

BUOYANCY EFFECTS IN STRONGLY-PULSED, TURBULENT DIFFUSION FLAMES

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The objective of this experiment is to better understand the combustion behavior of pulsed, turbulent diffusion flames by conducting experiments in microgravity. The fuel jet is fully-modulated (i.e., completely shut off between pulses) by an externally controlled valve system leading to enhanced fuel/air mixing compared to acoustically excited or partially-modulated jets[1].

Experiments are conducted both in laboratories at UW and WPI and in the GRC 2.2s Drop Tower. A single fuel nozzle with diameter $d = 2$ mm is centered in a combustor 20×20 cm in cross section and 67 cm in height. The gaseous fuel flow (ethylene or a 50/50 ethylene/nitrogen mixture by volume) is fully-modulated by a fast-response solenoid valve with injection times from $\tau = 4$ to $\tau = 300$ ms. The nominal Reynolds number based on the fuel velocity during injection, U_{jet} , is 5,000. A slow oxidizer co-flow properly ventilates the flame[2] and an electrically heated wire loop serves as a continuous ignition source. Diagnostic techniques include video imaging, fine-wire thermocouples and thermopile radiometers, and gas sampling and standard emissions instruments (the last in the laboratory only).

The normalized flame lengths of fully-modulated diffusion flames consisting of isolated, non-interacting structures at low duty cycle, α (i.e., low jet-on fraction) are shown in Fig. 1. The flame length scales well with the parameter $P(1+\psi)^{1/3}$, where $P \equiv (U_{jet}\tau/d)^{1/3}$ and ψ is the stoichiometric air/fuel ratio[1]. The linear scaling persists to $P \approx 8$ where a transition from compact puffs to elongated flame structures begins. The visually-observed celerity of flame puffs near burn-out is generally less in microgravity than in normal gravity and the flame puffs in microgravity generally take a longer time to burn out. These two effects appear to be offsetting, with the result that the flame length of isolated, compact puffs in the linear scaling region is insensitive to buoyancy. By contrast, the mean length of flames with elongated, isolated structures ($P > 8$) does increase as buoyancy is removed.

The flame length in fully-modulated diffusion flames can also be significantly impacted by the off-time (or duty cycle) as shown in Fig. 2. Decreasing the off-time 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 effect is greatest for the most compact puffs with the shortest injection time (lowest values of P). An example of a microgravity flame at a duty cycle sufficiently high to result in significant structure-structure interaction is shown in Fig. 3.

The combination of increasing flame puff size and decreasing puff celerity with downstream distance changes the separation between puffs, effectively increasing the duty cycle locally. This effect 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 is correspondingly greater in microgravity. This is in qualitative agreement with the experiments.

Buoyancy appears to have a strong effect on the thermal characteristics of fully-modulated turbulent diffusion flames[3]. 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. The highest average centerline temperature (Fig. 4) appears to decrease, then to become roughly constant as P is increased. The transition occurs at $P \approx 8$ (similar to value for the transition in flame length mentioned previously).

The highest emission indices of CO and unburned hydrocarbons (UHC) were found for compact, isolated puffs and were roughly an order of magnitude higher than emissions from elongated flames[4]. The levels of CO, UHC, and NOx for all fully-modulated flames approached the low, steady-flame values for a duty cycle of approximately $\alpha \geq 0.4$, with a flame length significantly shorter than that of the steady flame. All emissions data were acquired in 1-g; the emissions levels of flames in microgravity have not yet been investigated.

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References

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- [3] Page, K.L., Stocker, D.P., Hegde, U.G., Hermanson, J.C. and Johari, H., *Third Joint Meeting of the U.S. Sections of The Combustion Institute*, Chicago, IL, March, 2003.
- [4] Johari, H., Ghaem-Maghani, E., and Hermanson, J.C., *Combustion Science and Technology*, in press, 2004.

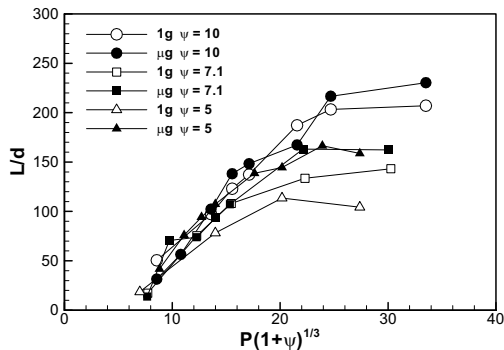


Fig. 1 Normalized flame length for fully-modulated flames.

