AN INVESTIGATION OF FULLY-MODULATED, TURBULENT DIFFUSION FLAMES IN REDUCED GRAVITY

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INTRODUCTION

Pulsed combustion appears to have the potential to provide for rapid fuel/air mixing, compact and economical combustors, and reduced exhaust emissions. The objective of this Flight-Definition experiment (PuFF, for Pulsed-Fully Flames) is to increase the fundamental understanding of the fuel/air mixing and combustion behavior of pulsed, turbulent diffusion flames by conducting experiments in microgravity. In this research the fuel jet is fully-modulated (i.e., completely shut off between pulses) by an externally controlled valve system. This gives rise to drastic modification of the combustion and flow characteristics of flames,[1-3] leading to enhanced fuel/air mixing mechanisms not operative for the case of acoustically excited or partially-modulated jets.[4] The fully-modulated injection approach also simplifies the combustion process by avoiding the acoustic forcing generally present in pulsed combustors. Relatively little is known about the behavior of turbulent flames in reduced-gravity conditions, even in the absence of pulsing. Fundamental issues addressed in this experiment include the impact of buoyancy on the fuel/air mixing and combustion characteristics of fully-modulated flames. It is also important for the planned space experiments to establish the effects of confinement and oxidizer co-flow on these flames.

EXPERIMENTAL APPROACH

As part of this program experiments are conducted both in the laboratory at WPI and in the GRC 2.2s Drop Tower. In both cases the combustor configuration consists of a single fuel nozzle with diameter $d = 2$ mm mounted on the centerline of a combustor 20×20 cm in cross section and 67 cm in height. The gaseous fuel jet flow is fully-modulated by a fast-response solenoid valve (Parker Hannifin Series 9) controlled by a Parker Hannifin Iota One control unit. The mean fuel velocity during injection, U_{jet}, gives Reynolds numbers from 3,000 to 10,000. A slow oxidizer co-flow (standard air for laboratory experiments; an oxygen/nitrogen mixture for the Drop Tower rig) is provided to properly ventilate the flame. An electrically heated *Kanthal* wire coil of 0.24 mm diameter situated at the nozzle exit serves as a continuous ignition source.

Four types of diagnostic techniques are employed in the experiments. First, video imaging is used to study the turbulent structure of the pulsed flames and to determine the corresponding flame lengths. Second, temperatures and radiant emissions are determined using fine-wire thermocouples and thermopile detectors. Particle Image Velocimetry (PIV) is employed to calculate the rate of air entrainment into the flame. Finally, the concentrations of stable gas species (CO, CO_2, O_2, NO_x, and unburned hydrocarbons) in the post-flame region are measured by gas sampling and standard emissions instruments. The emissions measurements and PIV are performed in the laboratory only; the thermal measurements and video imaging are performed both in the laboratory experiments and in the Drop Tower tests.

SELECTED EXPERIMENTAL RESULTS

Images of fully-modulated turbulent diffusion flames are shown in Fig. 1 for ethylene fuel. The results presented here were obtained in normal gravity in the laboratory. For the relatively long injection time of the flame in Fig. 1a (τ=119 ms), an elongated flame structure is produced, which is similar in appearance and in length to the steady-state flame. For shorter injection times, the flame length becomes noticeably shorter and a rounded vortex structure is generally apparent in the region of the flame near the flame tip, with a "tail" attached to the trailing portion of the burning fuel puff (Fig. 1b, τ = 46 ms). For very short injection times (Fig. 1c, τ = 5.7 ms), the puff-like structure typically exhibits a blue luminescence and appears to contain very little soot. The transition from compact, puff-like flame to elongated flame behavior can be characterized in terms of the injection parameter[1] $P \equiv [(4V_0/\pi d^2)/d]^{1/3}$, where V_0 is the injected volume. Generally, puff-like behavior is seen for values of P less than approximately eight for ethylene/air flames.[1] The values of the parameter for the fully-modulated flames shown in Fig. 1 are $P = 11$, $P = 8$, and $P = 4$, respectively.

The mean flame lengths for fully-modulated flames are shown in Fig. 2 for several values of co-flow strength. In all cases shown the duty-cycle was sufficiently small ($\alpha < 0.1$) so that there was essentially no interaction between puffs. For the compact puffs ($P < 8$) the addition of co-flow generally increased the mean flame length. The effect of co-flow on the flame length of pulsed flames with longer injection times ($P \geq 11$), as well as steady flames, was less significant. Comparison with free (unducted) flames with the same injection conditions suggests that a co-flow strength of less than $U_{co}/U_{jet} = 0.005$ is sufficient to properly ventilate the flame in a space experiment.

In addition to the injected volume, the flame length in fully-modulated diffusion flames can be significantly impacted by the duty-cycle.[1,3] Increasing the duty-cycle results in closely-packed, interacting flame structures that show mixing and combustion characteristics similar to steady-state flames. The effects of duty-cycle are most apparent for the compact puffs ($P < 8$). The extent of interaction between neighboring structures for puff-like flames can be characterized in terms of a dimensionless interaction parameter $\Pi = V_0^{2/3}(1-\alpha)/A\alpha$, where A is the cross sectional area at the fuel nozzle exit.[1,3] This parameter collapses the mean flame length data, as shown in Fig. 3. The normalization used in the ordinate allows for variations in flame length arising solely from variations in injected volume. Thus the effects of duty-cycle on mean flame length appear to begin to become significant for a value of the interaction parameter less than approximately $\Pi = 80$.

