CO_2 Suppression of PMMA Flames in Low-Gravity

G. A. Ruff[1], M. Hicks[1], W. Mell[2], R. Pettegrew[3], and A. Malcom[3]
[1]NASA Glenn Research Center, MS 77-5, 21000 Brookpark Road, Cleveland, OH 44135
[2]University of Utah, 50 South Campus Drive, Salt Lake City, UT 84112
[3]National Center for Microgravity Research, 21000 Brookpark Road Cleveland, OH 44135

INTRODUCTION

Even though much has been learned about the effects of microgravity on material flammability, flame spread, and suppressant effectiveness, uncertainties remain regarding some of the practical aspects of fire protection in spacecraft. The experiments and simulations underway in this project are aimed directly at testing, understanding and improving NASA's existing policies and practices toward fire safety in spacecraft and extraterrestrial habitats. Specifically, the objectives of this research are:

1. Determine systematically the conditions that will ignite onboard flammable materials upon passage of an initial premixed gas, firebrand, or aerosol flame over these materials.
2. Test the effect of firebrands and configuration spacing.
3. Determine the effectiveness of the flow of CO_2 extinguisher or other extinguishing agents.

Experimental and computational investigations are planned to achieve each of the three objectives above. Even though progress has been made in all of the areas, the majority of data has been collected for objective (3). Current results from these investigations are discussed below.

EXPERIMENTAL INVESTIGATION

Determining the effectiveness of a flow of CO_2 to extinguish a fire and whether secondary fires can occur when oxygen is re-introduced after initial extinguishment is the objective of the first set of experiments conducted in this investigation in the Spacecraft Fire Safety Facility (SFSF), a test facility designed for operation on NASA's low gravity aircraft. To examine the effectiveness of CO_2 to extinguish fires, an oxidizer flow is established over a hollow cylinder (tube) of PMMA (polymethyl methacrylate) 25 mm long and 19 mm in diameter. The inner diameter of the tube is 9.5 mm. A cartridge heater in the center of the tube pre-heats the sample to 100 deg C to help ensure a uniform and repeatable ignition. Thermocouples are located on the external surface of the inserted cartridge heater and on the external surface of the PMMA test sample at the downstream stagnation point to monitor these temperatures.

Flame extinguishment at flow velocities between 0 and 10 cm/s and 1 atm pressure were investigated. To begin a test, the oxidizer flow is established at the desired velocity. As the aircraft exits a parabola, the igniter is energized until a sustained flame is observed on the PMMA. The igniter is then turned off and the flame becomes well-established through the remainder of the 2-g pull-up. During the microgravity period, the flame is observed to determine if it extinguishes because of the low flow rate. If the flame is sustained through this first microgravity period, it is allowed to burn through a second 2-g pull-up, during which it increases in intensity. At the end of the pull-up, the flow is quickly switched from oxidizer to a suppressant mixture (either a mixture of CO_2/air or He/air) so that the suppressant reaches the sample after the first few seconds of low gravity. The flame is then observed to determine if it (i) extinguishes during the low-gravity period,

(ii) continuously decreases in intensity during low gravity but does not extinguish, or (iii) maintains a fairly stable intensity and does not extinguish within the low gravity period (approximately 20 sec).

Tests have been conducted for oxidizer mixtures of 21% O_2/79% N_2 (standard air) and 25% O_2/75% N_2 (rich air). Suppressant mixtures having 12.5%, 25%, and 50% CO_2 with the balance being either standard or rich air, depending on the oxidizer, have been evaluated. Data has also been obtained with He replacing CO_2 in the suppressant at similar concentrations. To date, tests have been conducted on 26 flights and a total of 142 data points have been obtained. A series of ground tests have also been conducted so that 0-g and 1-g behavior can be compared.

