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

Y. DONG, G.R. SPEDDING & F.N. EGOLFOPOULOS
Department of Aerospace & Mechanical Engineering
University of Southern California
Los Angeles, California 90089-1453

and

F.J. MILLER
National Center for Microgravity Research
21000 Brookpark Rd
Cleveland, OH 44135-3191

INTRODUCTION

Near-limit flames cannot be studied under normal-gravity conditions, as the induced buoyant flow does not allow for their stabilization. Such flames are of significant fundamental interest as they are particularly sensitive to chain-mechanism competitions, thermal radiation, and unsteadiness [*e.g.* 1]. Furthermore, the dynamics of such flames are of interest in terms of fire safety in reduced gravity environments such as the space station and space vehicles. This point has been realized and indeed the extinction limits of such flames have been measured in drop towers [2, 3]. Those measurements have been independently conducted in counterflow configurations in which symmetric premixed flames were stabilized and subsequently extinguished. The determination of the extinction limits was based, however, on global strain rates, as detailed fluid mechanics diagnostics were not available on drop towers. While global strain rates do demonstrate qualitatively the effect of fluid mechanics on the flame response, the details of the flow-field at the flame vicinity can also have a first order effect on the flame dynamics especially for near-limit concentrations. More specifically, the very low velocities that are involved may result in rather thick boundary layers so that assumptions such as top-hat velocity profiles at the nozzle exit could be incorrect. Furthermore, the local strain rate just before the flame can be noticeably different compared to the value derived based on global description.

OBJECTIVES

The main objective of this research is to introduce accurate fluid mechanics measurements diagnostics in the 2.2-s drop tower for the determination of the detailed flow-field at the states of extinction. These results are important as they can then be compared with confidence with detailed numerical simulations so that important insight is provided into near-limit phenomena that are controlled by not well-understood kinetics and thermal radiation processes. Past qualitative studies did enhance our general understanding on the subject. However, quantitative studies are essential for the validation of existing models that subsequently be used to describe near-limit phenomena that can initiate catastrophic events in micro- and/or reduced gravity environments.

EXPERIMENT APPROACH

As part of this research, a new Digital Particle Image Velocimetry (DPIV) system has been developed appropriate for the GRC 2.2-s Drop Tower. A schematic of the system is shown in

Fig.1. A dual head Nd-YAG laser with beam conditioning optics is focused into a quartz fiber optic cable with a 1 mm diameter core. The laser operates at 532 nm and each head has a repetition rate of up to 30 Hz, a pulse length of 5 ns, and theoretical pulse energy of up to 30 mJ (both the pulse rate and energy are user selectable). On the rig end of the fiber we measured a pulse energy of 13 mJ/pulse without having the laser on its highest capacity, which provided plenty of energy for particle illumination. The wide beam divergence from the fiber requires some trial and error with lenses to get a light sheet that is both thin and illuminates the region of interest. We settled on a bi-convex spherical lens with a focal length of 88.3 mm, followed by a plano-convex cylindrical lens of focal length 150 mm to form the light sheet. Given the space limitation of the rig, a L-shaped light path is used. In order to decrease the laser scattering, the test section is almost fully closed using aluminum sheet with black paper cover.
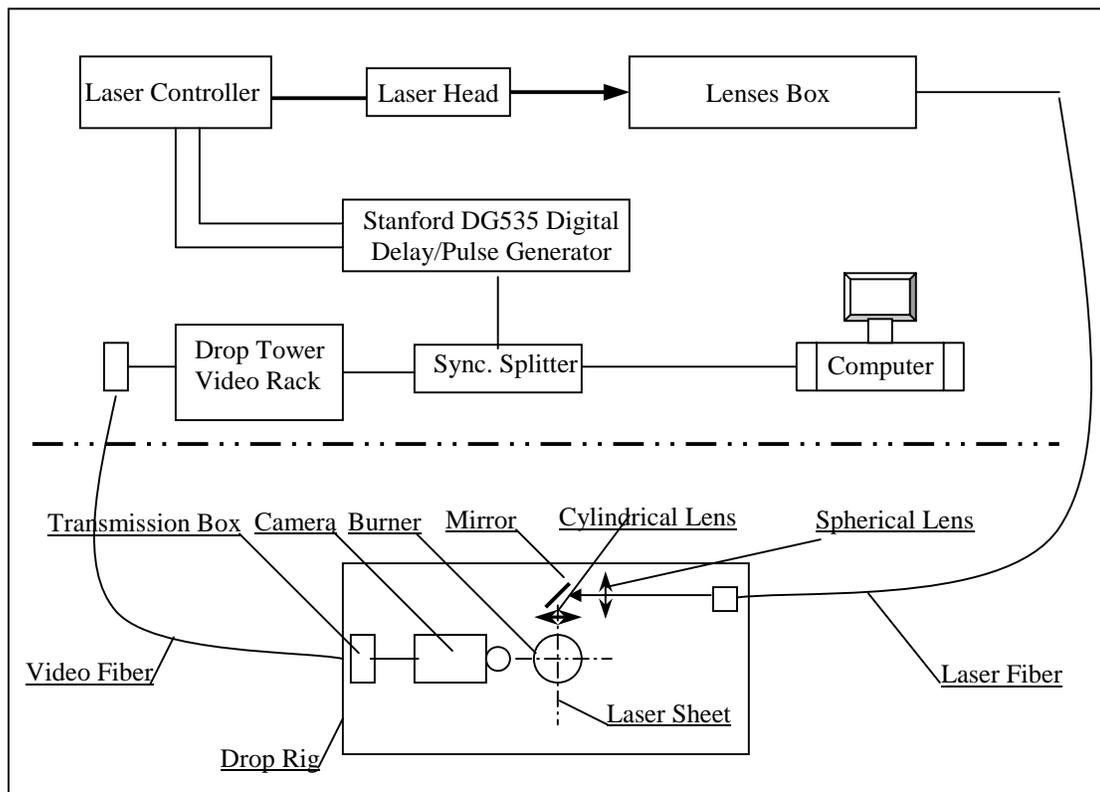