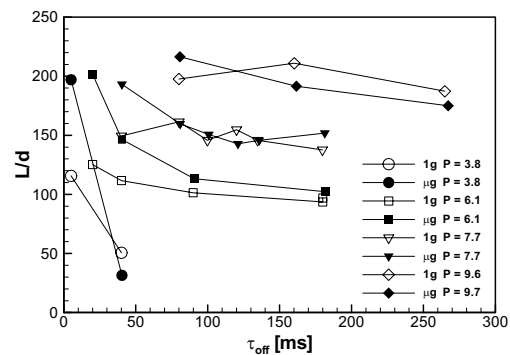


Fig. 2 Effect of injection off-time on normalized flame length for fully-modulated flames for $\psi = 10$.



Fig. 3 Sequence of fully-modulated flames in microgravity showing the merging of large-scale turbulent structures. $P = 7.6$, $\alpha = 0.5$.

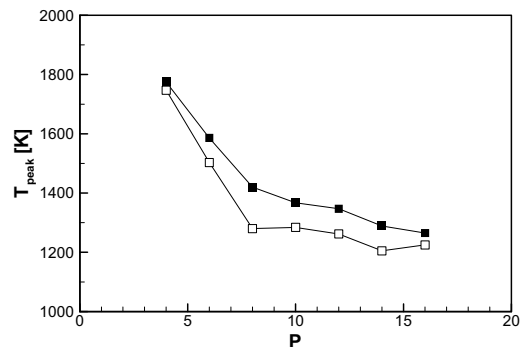


Fig. 4 Highest values of the average centerline temperature.

PROBLEM STATEMENT

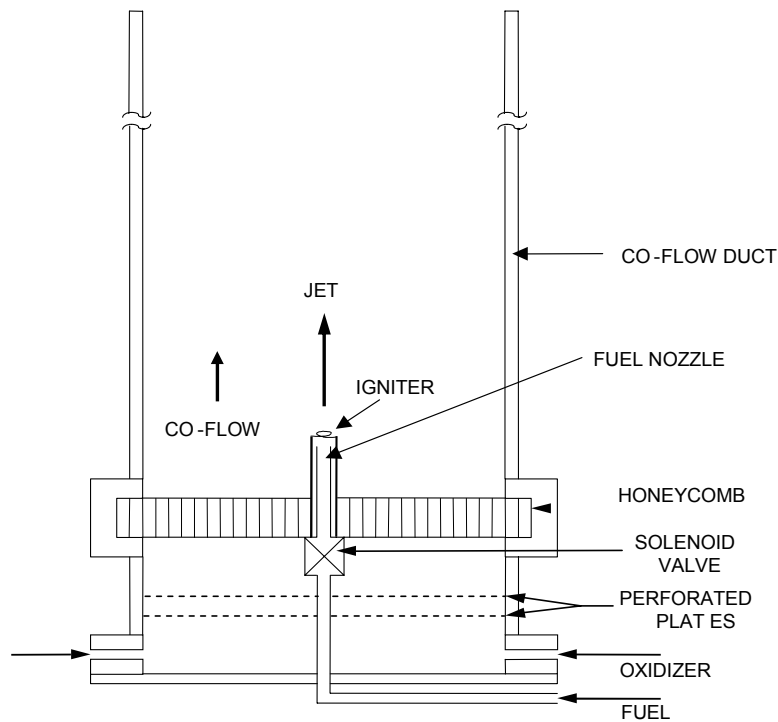
Fundamental issues in turbulent, non-premixed flames include the nature of the interaction between the dominant large-scale structures and the implications of these dynamics for air entrainment, the air/fuel mixing, combustion temperatures, and exhaust emissions. In normal gravity, the evolution of the turbulent structure of pulsed diffusion flames is governed by a combination of momentum-driven and buoyant instabilities. The removal of buoyancy in microgravity can thus be expected to have a significant effect on the characteristics of fully-modulated flames, as well as on steady flames.

