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QUANTITATIVE STUDIES ON THE PROPAGATION AND EXTINCTION OF NEAR-LIMIT PREMIXED FLAMES UNDER NORMAL- AND MICRO-GRAVITY

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INTRODUCTION

Strained laminar flames have been systematically studied, as the understanding of their structure and dynamic behavior is of relevance to turbulent combustion [e.g. 1,2]. Most of these studies have been conducted in opposed-jet, stagnation-type flow configurations. Studies at high strain rates are important in quantifying and understanding the response of vigorously burning flames and determine extinction states. Studies of weakly strained flames can be of particular interest for all stoichiometries. For example, the laminar flame speeds, S_u^o, can be accurately determined by using the counterflow technique [2] only if measurements are obtained at very low strain rates [3]. Furthermore, near-limit flames are stabilized by weak strain rates. Previous studies [4] have shown that near-limit flames are particularly sensitive to chain mechanisms, thermal radiation, and unsteadiness. The stabilization and study of weakly strained flames is complicated by the presence of buoyancy that can render the flames unstable to the point of extinction. Thus, the use of microgravity (μ-g) becomes essential in order to provide meaningful insight into this important combustion regime.

In our past studies [5,6] the laminar flame speeds and extinction strain rates were directly measured at ultra-low strain rates. The laminar flame speeds were measured [5] by having a positively strained planar flame undergoing a transition to a negatively strained Bunsen flame and by measuring the propagation speed during that transition. The extinction strain rates of near-limit flames were measured [6] in μ-g. Results obtained for CH_4/air and C_3H_8/air mixtures are in agreement with those obtained by Maruta *et al.* [7]

OBJECTIVES

The objective of this research is twofold. First, to develop accurate Digital Particle Image Velocimetry (DPIV) technique capable to accurately measure flow velocities and introduce it to the 2.2 sec drop tower. Current μ-g practices include global descriptions of fluid mechanics effects, which may not be accurate. Second, to perform Direct Numerical Simulations (DNS) of the counterflow in order to describe phenomena related to the phenomenon of transition to Bunsen flame and also provide insight into the effects of buoyancy for weakly burning flames.

EXPERIMENTAL APPROACH

Strained flames are produced by impingement of a round jet on a flat plate. The plate is also round to reduce slow time-scale instabilities caused by jet flow-boundary layer interactions on the plate. The jet is illuminated by a pulsed sheet of laser light, provided by a 2W A^+ laser, modulated by a polarizing shutter. The shutter pulses are phase-locked with the vertical drive signal from the Pulnix TM9701N (full frame, asynchronous reset) CCD camera. A custom timing circuit then generated pairs of pulses that straddle frame pairs. The effective exposure time (δt) for DPIV calculations is determined by the inter-pulse time, and the maximum repetition rate is 15 Hz. Frame pair sequences of 768 x 484 x 8 bit images are saved direct to PC RAM, and then saved to disk. Seeding is provided by particle with diameters less than 10 μm. Correlation Image Velocimetry (CIV) is used to calculate displacement fields from each image pair. CIV has the useful property that the search distances for performing correlations is decoupled from the search box size itself. This allows displacements and vector densities to be tuned independently to the appropriate flow characteristics. The former is determined exclusively by δt, the latter by the seeding density and flow complexity.

NUMERICAL APPROACH

The phenomenon of transition from flat to Bunsen flame in a stagnation flow configuration can not be described by quasi one-dimensional codes. Instead a DNS study was done by using a second order, fully compressible code developed at CERFACS. The simulations were conducted for conditions that closely resemble those of the experiments. One-step chemistry that results in $S_u^o \approx 33$ cm/s for a $\phi = 1.0$ CH_4/air atmospheric flame was used. Special treatment of the boundary conditions was implemented in order to minimize the effect of numerical waves.

SUMMARY OF RESEARCH

Development of DPIV for flame studies

Measurements were confined very close to the flow centerline, and Fig. 1 depicts a particle image and corresponding velocity field for a jet exit velocity of $U_{exit} = 61.6$ cm/s. The particle image streaks represent a necessary compromise between spatial resolution and available light from the shuttered 2W A+ laser. The vector field shows dense coverage (the vectors are independent) and measurements that pass through the flame front. The maximum correlation peak location is independent of secondary peaks caused by the image of the flame front itself. No extra optical filter was required.

