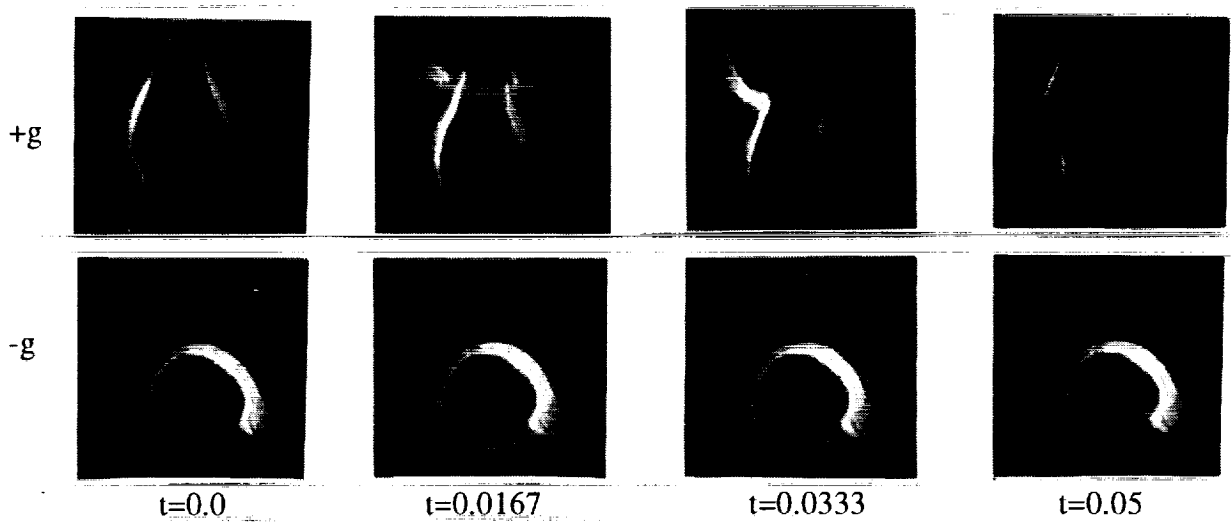


Figure 3: Time Sequence of Schlieren Images for Laminar Flame.

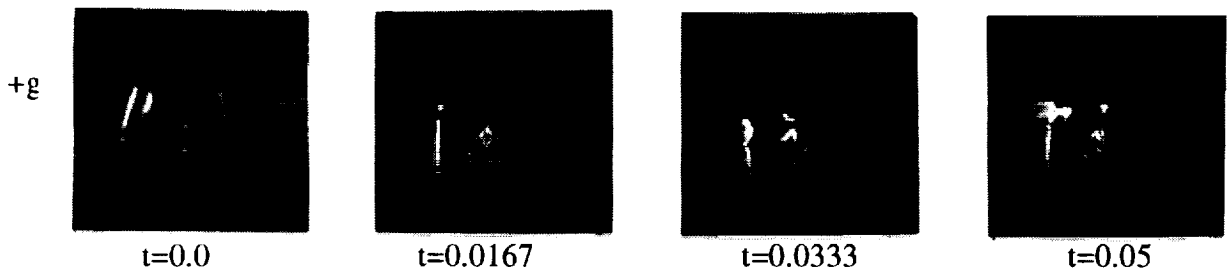


Figure 4: Time Sequence of Schlieren Images for Turbulent Flame.

