Suppression of Low Strain Rate Nonpremixed Flames by an Agent

A. Hamins, M. Bundy, I.K. Puri*, K. McGrattan, and W.C. Park**
NIST, Gaithersburg, Maryland 20899-8640
* Dept. Mechanical Engineering, University of Illinois at Chicago, Chicago, Illinois 60607-7022
** Permanent address: Safety Engineering, Pukyong National University, Pusan, 608-739, Korea

INTRODUCTION The agent concentration required to achieve the suppression of low strain rate nonpremixed flames is an important consideration for fire protection in a microgravity environment such as a space platform. Currently, there is a lack of understanding of the structure and extinction of low strain rate (<20 s^{-1}) nonpremixed flames [1]. The exception to this statement is the study by Maruta et al. [2], who reported measurements of low strain rate suppression of methane-air diffusion flames with N_2 added to the fuel stream under microgravity conditions. They found that the nitrogen concentration required to achieve extinction increased as the strain rate decreased until a critical value was obtained. As the strain rate was further decreased, the required N_2 concentration decreased. This phenomenon was termed "turning point" behavior and was attributed to radiation-induced nonpremixed flame extinction. In terms of fire safety, a critical agent concentration assuring suppression under all flow conditions represents a fundamental limit for nonpremixed flames.

Counterflow flames are a convenient configuration for control of the flame strain rate. In high and moderately strained near-extinction nonpremixed flames, analysis of flame structure typically neglects radiant energy loss because the flames are nonluminous and the hot gas species are confined to a thin reaction zone. In counterflowing CH_4-air flames, for example, radiative heat loss fractions ranging from 1 to 6 percent have been predicted and measured [3,4].

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 number of suppressants (N_2, CO_2, or CF_3Br) was considered as they were added to either the fuel or oxidizer streams of low strain rate methane-air diffusion flames.

EXPERIMENTAL METHOD Flame structure and extinction was investigated in normal gravity using a water-cooled counterflow burner with a diameter of 23.4 mm and a duct separation of 25 mm. Four 200 mesh stainless steel screens were secured at the opening of each duct to impose a top-hat velocity profile. The flow of dry air (with $[O_2]$=20.94%±0.04%) and methane (99.99%) were controlled using mass flow controllers that were calibrated using a dry cell primary flow meter with an uncertainty of better than 0.5%. The oxidizer flowed from the top duct, which was aligned with the gravity vector. The ratio of the velocity of the oxidizer stream to the velocity of the fuel stream was varied from 1:1 to 4:1 to position the flame such that conductive heat transfer losses to the burner were negligible, as verified by temperature measurements using 50 μm diameter thermocouples (see Fig.1). Analogous experiments are being prepared for the NASA/Cleveland drop towers.

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) was varied from 12 s^{-1} to 120 s^{-1} and is defined as:

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

The parameters V and ρ 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. Extinction measurements were repeated at least four times. The combined standard uncertainty (with a coverage factor of 2) in the agent extinction concentration based on repeat measurements and a propagation of error analysis was typically 1.3%.

Flame unsteadiness was reduced by placing the burner in an enclosure (0.5×0.5×0.6 m^3), which isolated it from ambient flow disturbances and facilitated experimentation on flames with a_g as low as 12 s^{-1}. The enclosure had a 10 cm exhaust port and was placed inside a chemical hood. Combustion products were removed by buoyancy, not forced ventilation.

NUMERICAL METHODOLOGY

Two flame codes were utilized. The structure and extinction of methane-air flames with CO_2 and N_2 addition were investigated using a one-dimensional numerical simulation [5] that employs detailed models of molecular transport and chemistry [6], but ignores buoyancy. 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 either a narrowband spectral model [7] or as an optically thin gray gas with temperature dependent Plank mean absorption coefficients for the participating gas species (CH_4, CO_2, H_2O and CO) [8]. A transient two-dimensional (axisymmetric) solution to the Navier-Stokes equations using a mixture fraction approach and including buoyancy [9] was used to investigate the impact of G-level on the structure of near-extinction methane-air diffusion flames with N_2 added to the fuel.

RESULTS AND DISCUSSION

Observations Undiluted, low strain rate counterflow methane-air flames are luminous. As CO_2 or N_2 was added to either reactant stream, flame luminosity decreased. Near extinction, the flames appeared to be completely nonluminous. This observation motivated simplification of the radiation model for these diluted flames, permitting exclusion of radiative emission by particulates. This was not the case for CF_3Br inhibited flames, which were very luminous.

