FIELD EFFECTS OF BUOYANCY ON LEAN PREMIXED TURBULENT FLAMES

R. K. Cheng[1], R. Dimalanta[1], M. P. Wernet[2], and P. S. Greenberg[2]
[1]Lawrence Berkeley National Laboratory, Berkeley, CA
[2] NASA John H.Glenn Research Center at Lewis Field, Cleveland OH

INTRODUCTION

Buoyancy affects the entire flowfield of steady turbulent flames and this aspect of flame buoyancy coupling is largely unexplored by experiments or by theory. Open flames and flames within large confinements are free to expand and interact with the surrounding environment. In addition to fluid and combustion conditions, their aerodynamic flowfields are determined by the flame brush orientation and geometry, wake of the stabilizer, enclosure size, and of course, the gravitational field. Because the flowfield consists mainly of cold reactants (mostly in the nearfield) and hot products (mostly in the farfield), buoyancy effects are manifested in the farfield region. In upward pointing flames, an obvious effect is a favorable axial pressure gradient that accelerates the products thereby increasing the axial aerodynamic stretch rate. Intrinsic to turbulent flows, changes in mean aerodynamic stretch also couple to the fluctuating pressure field. Consequently, buoyancy can influence the turbulence intensities upstream and downstream of the flame. Flame wrinkling process, and heat release rate are also directly affected. This backward coupling mechanism is the so-called elliptic problem. To resolve the field effects of buoyancy would require the solution of three-dimensional non-linear Navier Stokes equations with full specification of the upstream, wall and downstream boundary conditions.

BACKGROUND

The objective of our experimental study is to characterize the field effects of buoyancy through an extensive laboratory study of flames in normal gravity (+1g), and reversed gravity (-1g) that cumulate to a microgravity (μg) flight experiments to quantify the velocity and scalar flow fields of lean premixed turbulent flames. By comparing the results obtained at different gravitational levels and orientations, it would be possible to decipher the mechanism associated with the upstream coupling effects of buoyancy so that they can be treated properly in turbulent flame model.

Thus far, we have conducted laboratory studies of the effects of buoyancy on flame flickering frequency, stabilization limits, flame wrinkle structures, and mean and rms velocities for several flame configurations. Exploration of these phenomena helps to gain a knowledge base to define the appropriate configuration and conditions for microgravity flight experiments. As reported in our papers [1-3], these studies show that the effects of buoyancy can be prevalent and persist beyond the limits predicted by simple scaling arguments.

A significant finding of our investigations is that the premixed flame configuration is an important experimental parameter that controls which buoyancy phenomenon can be observed. For example, buoyancy driven flame flickering frequency is a distinctive and stable property of both laminar and turbulent conical flames. These frequencies can be correlated for a broad range of conditions including enhanced gravitational forces and sub-atmospheric pressures [1]. However, conical flames are not ideal for investigating buoyancy effects on the flowfield.

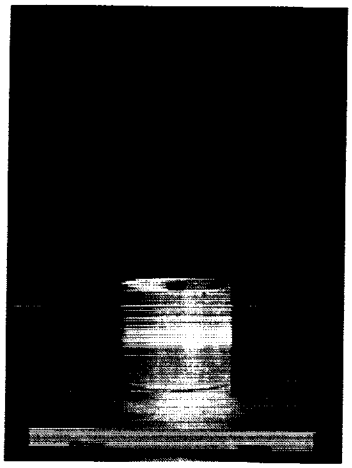

Figure 1 "Funnel" flame stabilized by a bluff body

Because of the divergent nature of the flow in the products counteracting buoyancy-induced acceleration, changes in the flowfields are not easily detectable. This is not the case for rod-stabilized v-flames. The products region is convergent and the presence (+1g) and absence (μg) of flow acceleration in the products show the influence of buoyancy. However, the coupling of the v-flames' plumes with the surrounding atmosphere is quite complex. Due to the flame edge effects that originate at the ends of the stabilizer rod, the flame flickering frequencies are not consistent and do correlate well with flow and mixture parameters. Velocity profiles made above the stabilizer rod also indicate the existence of a slight inflow due to an entrainment effect associated with the accelerating products. Therefore, the v-flame configuration is not ideal for our microgravity studies despite the large body of experimental and theoretical work available in the scientific literature.