APPROACH

This research employs a fully-modulated fuel injection approach in both normal- and microgravity. In this approach the fuel is completely shut off between pulses, positively controlling the generation and interaction of the large-scale turbulent flame structures. By regulating both the injection time as well as the jet off-time and thereby the injection duty cycle (the jet-off fraction of each pulsing cycle as set by the fuel valve controller), it is possible to study turbulent flames under conditions ranging from isolated structures, to interacting structures, to steady flames. Diagnostic techniques include video imaging of the visible flame, thermocouple temperature measurement, and measurement of stable emissions species.

Specific issues include the effects of buoyancy on large-scale structure growth, the nature of the dynamic interaction between neighboring structures, and the implications for air entrainment, air/fuel mixing, combustion temperatures, and exhaust emissions.

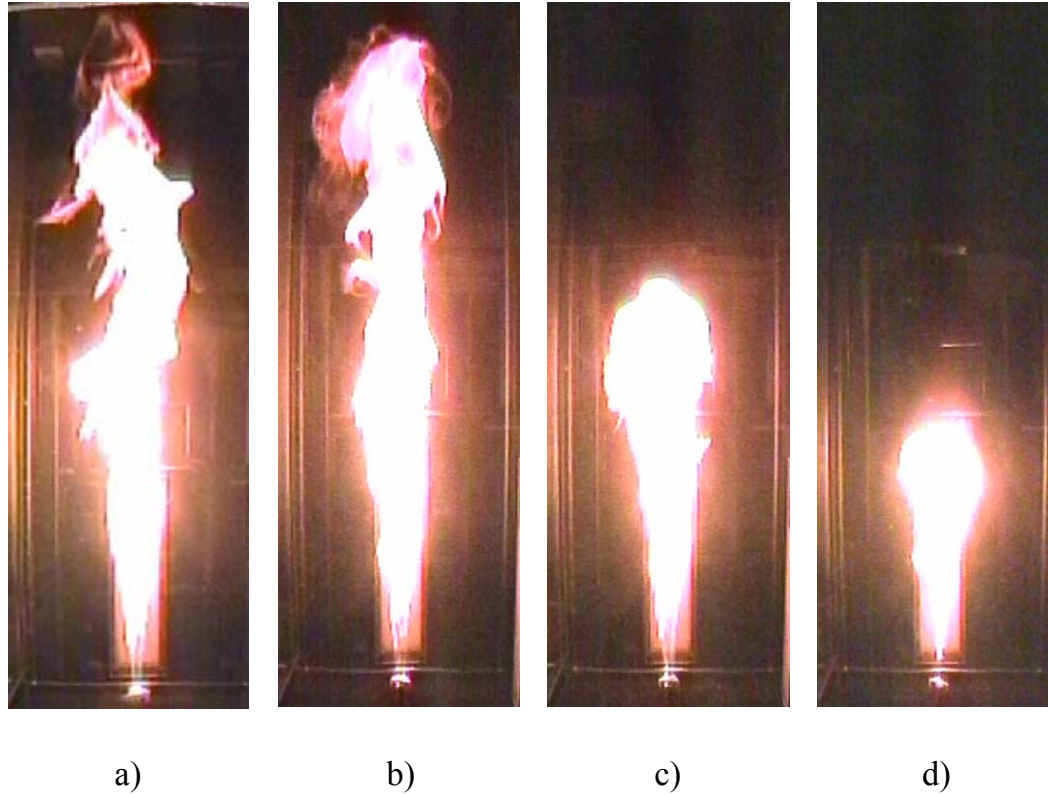
COMBUSTOR CONFIGURATION AND FLOW CONDITIONS



- Nozzle: 2 mm i.d.
- Combustor X- section: 20 x 20 cm
- Duct height: 56 cm
- Fuels: 50/50 C₂H₄/N₂; C₂H₄
- Fuel flow: $Re_d = 5000$
- Injection time: $\tau = 4$ to 300 ms
- Jet off-time: $\tau_{off} = 4$ to 500 ms
- Duty cycle: 0.02 – 0.9
- Co-flow: 21/79 O₂/N₂ ; 30/70 O₂/N₂
- Air/fuel ratio $\psi = 5-14.3$
- Co-flow : $\approx 0.5\%$ of jet velocity
- Reactants: unheated
- Pressure: ≈ 1 atm

Puff injection parameter $P = (U_{jet} \tau/d)^{1/3}$ where U_{jet} = jet-on injection velocity