Experimental Results

Figure 1 shows the PMMA surface temperature at the rear stagnation point as a function of mass flow rate of oxygen (%O_2 in flow x ρUA). The open symbols show conditions that self-extinguished. The closed symbols show conditions where the suppressant was applied with the solid circles indicating flames that were extinguished. The conditions represented by triangles did not extinguish within the 20 seconds of low-gravity. For O_2 flow rates below about 0.7 g/s (velocities below 5 cm/s for standard air) and surface temperatures below approximately 270 deg C, the flames extinguished within 20 sec with no addition of suppressant. Increasing either the flow velocity or the surface temperature allowed the flame to be sustained through the low-gravity period. This result is similar to that obtained by Goldmeer [1] who showed that increasing the sample temperature made the flame more difficult to extinguish. On this plot, there is no discernable boundary between flames that were extinguished by suppressant and those that were not. This is likely the result of the influence of a number of parameters such a g-jitter, sample pre-heat, flame shape, and duration of suppressant flow. The effect of these parameters will be the focus of future work.

Figure 2 shows the time-to-extinguish as a function of flow velocity for an oxidizer of rich air and the suppressant 25% CO_2/75% rich air. The time to extinguish plotted in the figure is the time from when suppressant reached the sample to extinguishment. The images show end views of the PMMA sample in flowing oxidizer after the flames became stable in low-gravity. At 1 cm/s, the flame extinguished within 4 sec, primarily because of the weak flame. The time to extinguish increased at 2 cm/s but was then observed to decrease with increasing velocity. At the higher velocities, the flame did not wrap completely around the cylinder but was open in the wake region. The luminosity and thickness of the flame increased with velocity, as did the width of the wake region where the flame was absent. These results show the interdependence of the flow velocity and subsequent flame intensity and structure on the suppression behavior. Additional tests are being conducted using lower CO_2 concentrations to elucidate the role of velocity and flame development on the time to extinguish.

THEORETICAL INVESTIGATION

Due of the limited duration of low gravity on the aircraft and the difficulty in quantifying the effect of g-jitter on suppression near the extinction boundary, a modeling effort is supporting the experimental program. A modified version of the Fire Dynamics Simulator (FDS) computer code [2,3] was used to conduct two-dimensional simulations of ignition and flame spread along (perpendicular to the axis) a PMMA cylinder. Prior to beginning calculations, the finite volume radiation solver in the FDS code was modified so that gas-phase radiation was properly accounted for when the finite rate chemistry model is invoked. This radiation solver determines the radiation flux on the surface of the PMMA and the divergence of the radiation flux in the gas. The ideal gases were assumed to be gray and non-sooting. Absorption coefficients for H_2O and CO_2 were determined using RadCal [4].

Following the work of previous researchers, the chemical reaction of MMA vapor generated by PMMA pyrolysis was modeled using a one-step overall chemical reaction ($F + O_2 \rightarrow CO_2 + H_2O$) and second-order Arrehnius kinetics [5,6]. Kinetic constants were obtained from Seshandri and Williams [7]. The specific heats of the gaseous species were assumed constant and equal; molecular transport coefficients were temperature-dependent [4]. In-depth heat transfer at each surface point on PMMA solid was modeled using a one-dimensional conduction equation. The net heat flux at each surface point was comprised of convective flux, incident radiation flux, re-radiation from the hot surface, and heat loss due to PMMA vaporization. The degradation of the PMMA solid and resulting mass flux of fuel gas was modeled assuming constant density, negligible surface regression, and first order kinetics [4].

The two-dimensional simulations assumed a symmetry plane oriented parallel to the imposed flow through the axis of the cylinder. Gas phase ignition occurred by placing a "hot wire" in the symmetry plane just upwind of the solid. Experimentally measured values of the incoming flow velocities and composition, igniter duration, acceleration disturbance, and the initial temperature of the PMMA were used. Most simulations used a uniform grid with 1 mm grid cell dimensions in a 4.5 cm x 10 cm domain.

