

**COUPLING OF WRINKLED LAMINAR FLAMES WITH GRAVITY****Benoit Bédard, Larry W. Kostiuik\* and Robert K. Cheng****Combustion Group  
Energy & Environment Division  
Lawrence Berkeley Laboratory  
Berkeley, CA 94720**

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**Introduction**

Turbulent combustion involves complex coupling of chemical and fluid mechanical processes and is considered as one of the most challenging fundamental combustion research problems today. Though the effects of gravity are not very significant in power generating systems (e.g., IC engines and turbines), laboratory burners with open flames, and small to medium furnaces and boilers are affected by buoyancy. Because the physical processes through which gravity affects combustion are poorly understood, it is difficult to access if flame orientation has any impact on extinction, burning rate, and formation of pollutants. Theoretically, buoyancy is often neglected in turbulent combustion models [1] for the sake of simplicity. Yet the modeling results are routinely compared with experiments of open laboratory flames that are obviously affected by buoyancy. This inconsistency is an obstacle to merging experiments and theories. Consequently, a fundamental understanding of the coupling between turbulent flames and gravity is significant to both turbulent combustion science and applications.

The overall effect of gravity relates to the dynamic interaction between the flame and its surrounding, i.e., the so-called elliptical problem. For laminar and mildly turbulent flames, the coupling of gravity, flame geometry, flow momentum and heat release determines the flowfield, flame shape, flame instability and perhaps burning rate. Although few aspects of the coupling of steady flames with gravity have been explored, fundamental studies of unsteady flame propagation have shown that gravity can affect flame speed and ignition limits [2,3]. Intuitively, the role of gravity should become much less important with increasing flow momentum. This is the justification for not including gravity in high Reynolds number turbulent combustion models. However, there has yet to be a systematically experimental investigation to determine the criteria or limits for the conditions under which gravitational forces would become insignificant.

The overall objective of our research is to understand flame-gravity coupling processes in laminar and low turbulent Reynolds number,  $Re_1$ , premixed flames (i.e. wrinkled laminar flames). The approach we have developed is to compare the flowfields and mean flame properties under different gravitational orientations. Key to our study is the investigation of microgravity ( $\mu g$ ) flames. These  $\mu g$  experiments provide vital information to reconcile the differences between flames in normal gravity (+g, flame pointing upward) and reverse gravity (-g, flame pointing downwards). Traditionally, gravity effects are assumed to be insignificant or circumvented in the laboratory, therefore, not much is available in the literature on the behavior of -g flames. As for  $\mu g$  premixed flames, Durox and co-workers investigated slightly to very rich laminar Bunsen flames and reported that these conical flames tend to grow slightly taller in  $\mu g$  [4] and the number of cells form in polyhedral flames are also affected. Their use of directly photography, however, did not enable them to extract quantitative information that are amenable for analysis.

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\* current address Department of Mechanical Engineering, University of Alberta, Edmonton, Alberta, Canada

## Diagnostics and apparatus

Laser schlieren is used in our  $\mu\text{g}$  experiments [5,6]. This technique requires relatively low power light source and the optics are relatively easy to align. We use a CCD cameras with high shutter speeds (up to 1/10000 sec) to capture the changes in mean flame properties. One innovation of our work is to exploit the interlace feature of standard video recording to double the recording rate from 30 to 60 Hz. The schlieren system is housed in a standard drop-package for the NASA LeRC 2.2 second drop tower. It employs a 0.5 mW He-Ne laser light source and has a field of view of 75 mm. An opaque spot etched on a glass window is used as the schlieren stop that produces a reverse field image (i.e., dark background), and regions of high density gradients appear bright. The burner 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. Turbulence is generated by placing a perforated plate 20 mm upstream of the exit. Two different flame configurations have been investigated. To generate v-flame, a rod of 2mm diameter is place across the center of the burner exit. To generate conical flames, a ring is fitted to the exit. This ring stabilizes very lean flames and has potential for use in practical application. A patent application has been filed for this stabilizer ring.