For our flight experiments, we have chosen to use an inverted conical flame configuration that we called a "funnel" flame. This flame is stabilized by a small bluff body placed at the center of a premixed flow of fuel and air. The small recirculation zone generated in the wake of the bluff-body provides the flame anchoring mechanism. This flowfield is axisymmetric and has most of the attributes of the v-flame, i.e. an inclined flame brush with products converging to the centerline.

Bluff-body stabilized flames in 1g

Despite the fact that there have been many studies of bluff body stabilized flames, a majority of them focuses on investigating the wake effects of large bluff-bodies. As our goal is to use the bluff body for flame attachment, the wake effects need to be de-emphasized by employing small bluff bodies. For our 25mm diameter burner, we constructed a 45^0 steel cone of 6.5 mm diameter. It was attached to a steel support rod centered at the burner nozzle. To infer the effects of buoyancy on the flames' flowfields, we used two component LDV to investigate +1g and–1g flames.

Figure 2 compares the centerline velocity profiles obtained for laminar +1g and –1g "funnel" flames and V-flames with Reynolds number Re = 1880 and equivalence ratio, ϕ of 0.7. For the +1g flames, both configurations has similar characteristics with the velocity

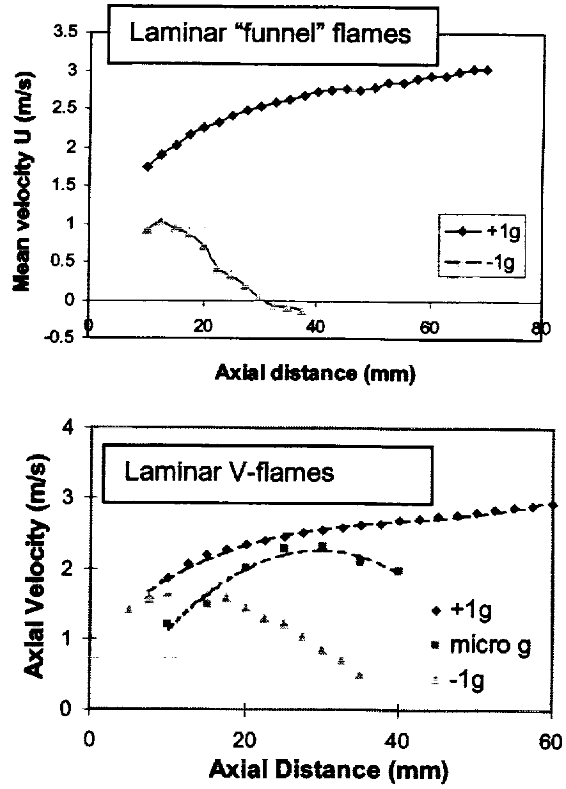

Figure 2 Centerline profiles of laminar "funnel" flames (top) and V-flames (bottom)

increasing rapid for $x < 20$ mm then leveling off to a more gradual acceleration. Differences shown by the $-g$ flames are more drastic. At $x > 30$ mm, the “funnel” flame has a stagnation point with a slight flow reversal forming further downstream.

Centerline profiles measured in turbulent “funnel” flames and v-flames of Re = 2500 and $\phi = 0.75$ are compared in Figure 3. It is clear that the deviations between the +1g and –1g “funnel” flame profiles occur much farther upstream and are more substantial. These results indicate that under identical flow conditions, buoyancy has a stronger effect on the flowfields of “funnel” flames than on those of v-flames. Therefore, “funnel” flames should be a more suitable configuration for characterizing field effects of buoyancy.