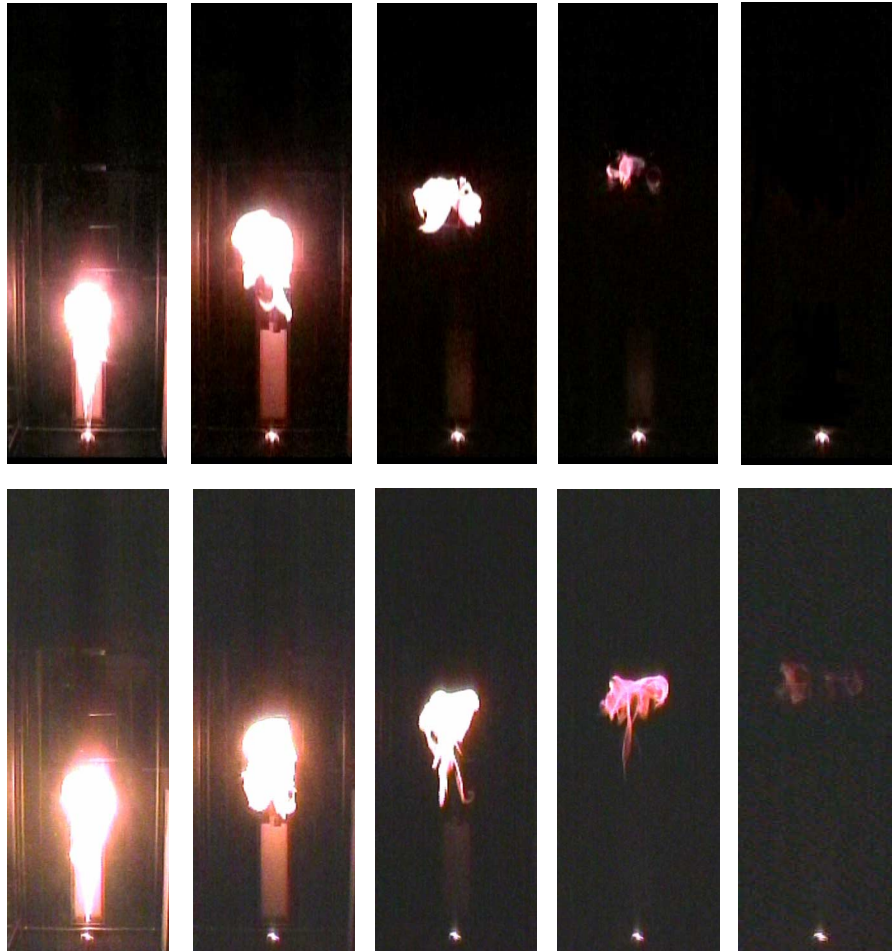
TURBULENT DIFFUSION FLAMES IN MICROGRAVITY



Turbulent ethylene/(30% oxygen in nitrogen) diffusion flames in microgravity near the end of the injection interval. a) Steady flame, b) fully-modulated flame with injection time $\tau = 300$ ms, $P = 15$; c) fully-modulated flame with $\tau = 200$ ms, $P = 13$; d) fully-modulated flame with $\tau = 40$ ms, $P = 7.7$. The vertical extent of all images is 55 cm.

FULLY-MODULATED FLAME SEQUENCES

Top, 1g; bottom, μ g.