Model Results

A number of experimental cases have been simulated and, in general, the trends observed in the experiments were reproduced. Interestingly, the simulation has also mirrored the sensitivity of the environmental conditions on the effect of suppressant just as in the experiment. For example, a test condition having an oxidizer of standard air at 8.5 cm/s and suppressant mixture of 12.5% CO_2 at 9.3 cm/s was simulated. A plot of the net surface heat flux from simulations with and without incident radiation flux is shown on Fig. 3a while the associated acceleration history is shown in Fig. 3b. It can be seen that up to the onset of reduced gravity ($t < 325$ s), the net flux is larger when gas-phase radiation incident on the PMMA is included. Although the contribution of incident radiant flux does not appear to be significant, relative to the net flux, it raises the PMMA surface temperature enough (i.e., preheats the PMMA) to ensure pyrolysis throughout the duration of reduced gravity and suppressant. When the gray-gas model was applied, the flame sustained because of the higher surface temperatures. It extinguished when the surface temperature was lower.

SUMMARY AND FUTURE WORK

A significant amount of data has been obtained and is being analyzed to extract the details about the effect of CO_2 and He suppressants in low gravity. The simulations have proven useful in identifying the effect of various parameters that are difficult to isolate in the experiment. Meanwhile, the preparations are underway to conduct the experiments to achieve objectives (1) and (2), as previously identified.

Acknowledgements

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References

1. Goldmeer, J. S., T'ien, J. S. and Urban, D. L., 1999, "Combustion and extinction of PMMA cylinders during depressurization in low-gravity," Fire Safety Journal, Vol. 32, pp. 61-88.

2. McGrattan, K.B. and Baum, H.R. and Rehm, R.G. and Hamins, A. and Forney, G.P. and Floyd, J.E. and Hostikka, S. and Prasad, K., “Fire Dynamics Simulator, Technical Reference Guide,” National Institute of Standards and Technology (NIST), 2002, NISTIR 6782, 2002 Ed., http://fire.nist.gov/bfrlpubs/
3. Mell, W.E., McGrattan, K.B., Baum, H.R., “g-jitter Effects on Spherical Diffusion Flames,” to be submitted to Microgravity Science and Technology.
4. Grosshandler, W. 1993, “A narrow band model for radiation calculations in a combustion environment,” NIST Technical Note (TN 1402).
5. Altenkirch, R.A., Tang, L., Sacksteder, K., Bhattachrjee, S., and Delichatsios, M.A., 1998, “Inherently unsteady flame spread to extinction over thick fuels in microgravity,” Proceedings of the Combustion Institute, Vol. 27, pp. 2515-2524.
6. Yang, C.T. and T’ien, J.S., 1998, “Numerical simulation of combustion and extinction of a solid cylinder in low-Cspeed cross flow,” J. Heat Transfer, Vol. 120, pp. 1055-1063.
7. Seshandri, K. and Williams, F.A., 1978, “Structure and extinction of counterflow diffusion flames above condensed fuels: Comparison between Polymethyl Methacrylate and its liquid monomer, both burning in nitrogen-air mixtures,” J. of Polymer Science: Polymer Chemistry Ed., Vol. 16, pp. 1755-1778.

