BUOYANCY EFFECTS IN FULLY-MODULATED, TURBULENT DIFFUSION FLAMES

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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 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,[1-2] leading to enhanced fuel/air mixing compared to acoustically excited or partially-modulated jets. Normal-gravity experiments suggest that the fully-modulated technique also has the potential for producing turbulent jet flames significantly more compact than steady flames with no increase in exhaust emissions. The technique also simplifies the combustion process by avoiding the acoustic forcing generally present in pulsed combustors. Fundamental issues addressed in this experiment include the impact of buoyancy on the structure and flame length, temperatures, radiation, and emissions of fully-modulated flames.

EXPERIMENTAL APPROACH

Experiments are conducted both in the laboratory at WPI and in the GRC 2.2s Drop Tower. The combustor configuration consists of a single fuel nozzle with diameter d = 2 mm centered in a combustor 20 × 20 cm in cross section and 67 cm in height. The gaseous fuel jet flow (ethylene or a 50/50 ethylene/nitrogen mixture by volume) is fully-modulated by a fast-response solenoid valve actuated in an on-off (rectangular wave) fashion for injection times ranging from $\tau = 4$ to $\tau = 300$ ms. The mean fuel velocity during injection, U_{jet}, gives a nominal Reynolds number of 5,000. A slow oxidizer co-flow with velocity of approximately 10 cm/s (air for laboratory experiments; an oxygen/nitrogen mixture of either 21% or 30% O_2 by volume for the Drop Tower rig) is provided to properly ventilate the flame.[3] An electrically heated wire loop of 0.24 mm diameter situated at the nozzle exit serves as a continuous ignition source.

Three types of diagnostic techniques are employed in the experiments. Video imaging is used to study the turbulent structure and flame length of the pulsed flames. Temperatures and radiant emissions are determined using fine-wire thermocouples and thermopile radiometers. 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 are performed in the laboratory only; the thermal measurements and video imaging are performed both in the laboratory experiments and in Drop Tower tests.

SELECTED EXPERIMENTAL RESULTS

Structure and flame length

The fully-modulated flames can be roughly divided into two categories: (i) injection time sufficiently short to result in a compact, puff-like structure, and (ii) injection interval longer, resulting in elongated flame structures. The parameter $P \equiv (U_{jet}\tau/d)^{1/3}$ can be employed to distinguish between the two cases.[1] Generally, puff-like behavior is seen for values of P less than approximately $P = 8$ for ethylene/air flames. For $P > 11$, elongated flames similar to steady jet flames but with a distinct cap are created.[1,3] Typical images of steady, elongated, and puff-like ethylene/air diffusion flames in microgravity are presented in Fig. 1.

The flame lengths of fully-modulated (f-m) diffusion flames can be substantially less that those of steady turbulent jet flames, as shown in Fig. 2. In all cases shown the duty cycle was sufficiently low to give isolated, non-interacting flame structures. The flame length for compact, puff-like structures appears to scale reasonably well with the parameter[2] $P(1+\psi)^{1/3}$, where ψ is the stoichiometric air/fuel ratio, up to values consistent with $P \approx 8$. For sufficiently high P, the mean flame length approaches that of the corresponding steady flame. The flame length interestingly does not appear to be highly sensitive to the action of buoyancy for all P. This is consistent with the results of Ichideria *et al.*[4] for piloted flames, but differs from the significant increase in length reported by Hegde *et al*.[5] in microgravity for unpiloted flames stabilized by reduced nozzle clearance.

The flame length in fully-modulated diffusion flames can also be significantly impacted by the duty cycle, as shown in Fig. 3. In general, increasing the duty cycle causes the discrete fuel puffs to give way to more closely-packed, interacting flame structures, which lead in turn to a longer flame length. This is to be expected since for the case of high duty cycles each flame structure has to "compete" with its neighbors for the same air, decreasing the rate of air entrainment. The greatest fractional increase in flame length appears to be for the shortest injection time, as seen previously in normal gravity[1]. This suggests a substantially lower impact of neighboring structures on the rate of entrainment and mixing for elongated flames than for their puff-like counterparts. For microgravity conditions the increase in flame length with increasing duty cycle can significantly exceed that seen in normal gravity.