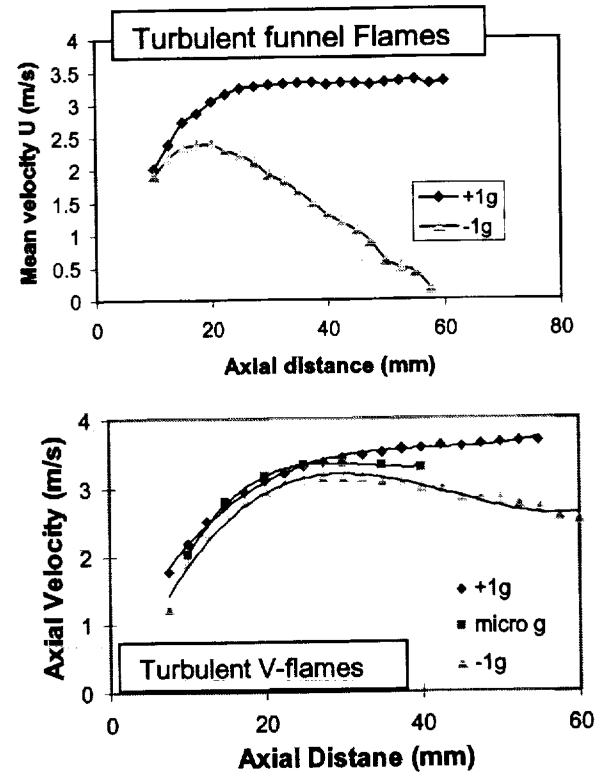

Figure 3 Centerline profiles of turbulent “funnel” flames (top) and V-flames (bottom)

Flight experiments

To design a flight experiment, one of the most important issues is whether or not our experiment can be scaled down to the flow and energy release requirements of the Combustion Integrated Rig (CIR) while preserving its integrity in terms of allowing the flame to interact with turbulence without extrinsic impediments. Using constant velocity scaling law and the integral turbulence length scale (3mm) as a criterion, the optimum burner diameter is established to be 18mm. To maximize the residence time for flame/turbulence interaction, the bluff-body stabilizer is reduced to 3 mm. As this stabilizer is the same size as the turbulence scale, concerns exist on how stable the flames would be. To ensure that the flame remains robust after ignition, engineers at NASA Glenn Research Center designed a ceramic conical bluff body that can be electrically heated. Figure 4 compares the lean-blow off ϕ for this stabilizer with and without heating. As can be seen, with a heated buff-body, the lean blow-off ϕ is lowered to about 0.5 close to the flammability limits of laminar flames.

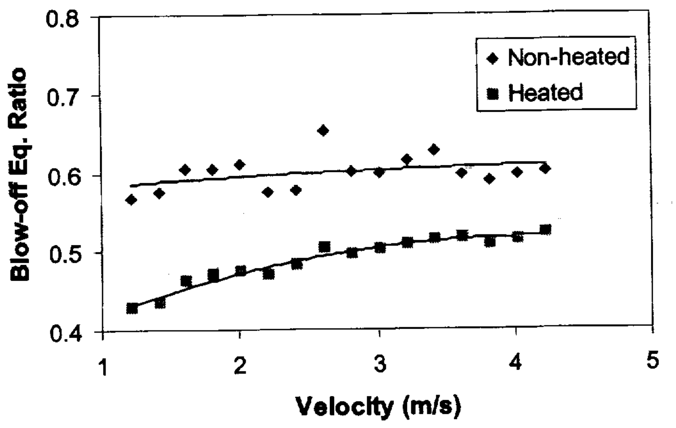

Figure 4 Comparison of ϕ at lean blow-off for turbulent “funnel flames stabilized by a 3 mm bluff body

