# SUPPRESSION AND STRUCTURE OF LOW STRAIN RATE NONPREMIXED FLAMES

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The agent concentration required to achieve suppression of low strain rate nonpremixed flames is an important fire safety consideration.  In a microgravity environment such as a space platform, unwanted fires will likely occur in near quiescent conditions where strain rates are very low.  Diffusion flames typically become more robust as the strain rate is decreased. When designing a fire suppression system for worst-case conditions, low strain rates should be considered

The first comprehensive extinction measurements of very low strain non-premixed flames in microgravity were reported by Maruta *et al.* [1].  The extinction of methane-air flames with $N_2$ added to the fuel stream was investigated using the JAMIC 10 s drop tower.  The minimum methane concentration required to sustain combustion was measured to decrease as the strain rate decreased until a critical value was observed. As the global strain rate was further reduced, the required methane concentration increased. This behavior was denoted as a "turning point" and was attributed to the enhanced importance of radiative losses at low strain rates. In terms of fire safety, a critical agent concentration assuring suppression under all flow conditions represents a fundamental limit for nonpremixed flames.

The objective of this study is to investigate the impact of radiative emission, flame strain, agent addition, and buoyancy on the structure and extinction of low strain rate nonpremixed flames through measurements and comparison with flame simulations. The suppression effectiveness of a suppressant ($N_2$) added to the fuel stream of low strain rate methane-air diffusion flames was measured. Flame temperature measurements were attained in the high temperature region of the flame (T $> 1200$ K) by measurement of thin filament emission intensity. The time varying temperature was measured and simulated as the flame made the transition from normal to microgravity conditions and as the flame extinguished.

## EXPERIMENTAL METHOD

Flame suppression and the temperature field in low-strain diluted methane/air non-premixed flames were measured in microgravity using a counterflow flame configuration. Experiments were performed at the NASA Glenn research facility using the 2.2 s drop. A 15 mm diameter stainless steel counterflow burner was enclosed in a 25 L cylindrical chamber. The duct separation distance was 15 mm.  The burner ducts were designed to have minimal dead volume as glass beads and a series of fine mesh steel screens were used to impose a near plug-flow velocity profile at the burner exit.

To control each of the reactant gas flows, a fast response time (~10 ms) pressure controller was used in series with a critical flow orifice. The total system response time was equal to the flow control response time plus the residence flow time from the mixing tee to the flame zone, estimated as 0.0665 s to 0.6397 s for strain rates of 50 s$^{-1}$ and 7 s$^{-1}$, respectively. The

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flow of dry air and methane were calibrated using a dry cell primary flow meter.  A 0.25 mm diameter, 7 cm long coiled resistance igniter wire (Pt + 30% Rh) positioned between the fuel and oxidizer ducts was used to ignite the flame.  A rotary brushless torque actuator was used to control the position of the ignition wire.

Extinction measurements were performed by incrementally increasing the agent flow, while maintaining a constant global strain rate ($a_g$), accomplished by simultaneously reducing the air or fuel flow. The value of $a_g$ in the axisymmetric counterflow configuration is defined as:

$$a_g = (-2V_O/L)\cdot(1 + [(V_F/V_O)\cdot(\rho_F/\rho_O)^{1/2}]) \qquad (1)$$

where $V$ and $\rho$ denote the velocity and density of the reactant streams at the boundaries, L is the duct separation distance, and the subscripts O and F represent the oxidizer and fuel streams, respectively. The standard uncertainty in agent extinction concentration was 2 % based on repeat measurements.

Measurement of the visible emission intensity from a 13 μm SiC filament placed along the burner centerline allowed the determination of  flame temperatures for T>1200 K. Radiation emitted by the filament was recorded using a digital CCD camera with a close-up lens. Spatial resolution of the image was 0.07 mm/pixel.  The camera exposure was adjusted to prevent image saturatation (over-exposure) at the maximum flame temperature.  The intensity measurements were calibrated using Oppdff [3]. The uncertainty is 50 K based on repeat measurements.

**NUMERICAL METHODOLOGY**

Two flame codes were utilized. The structure and extinction of methane-air flames with $N_2$ addition were investigated using a one-dimensional numerical simulation that employs detailed models of molecular transport and chemistry, but ignores buoyancy [2,3].  A term for the radiative heat loss rate was added to the energy equation in the one-dimensional flame code. Radiative losses were modeled with a narrowband spectral model [4]. A transient two-dimensional (axisymmetric) solution to the Navier-Stokes equations including buoyancy using either a mixture fraction approach or one-step chemistry based on the NIST Fire Dynamic Simulator (FDS) was developed [5].  The effects of global strain rate and buoyancy were investigated and results were compared to the one-dimensional Oppdif flame code at 0-g.