Figure 2a is a spline-interpolated reconstruction of the velocity field, which corrects for systematic bias in vector location due to particle displacements and also provides analytical calculation of spatial derivatives (and not grid-dependent finite differences). The development of the combined experimental/analytical technique has focused on the accurate determination of the minimum flow speed, $S_{u,ref}$, close to the flame front, and the maximum strain rate, $K \equiv -\partial U/\partial x$, occurring immediately before this point. Figure 2 depicts an example, where $S_{u,ref} = 27.6$ cm/s at $x = 1.55$ cm, and $\partial U/\partial x = -K = -107.3$ s^{-1} at $x = 1.44$ cm. The data come from time-averaged ensembles of velocity profiles and are correct if and only if the flow is steady. The variation of $S_{u,ref}$ and K themselves within each time series can be used as diagnostics of this. For a given (ϕ, U_{exit}) pair, each experiment is conducted at least 4 times, each involving sequences of at least 15 time-steps. Figure 3 depicts 10 separate points, from analysis of approximately 600 velocity fields. The standard deviation in both $S_{u,ref}$ and K are shown, and accounts for most, but not all of the deviation from the linear least squares fit. Improvements and modifications to the experimental design (to increase seeding scattering efficiency and light intensity) are adapted to microgravity application of these techniques.

DNS of the Phenomenon of Transition from Planar to Bunsen Flames

Transient simulations were conducted for a nozzle diameter D = 2 cm and a nozzle-plate separation distance L = 3.5 cm corresponding to L/D = 1.75. A $\phi = 1.0$ atmospheric CH_4/air flame was modeled for U_{exit}'s ranging from 140 cm/s to 65 cm/s.

It was found that for large U_{exit}'s the flow is of the stagnation-type throughout the domain of interest. For low U_{exit}'s, however, it was found that the flow is hybrid between a near-jet flow close to the nozzle and a stagnation-type flow close to the stagnation plate. Furthermore, as the U_{exit} decreases from 140 cm/s to values higher than about 65 cm/s, the flame is stabilized as nearly planar and at greater distances from the stagnation plane. The shape of such flames was found to be in general planar but with a small concave curvature around the centerline and a stronger convex curvature at larger radii. It was found that while the concave curvature around the centerline results from the radial pressure gradients of the stagnation-type flow, the shear layer that develops between the jet and the surrounding gas causes the convex curvature at the larger radii. The presence of the shear layer results in reduced flow velocities and the flame moves further upstream in order to be stabilized at locations at which its speed equals the local flow velocity. It should be noted that the DNS results also reveal that there is no noticeable fuel dilution within the immediate vicinity of the jet to cause local reduction of the flame speed.

For U_{exit} = 65 cm/s, however, the flame can not be stabilized at a given location and undergoes an unassisted transition to conical Bunsen flame, in close agreement with the experimental observations. The phenomenon of transition was captured numerically at different times and insight was provided into the underlying mechanisms. Analysis shows that when U_{exit} = 65 cm/s the radial pressure gradients that are responsible for the establishment of planar, stagnation-type flames are so weak that the effect of flame curvature at the edges of the jet, which tends to favor the Bunsen flame configuration, dominates. Thus, there is a gradual movement of the curvature towards the system centerline resulting eventually in a Bunsen-type flame.

During that transition the minimum pre-flame flow velocity, $S_{u,ref}$, was monitored and is shown in Fig. 4. It first decreases as the flame moves slightly downstream with a very low displacement velocity. This physically happens because the radial pressure gradients are very weak and the radial profile of the axial velocity becomes planar eliminating thus the flame curvature around the centerline. Then, and after reaching a minimum value, $S_{u,ref}$ starts increasing due to the combined effect of moving curvature and the significant displacement velocity. The DNS confirm that during the transition there is a state at which the $S_{u,ref}$, equals the true laminar flame speed S_u^o. Detailed analysis of the numerical results reveal that both the strain rate and the total stretch (strain rate plus curvature) become zero at the state of $S_{u,ref} = S_u^o$. These results support the validity of the original thesis behind the proposed methodology for the direct measurement of S_u^o [5].

REFERENCES

1. Peters, N., *Prog. Energy Combust. Sci.* 10, pp. 221-252 (1984).
2. Law, C.K., *Proc. Combust. Inst.* 22: 1381-1402 (1988).
3. Vagelopoulos, C.M., Egolfopoulos, F.N. & Law, C.K., *Proc. Combust. Inst.* 25: 1341-1347 (1994).
4. Egolfopoulos, F.N., *Proc. Combust. Inst.* 25: 1375-1381 (1994).
5. Vagelopoulos, C.M. & Egolfopoulos, *Proc. Combust. Inst.* 27: 513-519 (1998).
6. Zhang, H. & Egolfopoulos, F.N. "Extinction of Near-Limit Premixed Flames in Microgravity," by H. Zhang and F.N. Egolfopoulos, *Proc. Combust. Inst.* 28, in press.
7. Maruta, K, Yoshida, M, Ju, Y. & Niioka, T., *Proc. Combust. Inst.* 26: 1283-289 (1996).