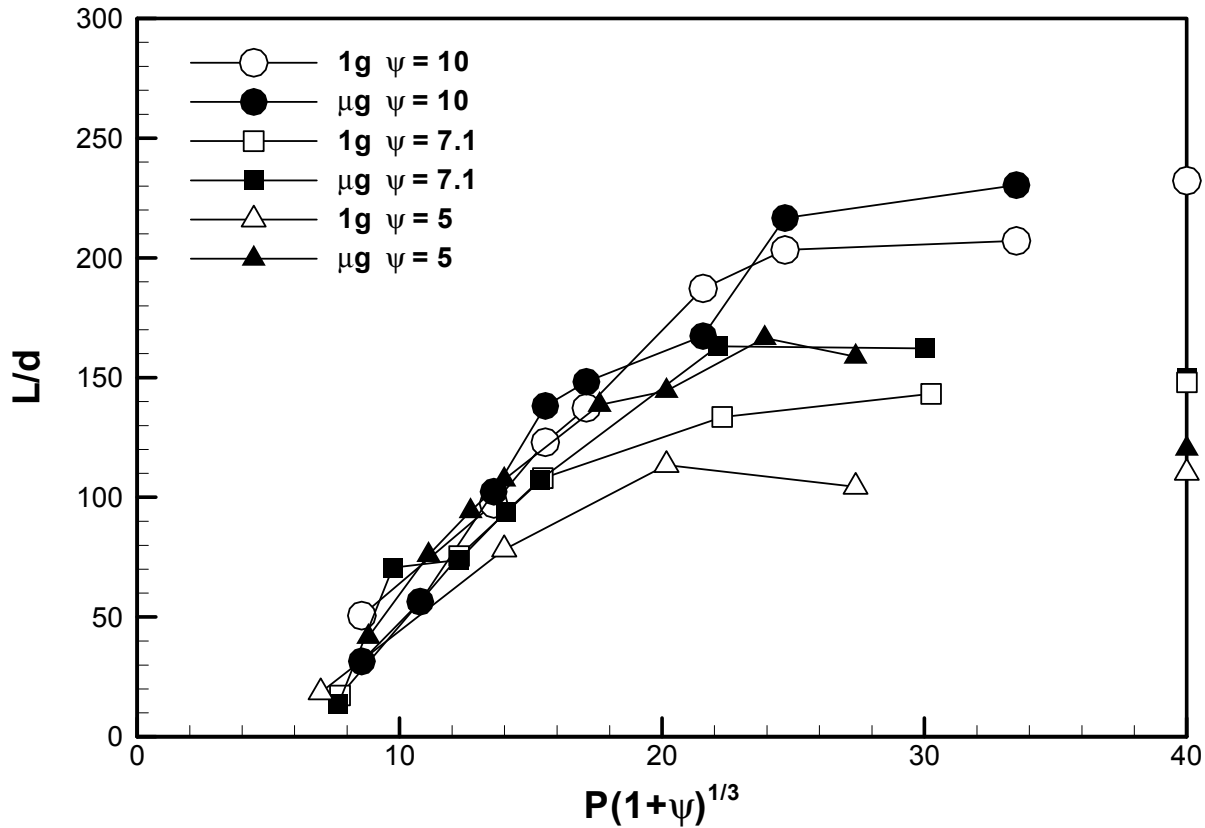


Fully-modulated ethylene/(30% oxygen in nitrogen) flames for $\tau = 40$ ms, $P = 7.7$. Time between images 33 ms. The sequences proceed from left to right. The image heights are 56 cm.

The celerity of the visible flame puff near burn-out is lower in microgravity than in normal gravity. These isolated microgravity flame puffs also exhibit a longer time to burn-out than puffs in normal gravity.

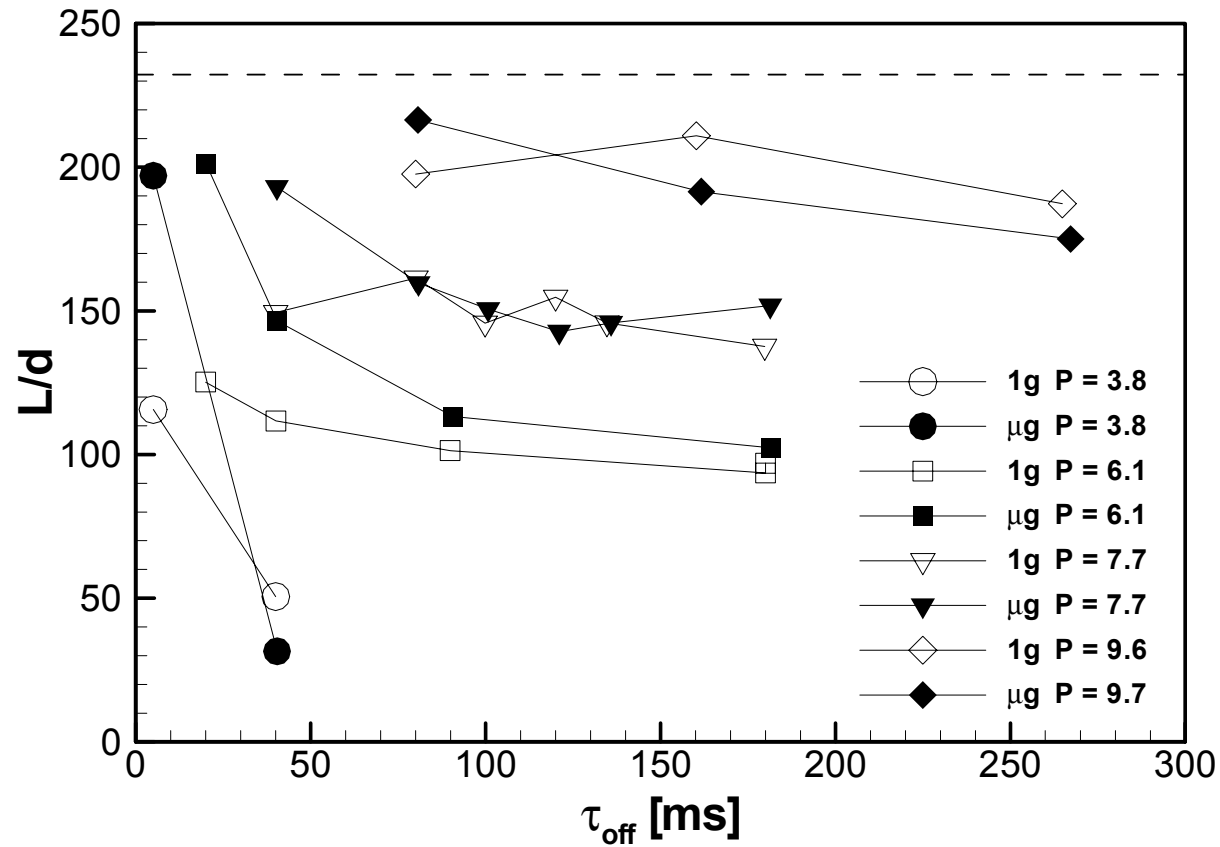
$P \approx 8$ is the approximate upper limit for puff-like flame structure; for higher P more elongated structures result.