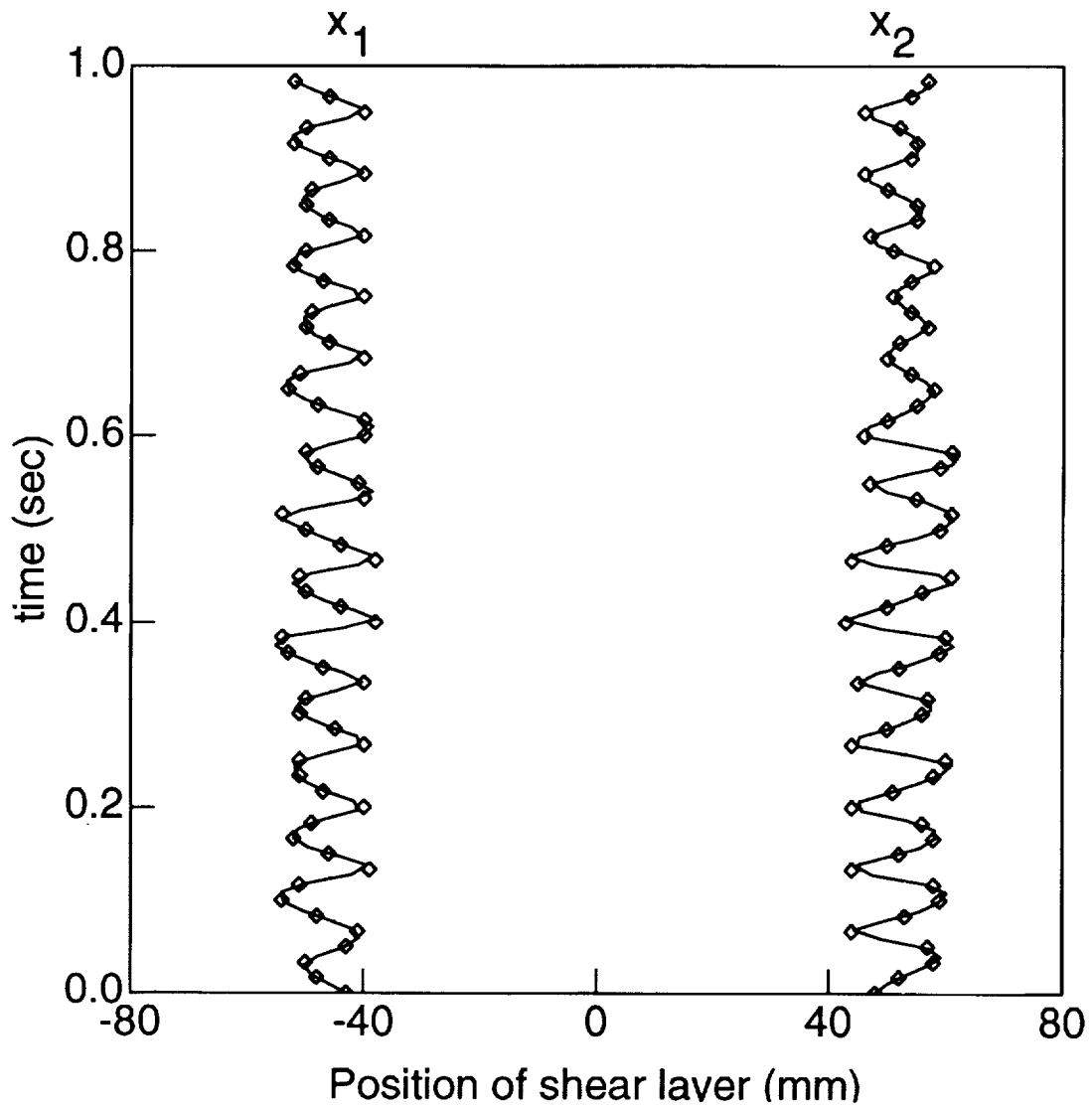


Figure 5: Radial Position of Air/Product Interface.

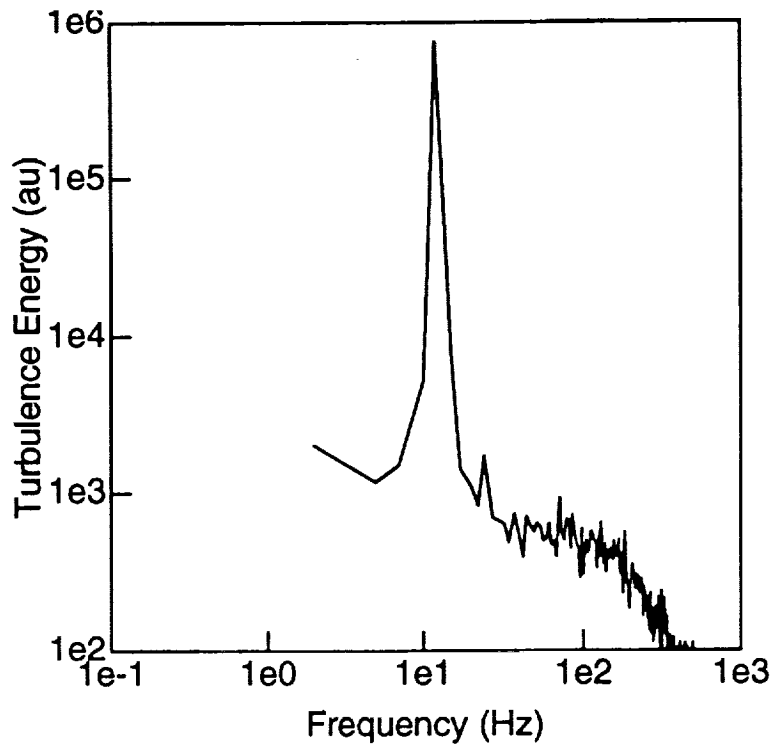


Figure:6 Velocity Spectra of Laminar Flame.

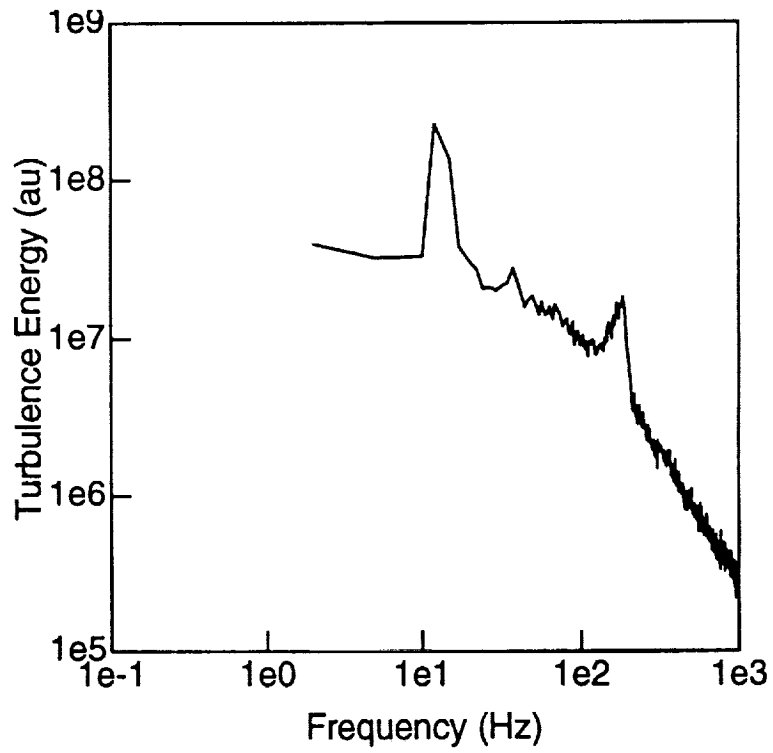


Figure7: Velocity Spectra of Turbulent Flame.