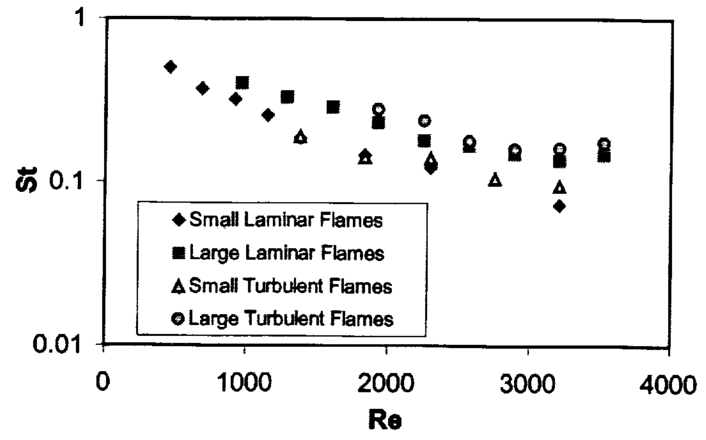

Figure 5 Comparison Strouhal number, St, based on flickering frequencies of funnel flames (0.75 < ϕ < 0.8)

CIR Chamber Effects

To date, all our microgravity flames are not enclosed. To investigate if there would be effects associated with enclosing these flames in the CIR chamber, we plan a 1g flame study in a CIR Chamber Simulator. Our first experiment will be to measure flame flickering frequency. This parameter encapsulates the overall field effects of buoyancy because our study of flame flickering frequencies in conical flames shows it to be sensitive to both upstream and downstream boundary conditions [1].

Figure 5 compares the Strouhal numbers, St, obtained from flickering frequencies of laminar and turbulent "funnel" flames in a 18mm and a 25mm burner. Unlike the conical flames where St increases with Re, St is a decreasing function of Re for funnel flames. None the less, the fact that the results are independent of turbulence level shows them to be consistent properties of flame buoyancy coupling. Comparison of St with and without CIR chamber will allow a first estimate on whether or not the enclosure effects would be significant.

Particle Image Velocimetry (PIV)

We also investigated the feasibility of using PIV to measure the flowfield of microgravity flames. An example of the 1g data is shown in Figure 6. The results are very encouraging and the velocity contours clearly show the converging plume at x > 15 mm. Comparison of these features with those measured in µg would be very useful to quantify the contributions of buoyancy to different flame flowfield regions.

ACKNOWLEDGEMENT

This work is supported by NASA Microgravity Combustion Science through the U. S. Department of Energy Contract No. DE-AC03-76F00098.

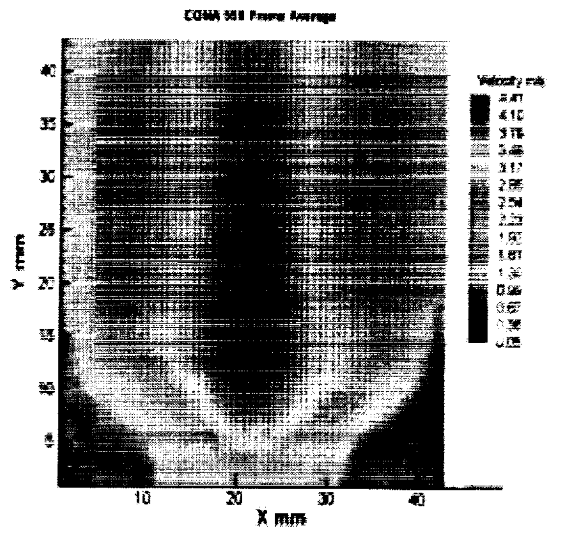

Figure 6 PIV data obtained in a turbulent "funnel " flame

REFERENCES

[1] Kostuik, L, W. and Cheng, R. K., *Combustion and Flame, 103*, 27-40 (1995)
[1] Bédat, B. and Cheng, R. K., *Combustion and Flame, 107,* 13-26 (1996).
[2] Cheng, R. K., Bédat, B., Kostiuk, L. W. *Combustion and Flame, 116* (1999).