MEAN FLAME LENGTH OF ISOLATED, FULLY-MODULATED DIFFUSION FLAME STRUCTURES



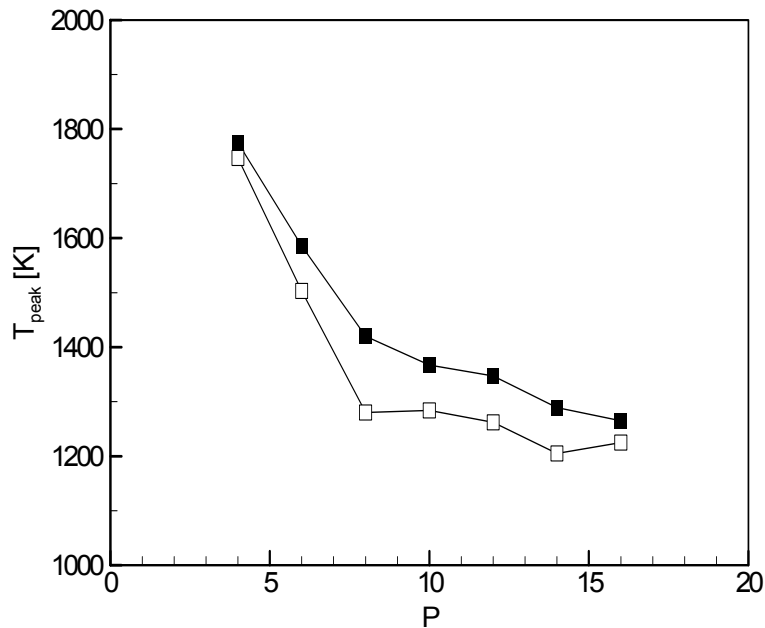
The flame lengths for steady flames are shown at $P(1+\psi)^{1/3} = 40$ for reference. The length of isolated (i.e., long off-time) fully-modulated flame puffs scales as $L/d \sim (1+\psi)^{1/3} P$ for $P \leq 8$.

