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Extinguishment of a Diffusion Flame over a PMMA Cylinder by Depressurization in Low-gravity

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The behavior of flames in low-speed flows in low-gravity is relevant to spacecraft fire safety (Friedman and Sacksteder, 1988). Previous work (Yang, 1995; Ferkul and T'ien, 1994; Olson et al., 1988) has shown that flames in the presence of low-speed flows in low-gravity may be more flammable than in the same flow in normal gravity. Additionally, fire suppression plans for the International Space Station includes the use of venting (depressurization) as an emergency option for extinguishing fires. This procedure would induce flows in the affected compartment that could temporarily intensify the fire, as was observed in flammability tests of solids conducted on board Skylab (Kimzey, 1986). Despite a general understanding, current knowledge of the effects of reduced pressure and forced flow on a burning solid in low-gravity is inadequate for the design of a venting extinguishment system. In the current work, the extinction of a diffusion flame burning over horizontal PMMA (Polymethyl Methacrylate) cylinders during depressurization was examined experimentally and via numerical simulations.

The experiments were conducted on board the NASA Lewis Research Center's reduced-gravity aircraft that provide twenty second periods of low-gravity (±0.01 g's). The PMMA cylinders were 1.9 cm in diameter and 2.5 cm in length. The experiments examined the low-pressure extinction limit in air as a function of pressure and solid-phase centerline temperature at a constant velocity of ten cm/s. Both quenching and blow-off extinction were observed. Quenching occurred with a centerline temperature below 320 K, and blow-off with a centerline temperature above 320 K. A flammability map was created using the experimental blow-off data (Figure 1). As the solid-phase centerline temperature increases, the extinction pressure decreases, and with a centerline temperature of 525 K, the flame is sustained to a pressure of 0.1 atm before extinguishing.

The numerical simulation used in this work iteratively couples a two-dimensional quasi-steady gas-phase model (Yang, 1995) with a transient solid-phase model that includes conductive heat transfer within the solid and surface regression due to vaporization (Goldmeer, 1996). The gas-phase model includes Navier-Stokes, continuity, energy and species equations with a one-step overall chemical reaction and Arrhenius kinetics. The model uses an energy balance at the gas/solid phase interface that equates the energy conducted in the gas-phase to the gas/solid phase interface to the sum of the energy used for vaporization, surface radiation, and sensible heat within the solid. The model does not include gas-phase radiation. The ratio of the solid-phase and gas-phase conduction terms in the energy balance is defined as Φ, which can be written as:

$$\Phi = \lambda_S(\partial T/\partial r)_S / \lambda_G(\partial T/\partial r)_G = 1 - \left[(\dot{m}L + Q_{RAD})/\lambda_G(\partial T/\partial r)_G\right]$$

in which L is the heat of vaporization, $\dot{m}$ is the vaporization rate and Q_{RAD} is surface radiation. This ratio varies in time and along the circumference of the cylinder. High values of Φ (near 0.9) occur at ignition, and Φ decreases as the gas-phase heats the solid-phase.

Initial simulations examine conditions similar to the low-gravity experiments and predict low-pressure extinction limits consistent with the experimental limits (Figure 2). Additional simulations examine velocities ranging from one to twenty cm/s, increases in the solid-phase temperatures (decreases in Φ) prior to depressurization, and lower depressurization rates (longer depressurization times). The effect of velocity on the extinction limit is not monotonic (Figures 3 and 4). At values of constant Φ, flames are sustained to lower pressures at ten cm/s than at one or twenty cm/s. Increasing the solid-phase temperature (decreasing Φ) by either a longer period of burning prior to depressurization, or an increase in the depressurization time decreases the extinction pressure. The model predicts blow-off extinction at twenty cm/s and quenching at one cm/s (Figure 3). At velocities of five and ten cm/s, the simulations predict quenching will occur in cases with a cooler solid-phase (Φ at the forward stagnation point greater than 0.25), and blow-off when the solid-phase is heated (Φ at the forward stagnation point less than 0.25). Transition of the extinction mode from quenching to blow-off, as the solid-phase temperature increases (decrease in Φ) at a constant velocity, was also observed experimentally. Additionally, the simulations predict that the path taken to the extinction boundary is not critical; extinction will occur at the boundary whatever the path taken (assuming a quasi-steady gas-phase process). This information could be used to refine the International Space Station's venting specifications, which state that the affected module would be depressurized

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from 1.0 atm to 0.3 atm within a period of ten minutes. This research suggests that an effective venting procedure would be to rapidly depressurize the affected module to a pressure of 0.1 atm, which would minimize additional heating of the solid-phase, minimize reductions in the extinction pressure, and most likely extinguish the fire.