Suppressant added to the Fuel Stream Equation 1 implies that a_g can be held constant for varying values of (V_O/V_F). A series of measurements and one-dimensional calculations were performed that determined the agent concentration required to achieve extinction as a function of (V_O/V_F) for constant a_g. The computations showed that while the flame position shifted, the maximum flame temperature and the required agent concentration was invariant. This was experimentally confirmed Using this strategy, Fig. 2 shows measurements of the required N_2, CO_2, and CF_3Br concentration in the oxidizer stream of nonpremixed CH_4-air flames as a function of the global strain rate for normal gravity and flames free of conductive losses. The most effective suppressant was CF_3Br, followed by CO_2 and then N_2. The critical suppressant concentration increased as the strain rate decreased, with its value leveling off near 30 s^{-1}, except for CF_3Br, which flattened near 40 s^{-1}. The results demonstrate the existence of turning point behavior in normal gravity diffusion flames, but at higher values of a_g then the microgravity measurements of Maruta et al. [2]. This implies that buoyancy impacts the near-extinction flame structure. These differences are being studied experimentally and computationally. Both the measurements and calculations show that as a_g decreases, the near-extinction peak flame temperature decreases and the flames broaden spatially. Removal of gravity also broadens the flames spatially (as well as shifting the flame location) as seen in Fig. 3, which compares the calculated temperatures from the two-dimensional code to thermocouple measurements conducted in normal gravity and the one-dimensional calculations for near-extinction N_2 diluted flames. Removal of gravity does not significantly change the calculated peak temperatures.

Suppressant added to the Oxidizer Stream Figure 4 shows measurements of the required N_2, CO_2, and CF_3Br concentrations as a function of the global strain rate for agent added to the oxidizer stream. Similar to the results for agent added to the fuel stream (Fig. 2), the results flattened at low strain rates suggestive of turning point behavior. Again, the most effective suppressant was CF_3Br, followed by CO_2 and then N_2. Flames with N_2 and CF_3Br addition showed turning point behavior at 40 s^{-1} and 30 s^{-1}, respectively. The larger turning point strain rate value for CF_3Br is attributed to enhanced radiative emission associated with CF_3Br addition.

SUMMARY AND CONCLUSIONS An experimental and computational study is underway to investigate the extinction of low strain rate diffusion flames by an agent. To illuminate the mechanisms of flame suppression at low strain rates, computational simulations that include radiative heat transfer were compared with measurements. An experimental apparatus is being completed for low strain rate microgravity experiments using the 2.2 s drop tower. The microgravity measurements will be compared to numerical predictions and 1G measurements.

ACKNOWLEDGEMENTS This research was partially supported by the NASA Microgravity Research Division through Contract No. C-32066-T (NIST) and Grant No. NCC3-694 (UIC), with Sandra Olson serving as Technical Monitor. M. Bundy was supported by the National Research Council as a NIST Post-Doctoral Research Associate (1999-2001).

REFERENCES

1. Hamins, A., Trees, D., Seshadri, K., & Chelliah, H., *Combust. Flame*, 99:221 (1994).
2. Maruta, K., Yoshida, M., Guo, H., Ju, Y., & Niioka, T, *Combust. Flame*, 112:181 (1998).
3. Lee, K. Y., Cha, D. J., Hamins, A., & Puri, I. K., *Combust. Flame* 104:27 (1996).
4. Chan, S. H., Pan, X. C., & Abou-Ellail, M. M. M., *Combust. Flame,* 102:438 (1995).
5. 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).
6. 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.
7. Grosshandler, W.L., RADCAL: NIST Technical Note 1402, National Institute of Standards and Technology, Gaithersburg, Maryland, 1993.
8. Tien, C. L., Thermal Radiation Properties of Gases in *Advances in Heat Transfer* (T. F. Irvine Jr. and J. P. Hartnett, Eds.), Vol. 5, 1968, p. 311.
9. Floyd, J., McGrattan, K., & Baum. H., *A Mixture Fraction Combustion Model for Fire Simulation Using CFD*, International Conference on Engineered Fire Protection Design, to appear, June 2001.

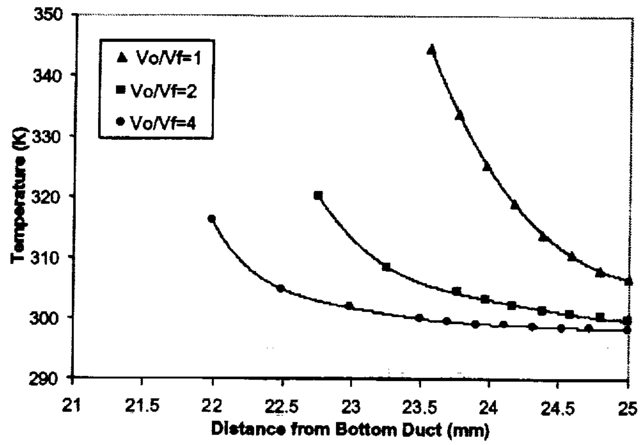

Figure 1. Thermocouple measurements in near-extinction CH_4-air nonpremixed flames with N_2 added to the fuel stream as a function of distance from the bottom (fuel) duct in normal gravity. The ratio of the velocity of the oxidizer stream to the velocity of the fuel stream (V_O/V_F) was varied from 1 to 4 with all flames at a global strain rate of 12 s^{-1}.