## Experimental Conditions

We have completed thus far three  $\mu\text{g}$  experimental campaigns. Two were performed in the 2,2 second tower and the latest one in the Learjet. The experimental conditions cover flow rates from 0.2 to 0.9 liter/sec (mean velocity,  $U$ , of 0.5 to 2.0 m/s), and methane/air equivalence ratio,  $\phi$ , from 0.65 to 1.0. The turbulent intensity is less than 1% for the laminar flame and is 8% when the perforated plate is used. These conditions produce flame that are classified as wrinkle laminar flames. The laboratory studies cover a wider range of experimental conditions to investigate if the +g and -g flames are indistinguishable at high flow rates. In addition to using laser schlieren, laser Doppler anemometry (LDA) was used to determined the mean and turbulent flowfields of +g and -g flames. These velocity data provide the necessary background of the flowfield to interpret changes observed in the  $\mu\text{g}$  flames.

## Results

### Conical Flames

Laser schlieren images of laminar and turbulent conical flames in +g, -g and  $\mu\text{g}$  are compared in Figure 1. Starting with the +g laminar case (top-left), the smooth conical flame is seen at the center. It is surrounded by a buoyancy driven unstable interface formed between the hot products and the ambient air. As shown on the videos, it pulsates at a regular characteristic frequency,  $\nu$ , and causes the flame to flicker. The schlieren image of the turbulent flame (bottom-left) is characterized by the wrinkled flame cone. The turbulent flame has no noticeable effect on the product/air interface. It remains wrinkle free and pulsates the same way as those of laminar flames. The effects of reversing the gravitational orientation are shown by the images of -g laminar flame (top-center) and -g turbulent flame (bottom-center). The most obvious change is that buoyancy causes the products to stagnate and reverse the flow direction. The product/air interface appears just below the tip of the flame and it curves up to cover the flame cone. These interfaces do not pulsate in the vicinity of the flame and so the flame ceases to flicker (top and bottom right). In the absence of buoyant forces,  $\mu\text{g}$  flames do not flicker. This is the same observation reported by Durox et. al [4]. Our schlieren videos show that product/air interface is no longer unstable and becomes invisible. This implies a decrease in the density gradients associated with broadening of the product/air interface thickness. Without buoyancy to transport the hot products away from the flame zone, the products form a pocket around the flame that expands into the ambient air. The

flow in this pocket lose its momentum quickly because of divergence. As the volume of this pocket can increase indefinitely, an interesting implication is whether or not  $\mu g$  flames ever attain steady states.