Fig.1 Schematic of 2.2s Drop Tower PIV System

The plane of the light sheet was aligned with a special jig to be along the burner centerline perpendicular to the optical axis of the camera. A Pulnix TM 9701 progressive scan CCD camera was used to record the PIV images and the video signal was sent to the top of Drop Tower via the video fiber. Once there, the signal was split by an odd field pulse delay box, with the video signal going to a Matrox frame-grabber, and the sync signal going to a digital delay/pulse generator, which in turn controlled the laser.

Similarly to our previous studies [3], the counterflow configuration is used for the flame stabilization. It consists of two burners equipped with 30 mm contoured-shaped nozzles that are separated by 50 mm. The seed particles used are 5 μm Al_2O_3, which are introduced into the lower burner and carried out by the flow. A 5 mm extension tube is used with the camera lens to

get the 200 pixels/cm resolution. An optical filter with a pass band from 460 nm to 540 nm is mounted in the front of the camera lens to minimize the luminous emission from the flames.

The Correlation Image Velocimetry (CIV) post-processing software 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.

SUMARY OF RESEARCH

The performance of nozzles that have been designed by using 5th polynomial contraction contour [4,5] was assessed experimentally. Figures 2a and 2b depict DPIV results from 1g tests. This kind of burner produces uniform velocity in the center area of the burner (Fig.2a). The thickness of the boundary layer decreases as the Reynolds number increases (Fig.2b). The existence of a boundary layer results in exit velocities at the centerline of the burner that are higher than the average velocity based on the flow rate. The exit velocity at the centerline can be 1.8 times more than the average velocity at low Reynolds number, when the velocity distribution is parabolic and no uniform area exists.
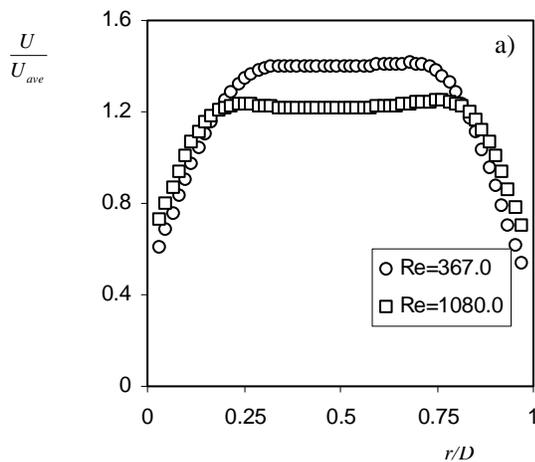

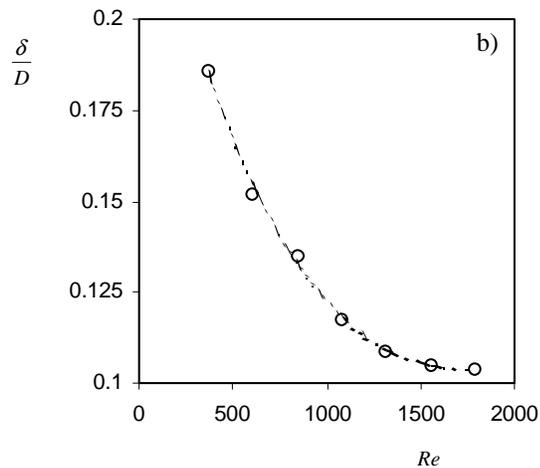Fig.2a Comparison of exit velocity distributions at different Reynolds number

Fig.2b Variation of thickness of boundary layer against Reynolds number

The flame structures at low strain rates at 1g were investigated. Figure 3a depicts an example, where the minimum velocity measured just before the dilatation zone $S_{uref} = 18.1$ cm/s at $x = 2.5$ cm, and for strain rate $K \equiv (-du/dx)_{max} = 26.01/s$ at $x = 2.25$ cm. It is interesting to note that, for this weakly strained flame, the velocity distribution from nearly uniform around the burner exit gradually evolves to a non-uniform curvature around the flame (Fig. 3b). This phenomenon was also reported in a previous investigation [6].