The time-averaged concentration of unburned hydrocarbons measured on the combustor centerline are shown in Fig. 4. The sampling probe was positioned 3 cm downstream of the maximum flame length in all cases. For the most compact puffs ($P < 6$) the concentration of unburned hydrocarbons appears to exhibit an increase, attain a maximum and decrease with increasing duty-cycle. For larger values of P, the concentration of unburned hydrocarbons lies within the sensitivity of the detector. These results suggest that while $P = 8$ appears to represent an upper limit on compact behavior from a standpoint of flame length, the threshold value based on hydrocarbon emissions (hence combustion efficiency) is closer to $P = 6$. The emissions of CO follow a similar trend to the unburned hydrocarbons results presented here.

PARTICLE IMAGE VELOCIMETRY

It is hypothesized that the short flame length of the puffs with the shortest injection time is primarily due to the increased entrainment rate of the surrounding air. Preliminary experiments has been conducted to assess the feasibility of utilizing the PIV technique for quantifying the entrainment. These experiments were done at GRC using the same fuel injector described above.

The injector was placed in a 25-cm diameter chamber. The fuel used was ethylene and the flow was fully-modulated with an injection time of 20 ms and a duty-cycle of 0.05 ($P = 6$, compact puffs). Seed particles 2.5 μm in diameter were injected upstream of the nozzle exit in the chamber. The particles were illuminated by a dual pulsed Nd:YAG laser operating at a wavelength of 532 nm and imaged by a Kodak ES 1.0 CCD camera. The images were processed by a cross-correlation scheme using 64×64 pixel windows and a 50% overlap. The image area was approximately 45 mm square resulting in a velocity vector grid spacing of 1.5 mm. The PIV system was synchronized with the solenoid valve.

A sample velocity field is shown in Fig. 5 for $\tau = 20\ ms$. At the instant shown, the velocity field is recorded 40 ms after the flow initiation. The tail of the flame structure is clearly visible in this field, along with the ambient air being drawn into it. Integration of the velocity normal to specific contours in the flow provides a measure of the rate of air entrainment into the flame.

NUMERICAL MODELING

The numerical analysis of fully-modulated turbulent diffusion flames is performed (U. Tokyo/NDA) using gaseous hydrogen/oxygen combustion because of its simple reaction mechanism compared to hydrocarbon fuels. The governing equation set consists of the unsteady, 3-dimensional, Navier-Stokes equation, multi-species diffusion equations, and a 2-equation, q-ω turbulence model. These equations are solved by a finite-difference TVD formulation and LU-ADI implicit time integration. A duty-cycle of $\alpha = 0.3$ was simulated for $1.6 < P < 2.8$. The axisymmetric calculation region (10 mm radius and 40 mm long) is divided into 53×83 grid points, with the 2 mm diameter circular injection tube located on the center axis.

The concentration fields of hydrogen and water vapor are shown in Fig. 6 for $P = 2.2$. The entrainment of surrounding air into the jet appears to give rise to a mushroom-shaped region of unburned hydrogen, which resembles somewhat the puff-shape structures observed in the experiments. Similar structure is suggested by the water vapor concentration field. A mean flame length was defined based on the region where the centerline temperature decreases to a value of 2000 K. Based on this criterion, it is found that the flame length of the injected puffs is linearly proportional to the injection parameter P, as seen in the experiment.

ACKNOWLEDGEMENTS

REFERENCES

[1] Hermanson, J.C., Dugnani, R., and Johari, H., *Comb. Sci. Tech.* **155**, 203-225, 2000.
[2] Hermanson, J.C., Usowicz, J., Johari, H., and Sangras, R., *AIAA J.*, submitted.
[3] Johari, H. and Motevalli, V., *Comb. Sci. Tech.* **94** (1-6), 229-245, 1993.
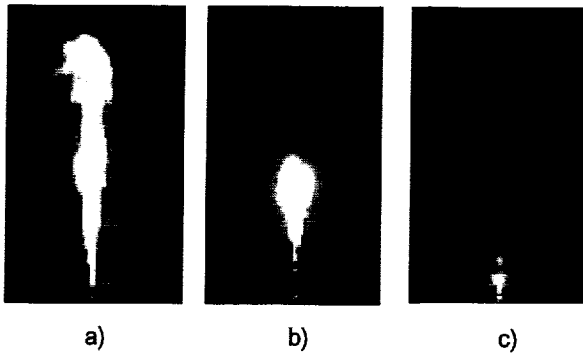[4] Lovett, J.A. and Turns, S.R., *AIAA Journal* 28(1), 38-46, 1990.