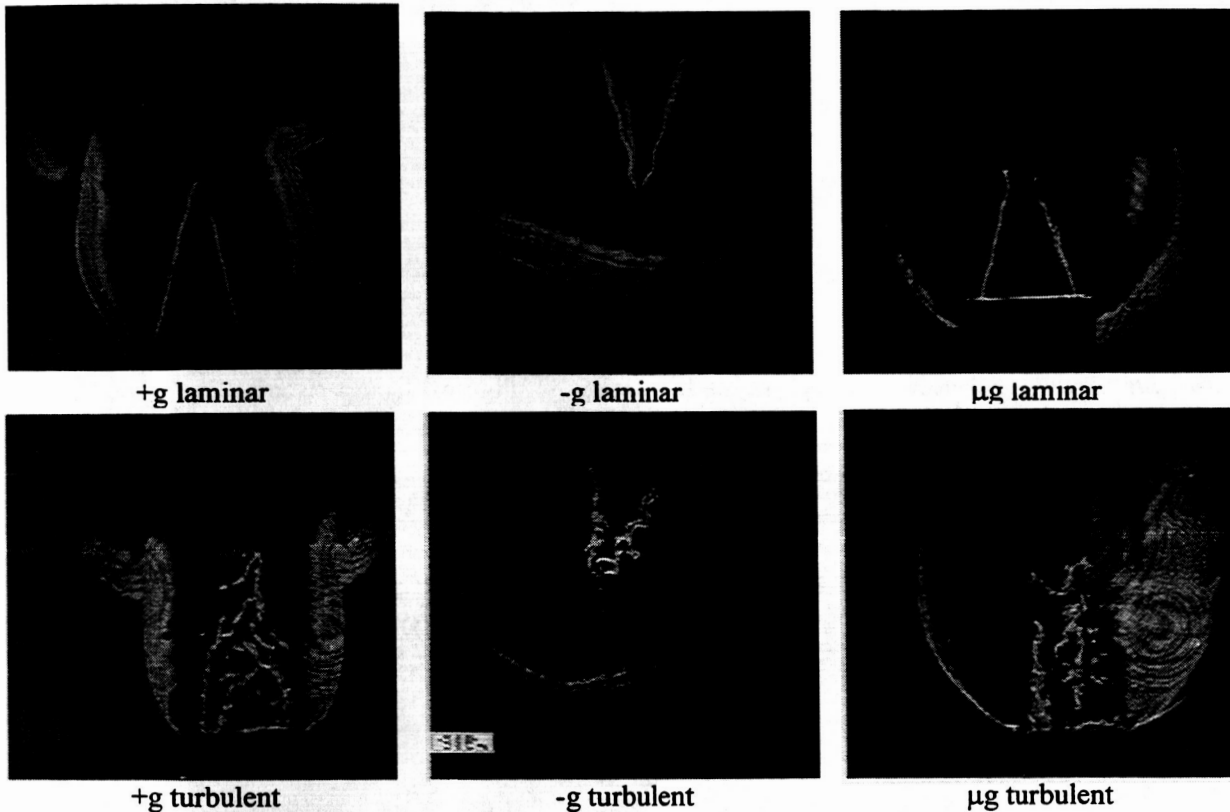


Figure 1 Schlieren images of laminar ( $\phi = 0.9$ ,  $Q = 0.42$  l/sec.) and turbulent ( $\phi = 0.75$ ,  $Q = 0.45$  l/s) conical flames

As the pulsating product/air interface of +g flame has far-reaching effects throughout the flame flowfield, analysis of the characteristic pulsating frequency,  $\nu$ , (i.e., the flame flickering frequency), would be useful to identify the relevant processes that control flame/gravity coupling. We begin the analysis by considering the relevant forces acting on the plume of hot gases. These forces are the momentum of the jet, viscous drag on the surroundings, buoyancy of the products, and a dynamic force that causes the flow to fluctuate. Ratios of these forces are the Strouhal number,  $St$ , the Richardson number,  $Ri$ , the Reynolds number  $Re$  and the Grashoff numbers. We adopted a reduced Strouhal number,  $St^* = (St/(\tau+1))$  to account for the effects of heat release ( $\tau$  is the heat release ratio of the combustion process). This analysis produces an empirical relationship that expresses the ratio between the fluctuation and buoyancy forces (expressed in terms of a reduced Strouhal number,  $St^*$  and the Richardson number,  $Ri$ ) to Reynolds number,  $Re$ . As demonstrated in Figure 2, the expression  $St^{*2}/Ri = 0.0018 Re^{2/3}$  correlated all of our data and most of the data of Durox. This correlation will be useful for theoretical prediction of buoyancy induced flame instabilities.

A comparison of the flame heights,  $h_f$ , obtained for  $\phi = 0.9$  in +g, -g and  $\mu g$  are compared in Figure 3. At lower flowrates the  $\mu g$  flames are taller than both +g and -g flames implying an opening of the flame cones. Durox et. al. also [4] observed flame grew taller in  $\mu g$  but did not quantify this change. The rate of  $h_f$  increase for -g flames, however, are higher than the rate of +g  $h_f$ . Their divergent trends show that the effects of gravity on mean flame properties may persists even with increase flow momentum.