Figure 4a is an example image from a cold flow microgravity test, and the corresponding vector map is shown in Fig. 4b. The weak point in the system remains the particle seeder, which is not always consistent. In order to avoid that problem, a nebulizer (a liquid particle generator) is introduced into the system. We use the nebulizer in 1g to produce 0.5 μm silicone oil droplet to trace the flow. The silicone oil does not have any observable effect on flames [7]. Two needle valves were used to adjust the ratio of the flow rate passing/not passing through the

nebulizer and subsequently control the seeding density. Test results demonstrate that silicone oil droplets work well.
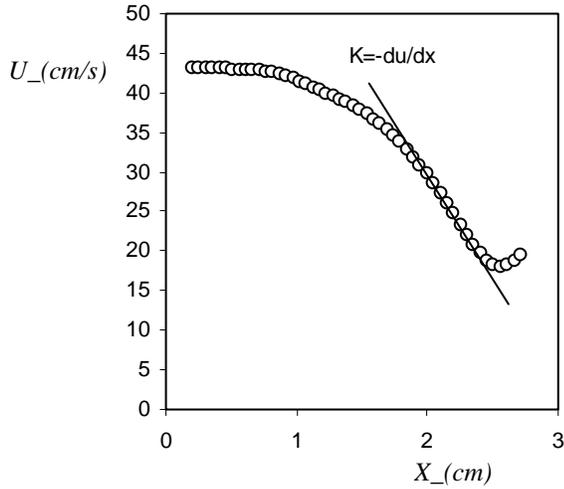

Fig.3a U(x) at the centerline of the jet from bottom burner, D=3.0cm, L=5.0cm, Φ(CH4/Air)=0.66
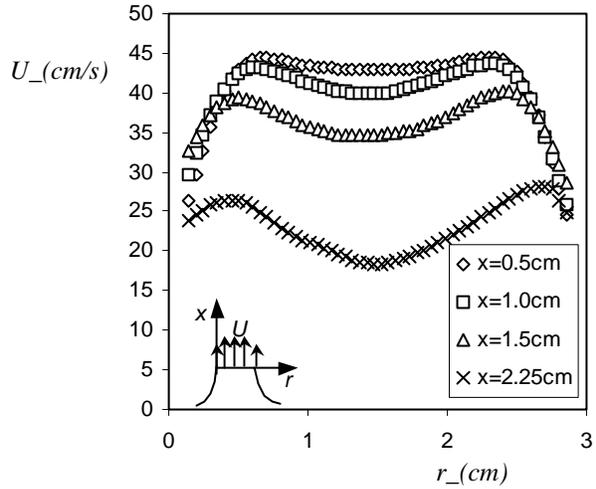
Fig.3b Evolution of velocity distribution along streamwise, D=3.0cm, L=5.0cm, Φ (CH4/Air)=0.66
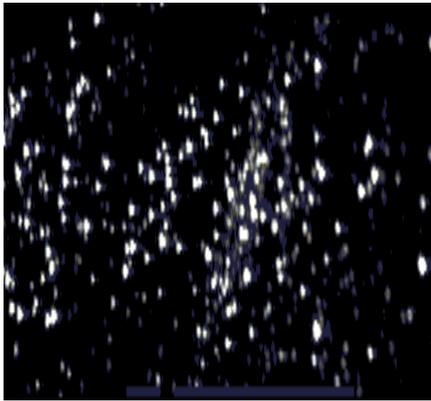
Fig.4a DPIV image from microgravity test
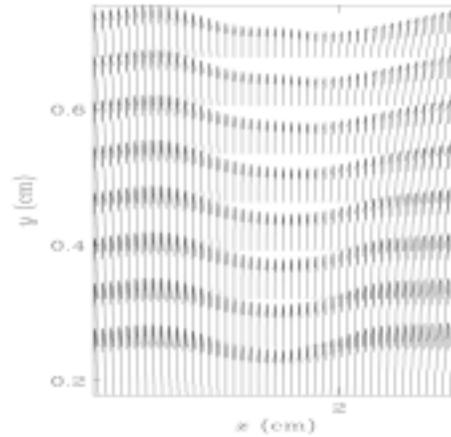
Fig.4b Calculated vector map for left image

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