**RESULTS AND DISCUSSION**

Figure 1 shows extinction measurements performed for stain rates of 7 s$^{-1}$ through 50 s$^{-1}$, confirming the "turning point" behavior observed previously by Maruta and coworkers [1] and confirming the viability of these 2 s duration extinction measurements.  The maximum nitrogen volume fraction in the fuel stream, $C_{a,ext}$, needed for extinction was found to be 0.855 ± 0.016 at a strain rate of 15 s$^{-1}$, consistent with the results of Maruta.  These values are different from analogous measurements performed in normal gravity [6], implying that the local oxidizer-side strain rate differs in normal and microgravity for small $a_g$.  On-going Particle Imaging Velocimetry (PIV) measurements are quantifying these differences.

Figure 2 compares a photograph of a 12 s$^{-1}$ near-extinction methane/air diffusion flame in normal gravity (fuel = 20% $CH_4$ + 80 % $N_2$) with the FDS simulation.  The flame curvature in 1g is captured by the simulation. Figure 3 compares drop measurements to FDS simulations of the position of the maximum flame temperature as a function of time after microgravity occurs for constant flow conditions, $a_g$=20 1/s and the fuel = 82 % $N_2$ + 18 % $CH_4$.  There is general agreement between the model and the measurements within measurement uncertainty.   Figure 4 shows agreement between the simulated (Oppdif and FDS) and measured (filament and
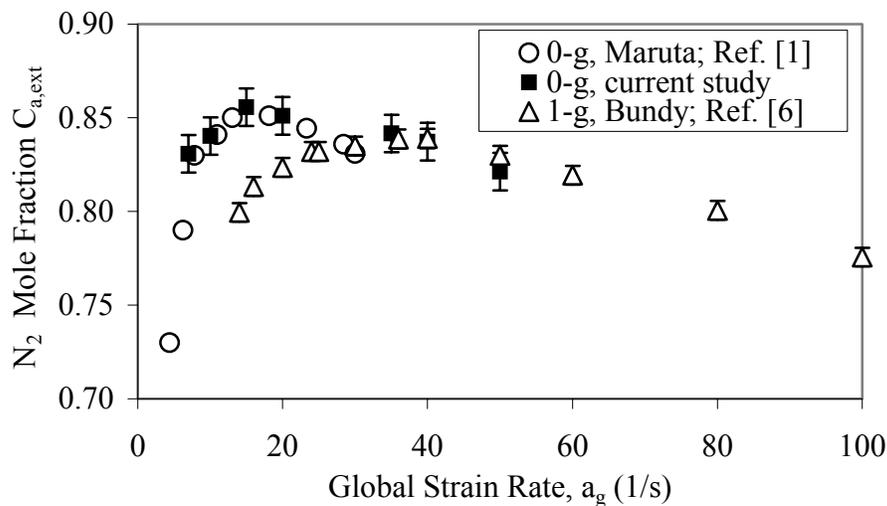
thermocouple) temperature profiles in normal and microgravity. Figure 5 shows consistent trends between the calculated (Oppdif) and measured peak flame temperatures in near-extinction methane/air diffusion flames in microgravity. As the strain rate decreases, the peak flame temperature decreases until low peak temperatures are observed (< 1400 K), rather unusual for a flamelet.

## REFERENCES

1.  Maruta, K., Yoshida, M., Guo, H., Ju, Y., & Niioka, T, *Combust. Flame*, 112:181 (1998).

2.  Bowman, C. T., Hanson, R. K., Davidson, D. F., Gardiner, Jr., W. C., Lissianski, V., Smith, G. P., Golden, D. M., Frenklach, M., & Goldenberg, M., "GRI-MECH 2.11", URL: http://www.me.berkeley.edu/gri-mech/, 1995.

3.  Lutz, A., Kee, R. J., Grcar, J., & Rupley, F. M., "A Fortran Program Computing Opposed Flow Diffusion Flames", SAND96-8243, Sandia National Labs, Livermore (1997).

4.  Grosshandler, W.L., RADCAL: NIST Technical Note 1402, National Institute of Standards and Technology, Gaithersburg, Maryland, 1993.

5.  McGrattan, K. B., Baum, H. R., Rehm, R. G., Hamins, A., Forney, G. P., Floyd, J. E., and Hostikka, S., "Fire Dynamics Simulator Technical Reference Guide," National Institute of Standards and Technology, Gaithersburg, MD (2001).