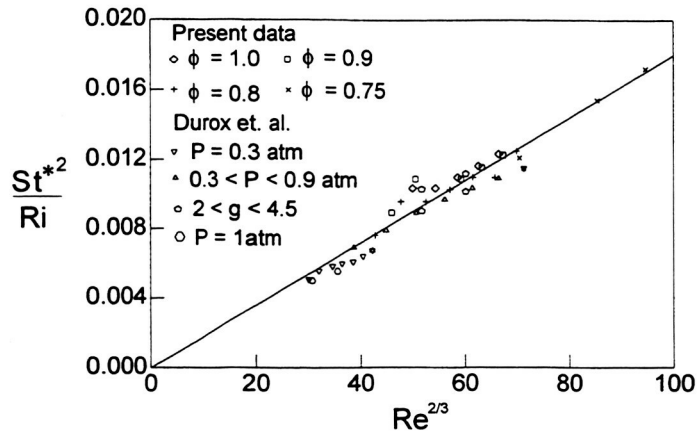


Figure 2 Empirical correlation for the pulsating frequency generated by conical flames

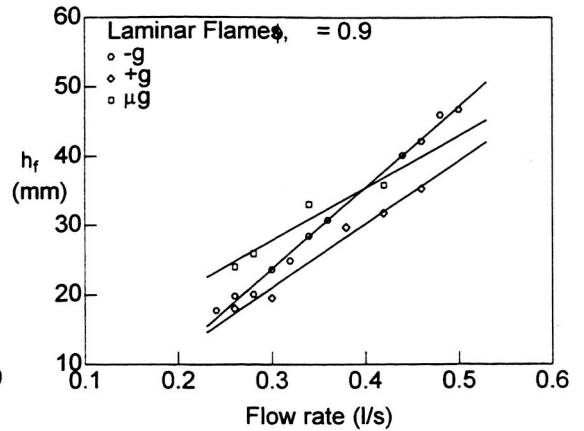


Figure 3 Comparison of flame height of +g, -g and  $\mu g$  flames.