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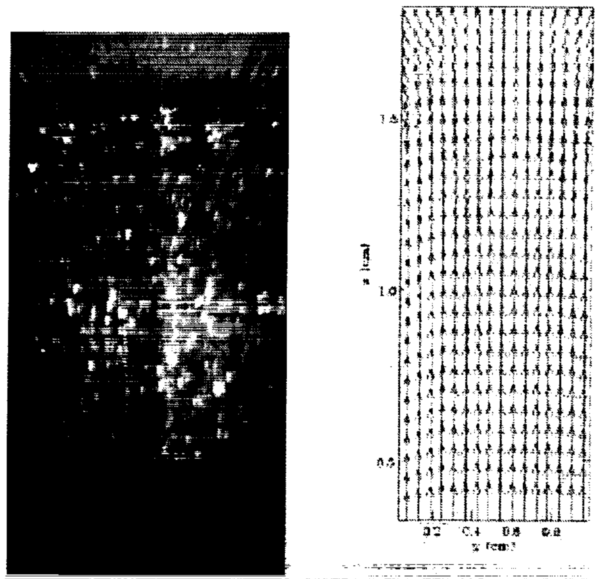

Figure 1. DPIV image and calculated velocity field for a ϕ=0.75 flame close to the jet centerline.

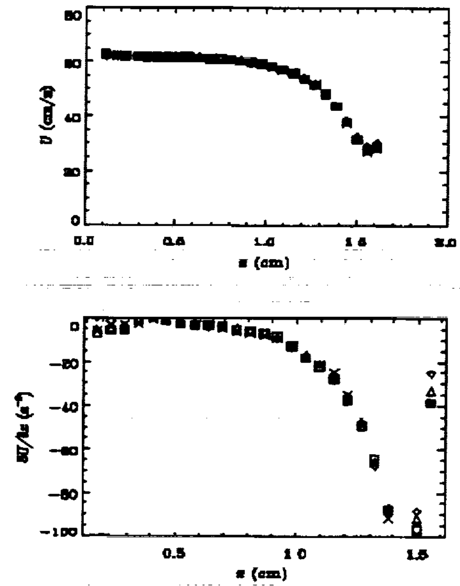

Figure 2. (a) $U(x)$ close to the jet centerline, and (b) -K = $\partial U/\partial x$ for a ϕ=0.75 flame

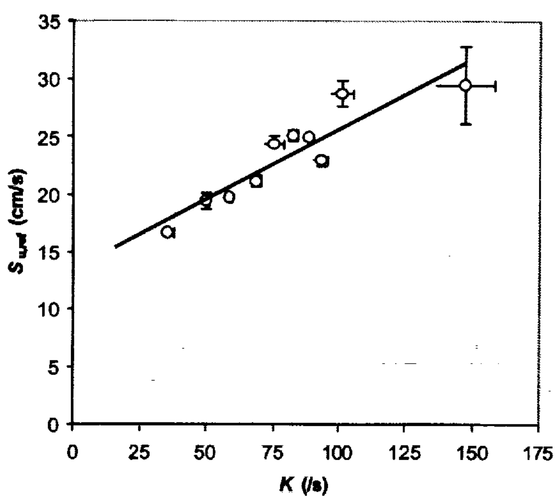

Figure 3. DPIV results for the variation of $S_{u,ref}$ with K for a ϕ=0.75 flame

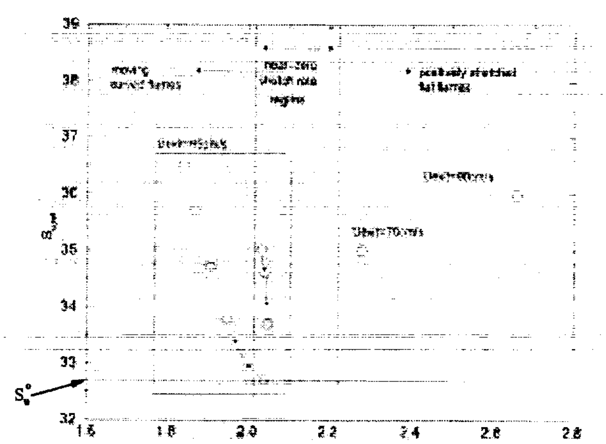

Figure 4. DNS results for the variation of $S_{u,ref}$ with flame position for a ϕ=1.0 flame. Note the variation of $S_{u,ref}$ for the same U_{exit} = 65 cm/s and that the state for which $S_{u,ref} = S_u^o$ is achieved.