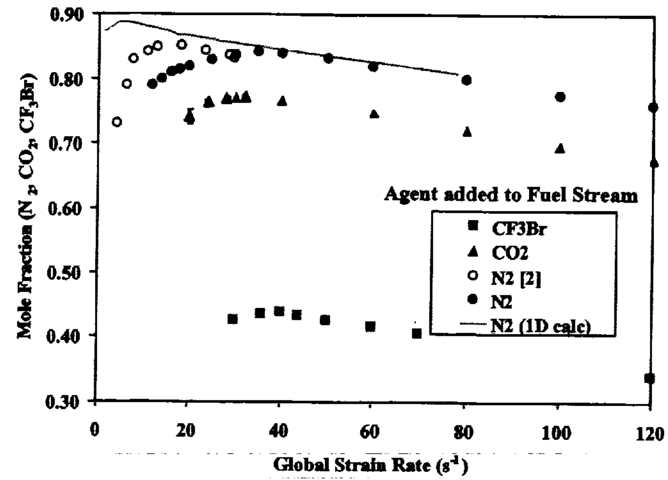

Figure 2. The critical agent mole fraction in the fuel stream required to extinguish CH_4-air nonpremixed flames measured in normal gravity. Also shown are Maruta's microgravity results for N_2 [2], and the one-dimensional (1D) flame calculations (using the narrowband model), which show agreement with the N_2 measurements for $a_g \geq 40\ s^{-1}$.

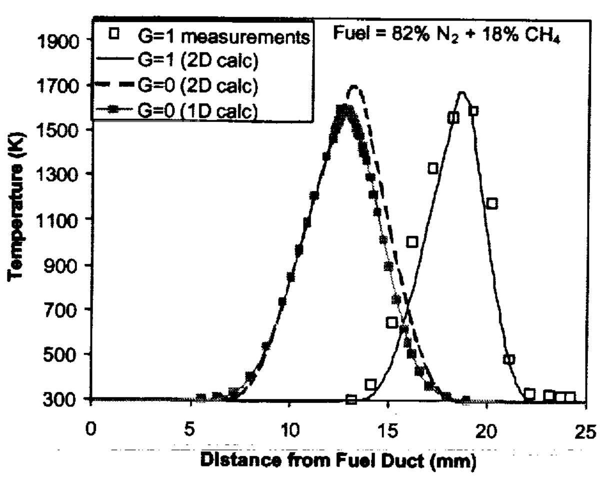

Figure 3. The temperature of near-extinction CH_4-air nonpremixed flames with N_2 added to the fuel stream as a function of distance from the fuel duct. The global strain rate = 20 s^{-1} and $V_O/V_F = 1$. Normal gravity (G=1) thermocouple measurements (uncorrected for radiative losses) are compared to the results from the two-dimensional (2D) calculation. In addition, results from the one-dimensional (1D) calculation (using the narrowband model) are compared to those of the two-dimensional calculation with the buoyancy force set to zero (G=0).

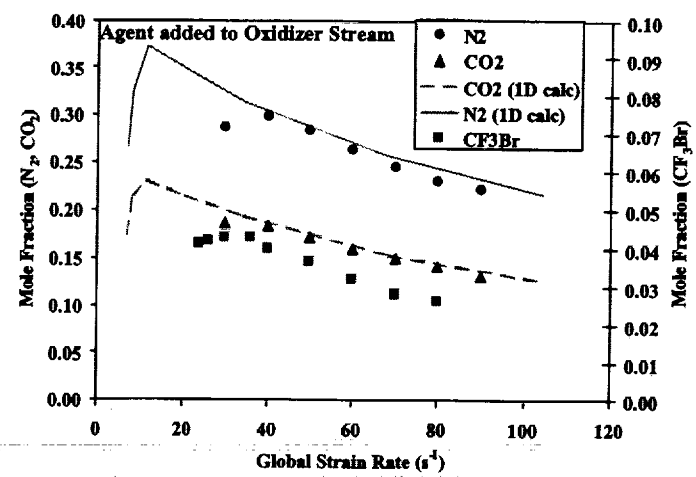

Figure 4. The critical agent mole fraction in the oxidizer stream required to extinguish CH_4-air nonpremixed flames measured in normal gravity. Also shown are the one-dimensional (1D) flame calculations (using the narrowband model), which show agreement with the measurements for $a_g \geq 40\ s^{-1}$.