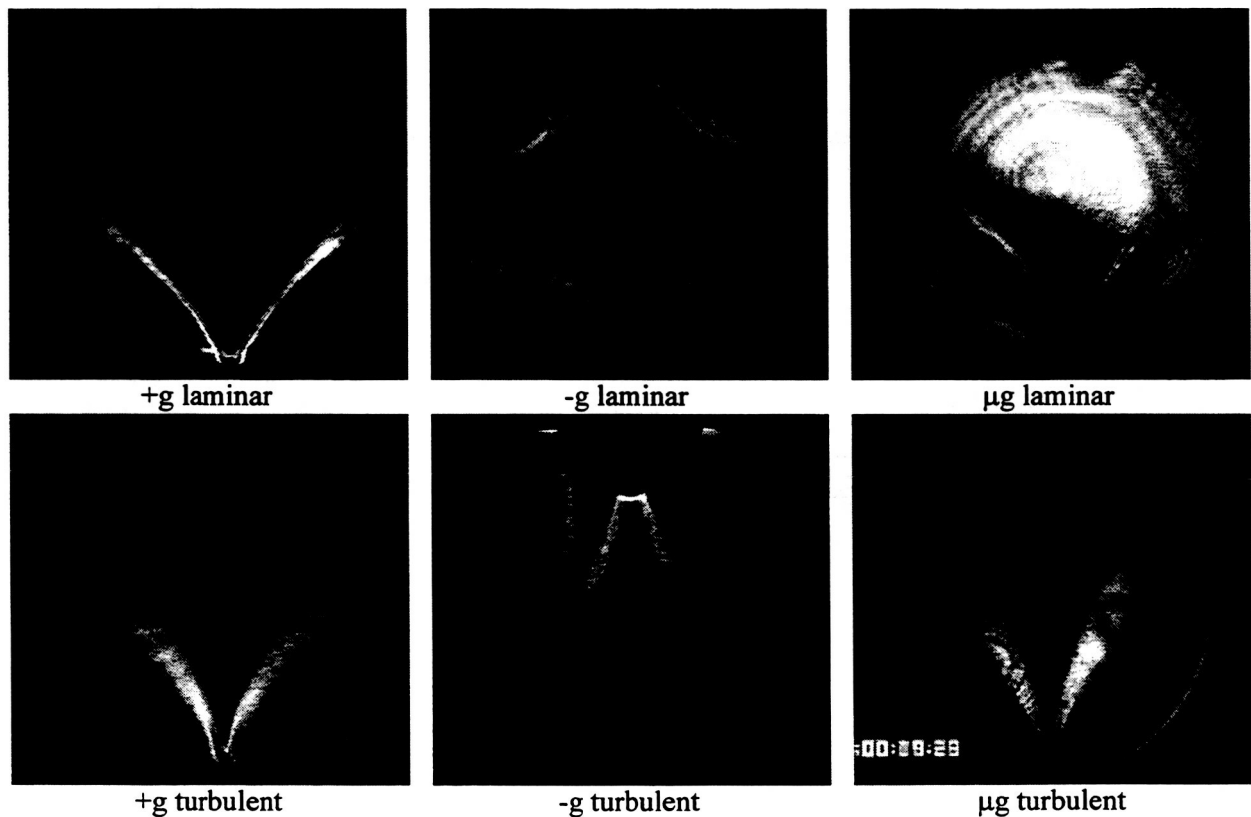


Figure 4 Composite schlieren images of laminar ( $\phi = 0.8$ ,  $Q = 0.6$  l/sec.) and turbulent ( $\phi = 0.7$ ,  $Q = 0.8$  l/s) v-flames flames

### V-Flame Studies

Schlieren images of laminar and turbulent v-flames in +g, -g and  $\mu g$  are compared in Figure 4. These images are not individual frames. They are composite images obtained by summing 200 frames for use in determining the mean flame angle. The +g laminar flame image (top-left) shows two relatively smooth flame fronts evolving into a broader flame zone far away from the stabilizer. The video shows that the broadening is caused by buoyancy induced pulsation. An estimate of this pulsating frequency

shows that it is comparable to those observed in the conical flames. Broadening of the flame zone is not found in -g (top-center). For the case shown here with relatively low flow velocity, attachment of the flame to the burner exit rim is shown. Flame attachment is also shown on the image of the  $\mu g$  flame (top right). Note that only the right side is attached. The schlieren sequence shows that the flame is not attached in normal gravity. Attachment only occurs about 0.5 second after the start of the drop. The schlieren image of the +g turbulent flames show two broadened flame brushes. Because the v-flame brushes are parallel to the laser beam direction, details of the flame wrinkles are difficult to discern. Compared to the +g flame, it is clear that the flame brush thickness is increased due to turbulence. The -g turbulent flame (bottom center) appears much shorter than the +g flame. This is because the inherent unstable -g situation generated larger flame wrinkles structures and the composite schlieren appears to be diffused. The  $\mu g$  turbulent flame image (bottom right) does not look very different than the +g turbulent flame except that the  $\mu g$  flame brushes are not as curved as the +g flame brushes.

The mean flame angles for the laminar v-flames in +g, -g and  $\mu g$  are compared in Figure 5. These angles are obtained by linear fit of the centroid of the schlieren silhouettes. Only the linear flame portion close to the stabilize are used. This avoids the need to correct for the flame curvature. The results are normalized by  $\alpha_t^*(\tau-1)$  where  $\alpha_t$  is the theoretical flame angle  $\sin^{-1}(S_L/U)$ . The comparison show that the +g and -g flame angles are only different when the flow velocity is below 1.0 m/s. The +g and -g results seem to merge at higher velocities. All the  $\mu g$  v-flames we have investigated have velocities larger than 1.0 m/s. Their flame angles are also consistent with those of +g and -g flames. This results together with our analysis of the conical flame height clearly illustrate the effects flame-gravity coupling are strongly dependent on the flame configuration.