6.  Bundy, M., Hamins, A., & Lee, K.Y., *Combust. Flame*, to appear (2003).

Figure 1. Critical mole fraction of $N_2$ in the fuel stream required to extinguish a methane/air diffusion flame in normal and microgravity. The results of Maruta et al. [1] are also shown. Flammable region is below the data points.
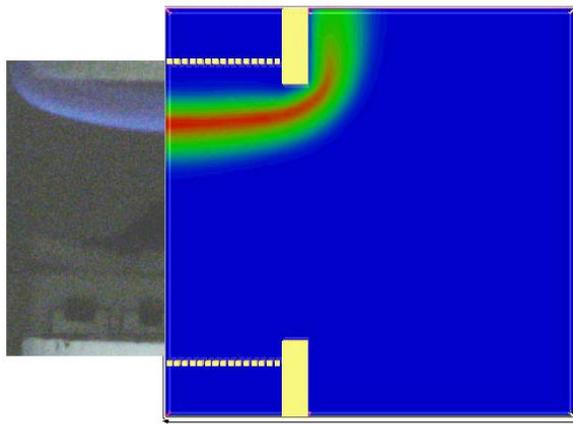
Figure 2. Photograph and simulation of a $12 \text{ s}^{-1}$ diluted methane/air diffusion flame in normal gravity. (Fuel $=20\%CH_4 + 80 \% N_2$)
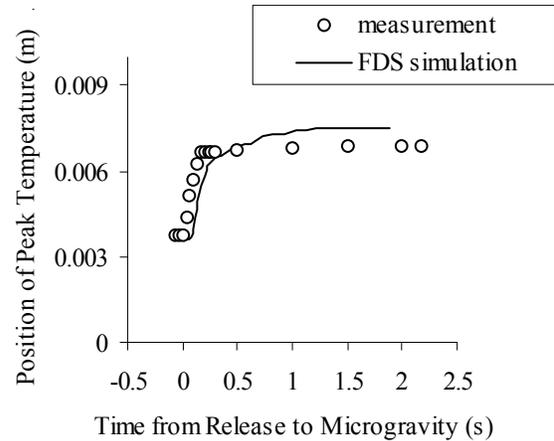


Figure 3. The measured and calculated (FDS) position of the peak flame temperature as a function of time after microgravity occurs. $a_g=20 \text{ s}^{-1}$, 18% $CH_4$
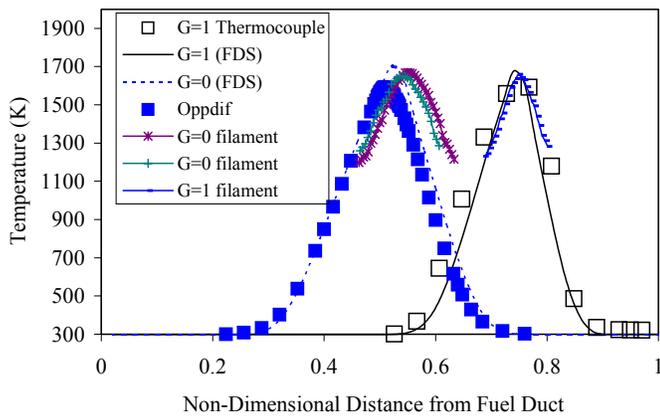


Figure 4. Comparison of the calculated (FDS and Oppdif) and measured (SiC filament intensity and thermocouple) flame temperatures in diluted methane/air diffusion flames in normal and microgravity with $a_g=20 \text{ s}^{-1}$ and the fuel composed of ~20 % $CH_4$ + 80 % $N_2$.
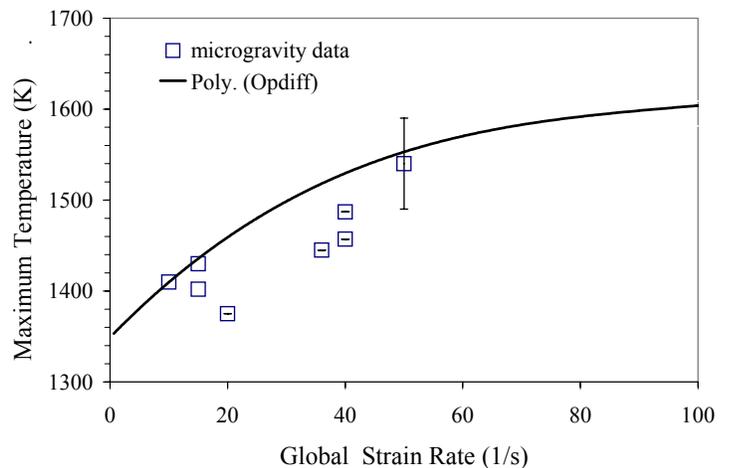


Figure 5. Comparison of the calculated (Oppdif) and measured peak flame temperature in near-extinction methane/air diffusion flames in microgravity. Conditions were extremely near extinction, such that the agent concentration was > 99.4 % of that required for extinction, corresponding to the conditions shown in Fig. 1.