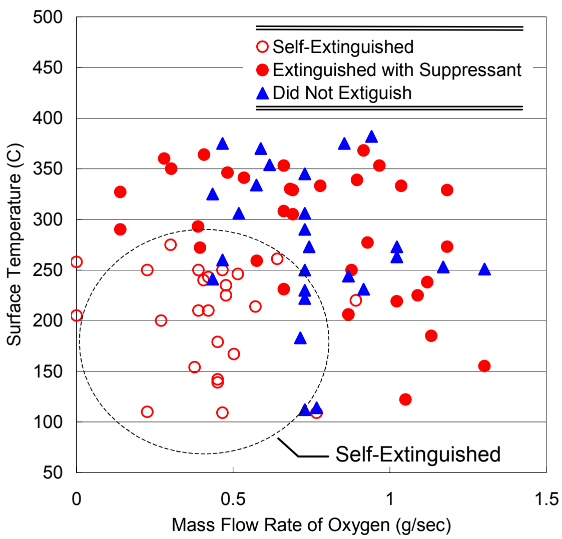


Figure 1. Low-gravity sustained flammability map

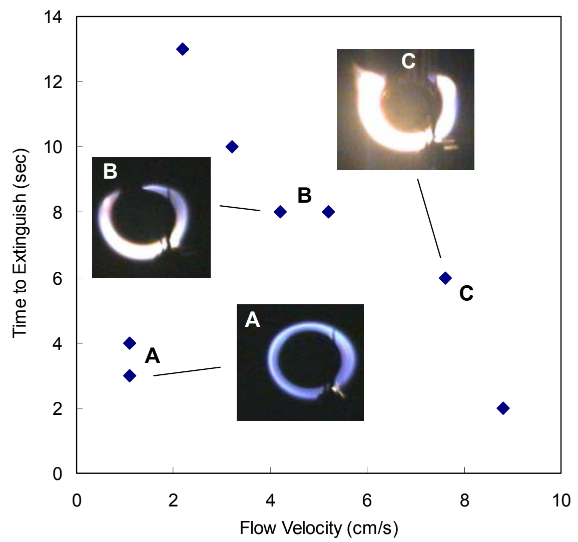
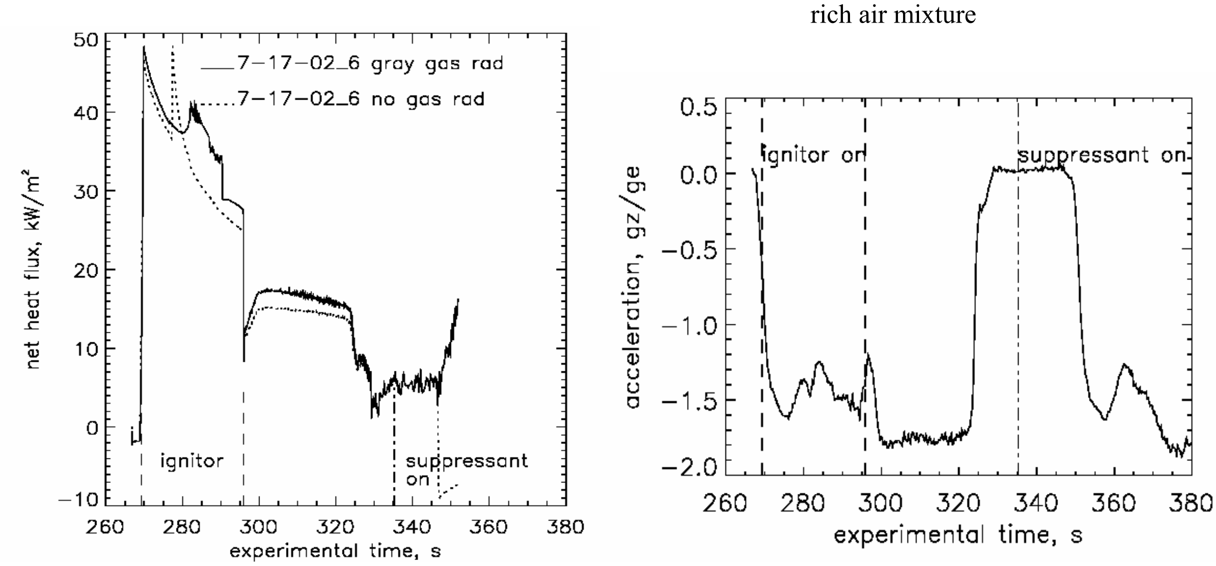


Figure 2. Time to extinguish for 25% CO_2/75% rich air mixture



a. Net heat flux

b. Acceleration

Figure 3. Effect of gas radiation model on suppression