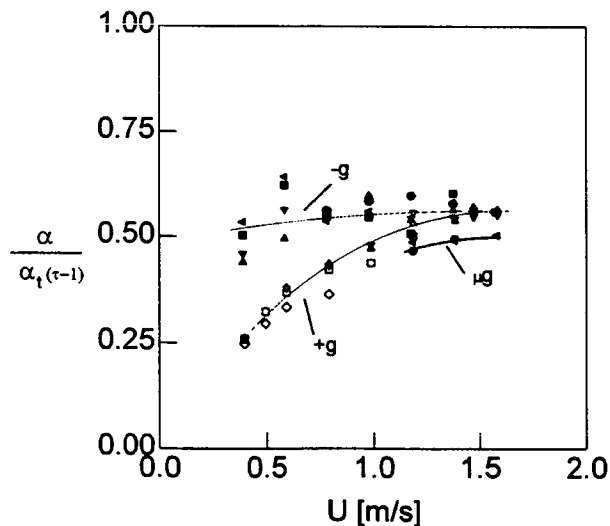


Figure 5 Normalized mean v-flame angles under +g -g and  $\mu g$  conditions with  $0.62 < \phi < 0.85$ .

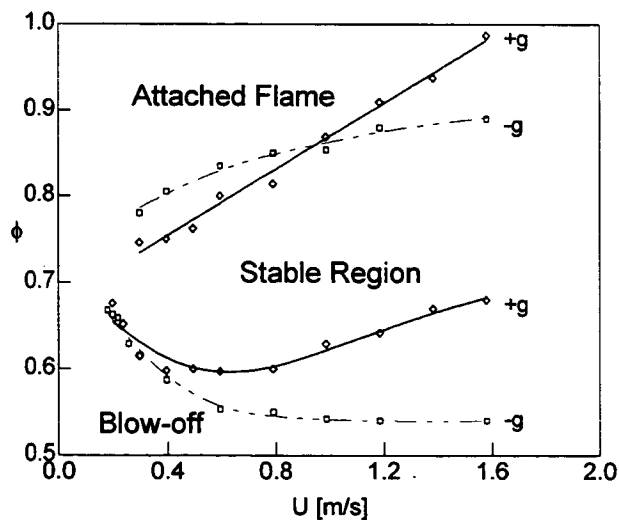


Figure 6 Effect of gravity on blow-off and attached limits of laminar v-flames

During the course of our  $\mu g$  experiments, we observed that the lean flame blow-off limit is also affected by gravity. Laboratory investigation of the lean blowoff limits in +g and -g would be useful. The results obtained for laminar v-flames is shown in Figure 5. These results show that reversing the gravity extends the blow-off limit to much leaner conditions. We also discovered that reversed gravity can stabilize freely propagating adiabatic laminar flames. Under the appropriate conditions, flow divergence induced by the buoyant products generate the flowfield for the flame to be stabilized away from the burner rim. These flames are very stable and flat. Heat loss is minimal because the flame is not in contact with any physical surfaces. We are continuing with the characterization of the conditions under which these flame

can be stabilized. We also plan to make detailed velocity and density measurements. We believe that this adiabatic flame would be of interest to fundamental studies of combustion chemistry for it does not have the upstream heat transfer problem as in the flat flame burner which is the current standard.

### **Planned activities and diagnostic development**

We plan to continue with the analysis of the v-flame data to compare the turbulent flame angles. Measurement of the pulsating frequencies of laminar and turbulent v-flames will test the generality of the correlation we have found for the conical flames. Investigation of the buoyancy stabilized laminar that we have discovered will continue with detailed measurement of the velocity flowfield by LDA and density measurements by Rayleigh scattering. Our schlieren studies of  $\mu\text{g}$  flames point to the need of more sophisticated quantitative laser diagnostics to characterize the changes in flame properties. One of the techniques we shall consider is a single beam schlieren technique which 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. Another option is to use tomography to determine in two dimensions the flame wrinkle scales. The use of laser tomography represents a major effort in development of diagnostics for  $\mu\text{g}$  research. We are evaluating the possibility of developing this technique in collaboration with other participants of the NASA Microgravity Combustion Program.

### **Acknowledgment**

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