The celerity for flame puffs near burn-out, taken from the slope of the puff trajectory versus time, is generally less in microgravity than in normal gravity. This is consistent with the longer time to burn-out observed for microgravity flame puffs. These two effects appear to be offsetting, with the result that the flame length of isolated, compact puffs is insensitive to buoyancy.

The combination of increasing flame puff size and decreasing puff celerity with downstream distance serves to change the separation between puffs, effectively increasing the duty cycle locally. The amount by which the duty cycle near the flame tip exceeds the injection duty cycle is greater in microgravity than in normal gravity due to the lower celerity in the former case, suggesting that the change in flame length with increasing injection duty cycle would be correspondingly greater in microgravity. This is in qualitative agreement with the experiments.

Varying the duty cycle allows for the systematic examination of the interaction and merging of the large structures, especially for the case of slowed flame motion in microgravity. An example of a microgravity flame at a duty cycle sufficiently high to result in significant structure-structure interaction is shown in Fig. 4, where the merging of discrete flame structures is shown.

Thermal characteristics

Buoyancy appears to have a strong effect on the thermal characteristics of fully-modulated turbulent diffusion flames.[6] The cycle-averaged centerline temperatures are generally higher in the microgravity flames than in normal gravity, especially at the flame tip where the difference was as much as 200 K. This is shown in Fig. 5 for P = 12 and α = 0.5. The flame is 50/50 ethylene/nitrogen in 21/29 oxygen/nitrogen (ψ = 7.1). It can be seen that centerline temperature is higher in microgravity than in normal gravity throughout the length of the flame. The cycle-averaged thermal radiation appears to be more strongly influenced by gravity than the temperature, and can be as much as 60% greater in microgravity than in normal gravity.

Elevated values of temperature and radiation intensity are also found for other values of P. The peak values of cycle-averaged centerline temperature are roughly 80 K greater in microgravity for all values of P. The peak radiation was about 30% to 60% greater in microgravity than normal gravity. The peak temperature appears to decrease, then to become roughly constant as P is increased, with the transition occurring at $P \approx 8$ (a similar value as that for the transition in flame length mentioned previously). By contrast, the radiation increases with P, and appears to level off at sufficiently high P in a similar fashion to the flame length.

Emissions

Time-averaged emissions were measured on the combustor centerline downstream of the visible flame tip in normal gravity[7]. The time-averaged CO emission index (g CO/kg fuel) for fully-modulated flames is shown as a function of the injection duty cycle in Fig. 6. The highest emission indices of CO were found for compact, isolated puffs and were roughly an order of magnitude higher than emissions from elongated flames. The amount of CO for compact puffs decreased substantially as the duty cycle (and the flame length and residence time). The emission indices of CO for all fully-modulated flames approached the low, steady-flame values (dashed line) for a duty cycle of approximately 0.35, while flame length in some cases was significantly shorter than that of the steady flame. The emissions of unburned hydrocarbons follow similar trends to those of CO. The trends in NO_x for fully-modulated flames have not yet been established. Further, all of the preceding results were acquired in the laboratory in normal gravity; the emissions levels of flames in microgravity have not yet been investigated.

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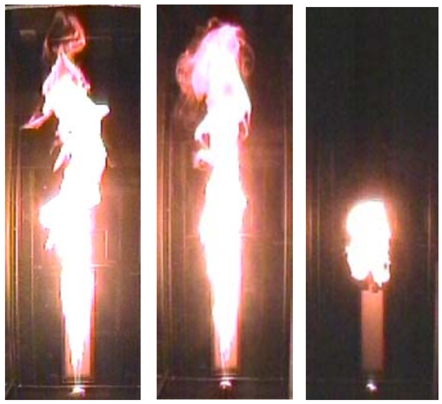

Fig. 1 Turbulent ethylene/(30% O_2 in N_2) diffusion flames in microgravity. Left, steady flame, middle, f-m flame with τ = 300 ms, P = 15, right, τ = 40 ms, P = 7.7.