Acknowledgments

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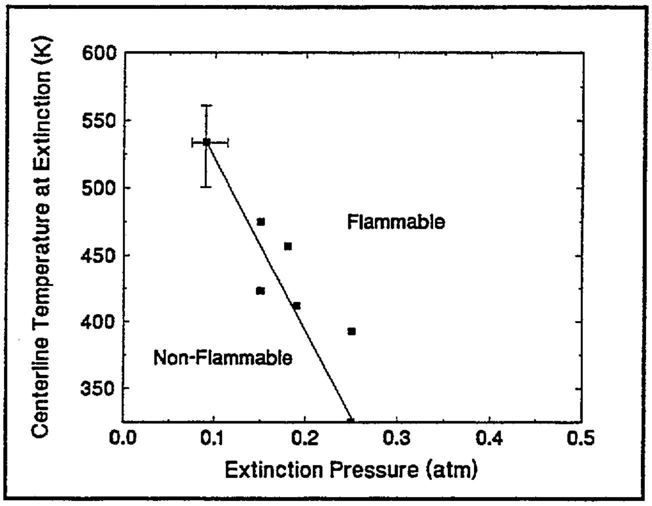

Figure 1
Experimental extinction boundary at constant velocity (10 cm/s)

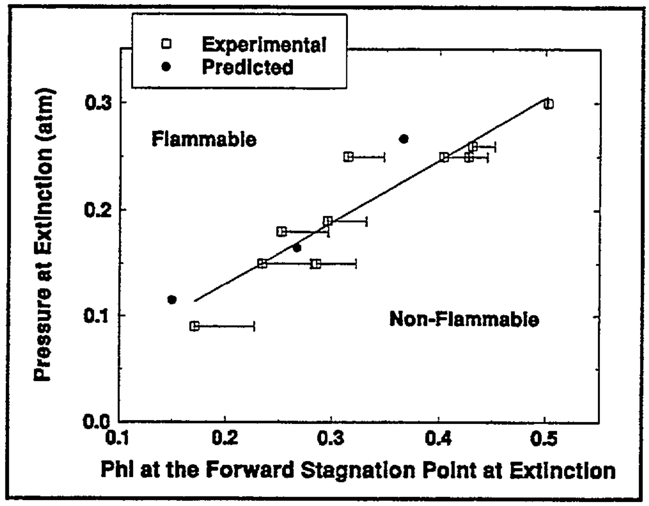

Figure 2
Comparison of Experimental and Predicted Extinction Boundaries at 10 cm/s

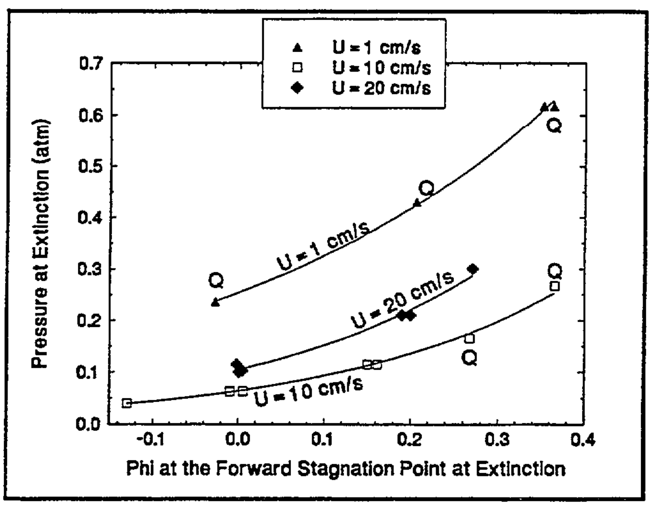

Figure 3
Predicted extinction boundaries at constant velocity (Quenching occurs at points labeled Q)

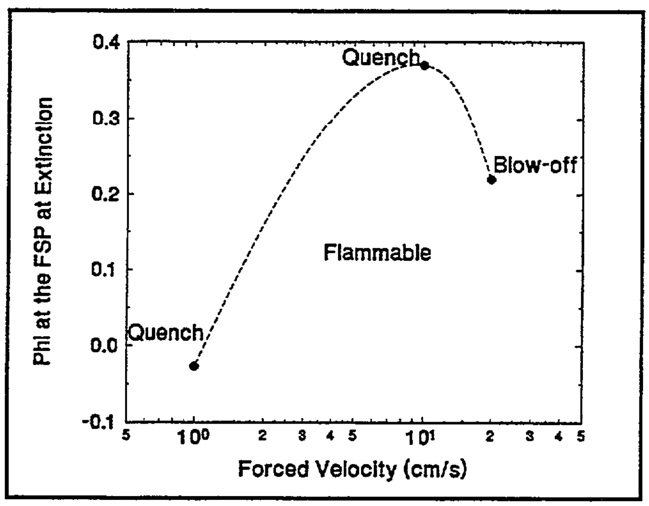

Figure 4
Predicted extinction boundary at constant pressure (P = 0.25 atm)