MEAN FLAME LENGTH OF FULLY-MODULATED DIFFUSION FLAMES WITH INTERACTING STRUCTURES

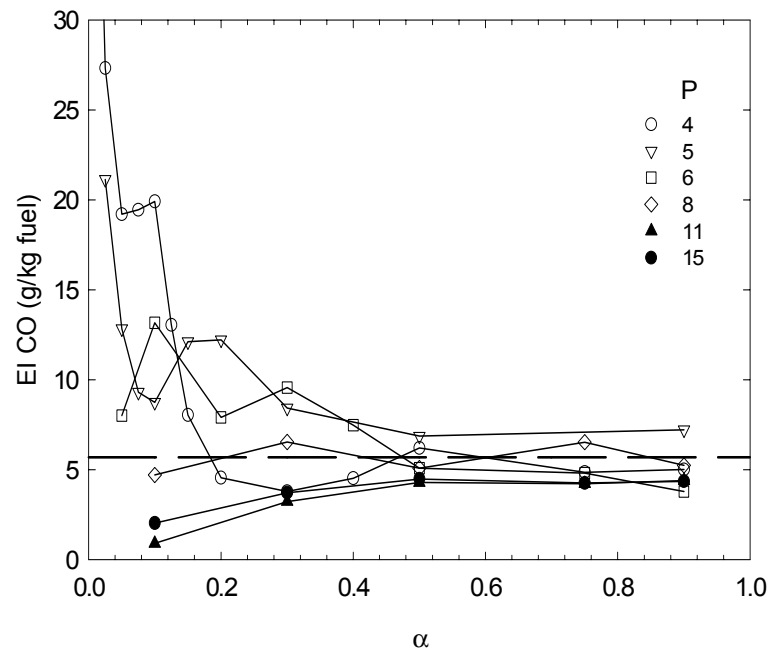


$\psi = 10$. The dashed line shows the length of steady flames. The flame length of puffs with the shortest injection time (smallest P) are influenced most by the interaction with nearby puffs as the off-time is decreased.

COMBUSTION TEMPERATURES AND EMISSIONS OF FULLY-MODULATED DIFFUSION FLAMES



Peak values, along the flame axis, of the cycle-averaged centerline temperature as a function of P . $\psi = 7.1$. Normal gravity (open symbols) and microgravity (solid symbols). A transition in temperature is apparent at $P \approx 8$.



Exhaust CO emissions of fully-modulated flames in normal gravity. $\psi = 14.3$. For all injection times low CO emissions comparable to that of the steady flame (dashed line) are achieved for duty cycles of $\alpha \geq 0.5$.

SUMMARY OF KEY RESULTS

- The mean flame length of isolated puffs in microgravity appears comparable to that of similar puffs in normal gravity, and scales in both cases with $P(1+\psi)^{1/3}$ up to a value of $P \approx 8$. $P \approx 8$ is the approximate upper limit for puff-like flame structure; for higher P more elongated structures result. The flame lengths for steady-state flames were also not significantly impacted by the elimination of buoyancy in microgravity. The flame length of isolated, elongated flame structures ($P > 8$) however does increase with the removal of buoyancy.
- In contrast to the case of isolated flame puffs, the flame length of interacting, fully-modulated puffs can be significantly impacted by the removal of buoyancy, with an increase in flame length most apparent for the shortest injection times.
- Buoyancy has a strong effect on the time-averaged centerline temperatures of fully-modulated flames, with the temperatures in μg generally higher than in 1g.
- The highest exhaust emission indices of CO (also unburned hydrocarbons) were found for compact, isolated puffs and were roughly an order of magnitude higher than emissions from elongated flames. The levels of all emissions for fully-modulated flames approached the low, steady-flame values for a duty cycle of approximately 0.4. The emissions levels of fully-modulated turbulent jet flames in microgravity are not known at present.

MAJOR CONCLUSIONS

- For some injection conditions, buoyancy has a significant impact on the mean flame length and, by implication, on the rate of oxidizer entrainment and mixing. The largest impact of buoyancy occurs for compact, interacting puffs. The lack of sensitivity of flame length to buoyancy for isolated, fully-modulated flame puffs is believed to be related to offsetting changes in flame puff celerity and time to burnout for the microgravity versus normal gravity cases.
- Several characteristics of fully-modulated flames appear to undergo a transition for a value of the injection parameter of approximately $P = 8$. For injection times corresponding to higher values of P the following occur: 1) a transition from compact, puff-like structures to more elongated structures, 2) a deviation from a linear scaling of flame length with $(1 + \psi)^{1/3} P$ for isolated structures, and 3) a change in the time-averaged centerline temperatures, leading to a value less sensitive to injection time than for the case of low P .
- As the duty cycle is increased the emissions levels of fully-modulated flames approach those of steady flames. At the same time, the flame length can be significantly shorter than that of the steady flame (by as much as 50%). The fully-modulated injection technique thus appears to have the potential to provide for compact, low-emissions turbulent jet diffusion flames.