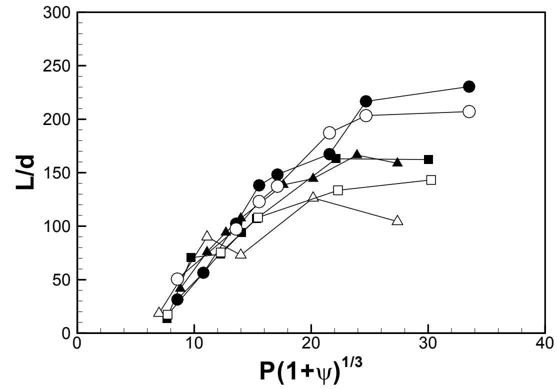

Fig. 2 Normalized flame length for f-m flames. Solid symbols, microgravity; open symbols, normal gravity. ○, ● ψ = 10; ■, □ ψ = 7.1, △, ▲ ψ = 5.

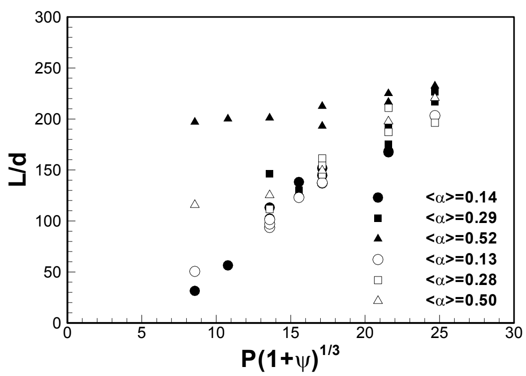

Fig. 3 Effect of injection duty cycle on normalized flame length for f-m flames for ψ = 10. Solid symbols, microgravity; open symbols, normal gravity.

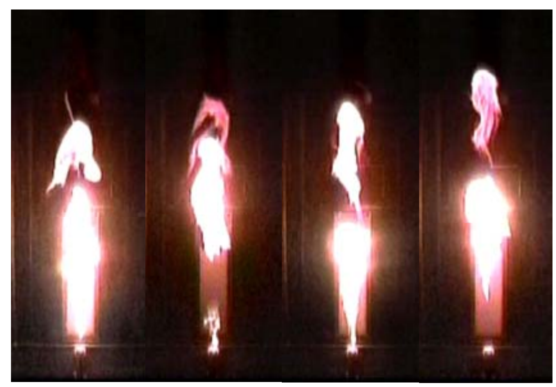

Fig. 4 Sequence of f-m flames in microgravity showing the merging of large-scale turbulent structures. P = 7.6, α = 0.5.

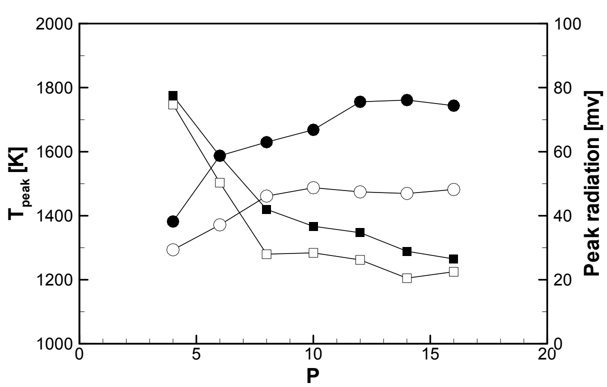

Fig. 5 Mean centerline temperatures and radiation for a P = *8* f-m flame. Solid symbols, microgravity; open symbols, normal gravity. ○, ● radiation; ■, □ temperature.

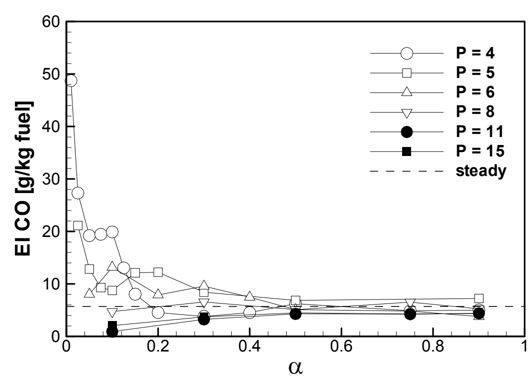

Fig. 6 CO emission index for f-m flames in normal gravity.