Fig. 1 Turbulent, fully-modulated ethylene/air flames. $U_{cof}/U_{jet} = 0.005$, $Re_{jet} = 5,000$. a) $\tau = 119\ ms$, $V_0 = 8.4\ cm^3$, b) $\tau = 46\ ms$, $V_0 = 3.2\ cm^3$; c) $\tau = 5.7\ ms$, $V_0 = 0.40\ cm^3$. The image height is 43 cm.
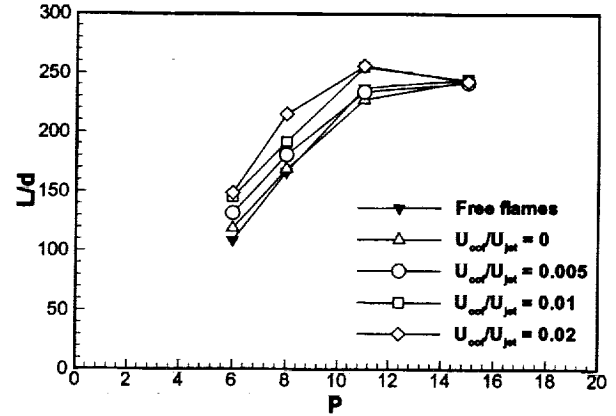

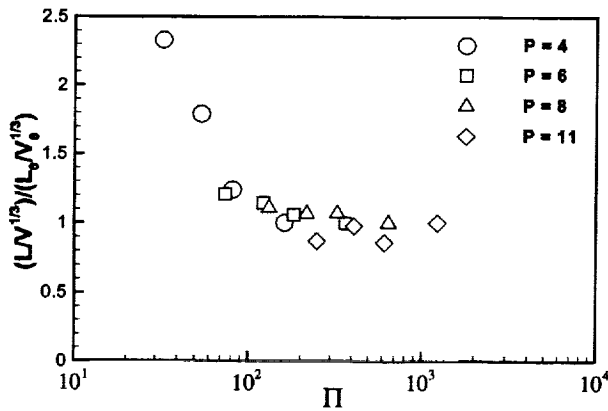Fig. 2 Effect of co-flow on normalized flame length for isolated, fully-modulated flame puffs.

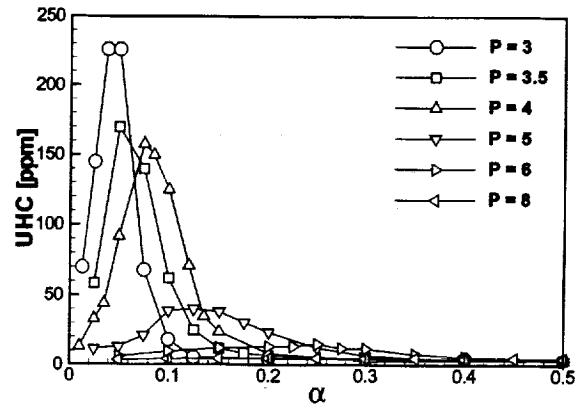Fig. 3 Effect of duty-cycle on normalized flame length of fully-modulated flames.

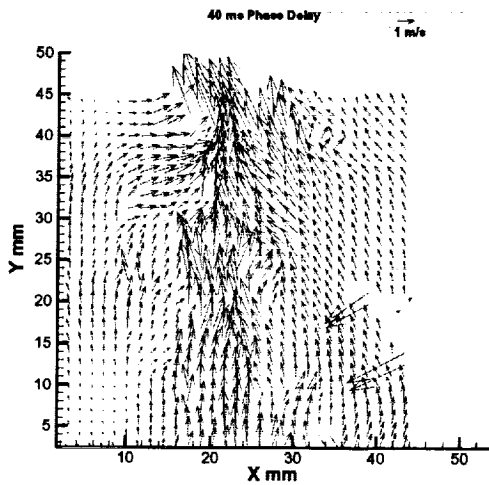Fig. 4 Centerline unburned hydrocarbon emissions of fully-modulated flames.

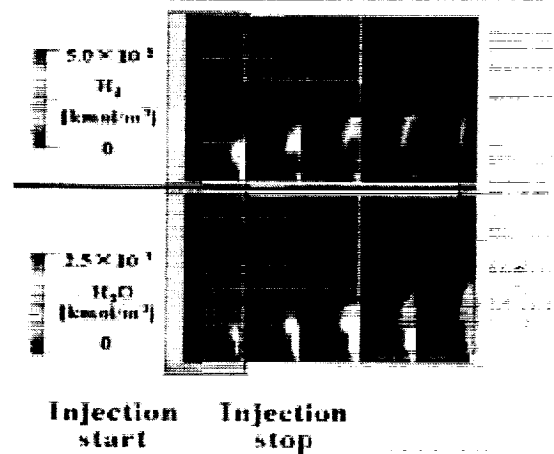Fig. 5 Velocity field of a fully-modulated ethylene/air flame, $\tau = 20\ ms$, $\alpha = 0.05$.

Fig. 6 Numerical simulation of a single fully-modulated flame puff, hydrogen/air chemistry, $P = 2.2$.