EXPERIMENTAL AND NUMERICAL EVALUATION OF GASEOUS AGENTS FOR SUPPRESSING CUP-BURNER FLAMES IN LOW-GRAVITY

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INTRODUCTION

Longer duration missions to the moon, to Mars, and on the International Space Station (ISS) increase the likelihood of accidental fires. NASA's fire safety program for human-crewed space flight is based largely on removing ignition sources and controlling the flammability of the material on-board. There is ongoing research to improve the flammability characterization of materials in low gravity; however, very little research has been conducted on fire suppression in the low-gravity environment. Although the existing suppression systems aboard the Space Shuttle (halon 1301, CF_3Br) and the ISS (CO_2 or water-based form) may continue to be used, alternative effective agents or techniques are desirable for long-duration missions.

The goal of the present investigation is to: (1) understand the physical and chemical processes of fire suppression in various gravity and O_2 levels simulating spacecraft, Mars, and moon missions; (2) provide rigorous testing of analytical models, which include detailed combustion-suppression chemistry and radiation sub-models, so that the model can be used to interpret (and predict) the suppression behavior in low gravity; and (3) provide basic research results useful for advances in space fire safety technology, including new fire-extinguishing agents and approaches.

APPROACH

In order to achieve these objectives we have embarked upon a comprehensive program involving experiments and numerical modeling of the extinction of diffusion flames with added suppressants. The experiments involve both a 1*g* testing (for baseline data and for model validation) and low-*g* testing program (in drop towers and the KC-135 aircraft). The numerical modeling uses a time-dependent 2-D direct numerical simulation with full chemistry (UNICORN) for simulating either the low-*g* or 1*g* flames, and interpreting the effect of gravity on the extinction process with and without a variety of agents (of types which act both physically and chemically). The configuration selected is a cup burner (a co-flow diffusion flame with a 2.8 cm diameter fuel source, either a liquid pool or a low-velocity gas jet, inside an 8.5 cm diameter chimney with oxidizer flowing at ~10 cm/s. The cup burner is a common metric for suppression agent performance in fire safety engineering and a large database is available for comparison to extinction in 1*g*. A low-*g* cup-burner test rig, equipped with a particle image velocimeter and a Mach-Zehnder interferometer, is nearly complete. For supporting development and validation of the kinetics, experiments and modeling are also performed for premixed Bunsen-type flames and counterflow diffusion flames.

RESULTS AND DISCUSSION

In a 1*g* laboratory, the combustion and extinction characteristics of the cup burner, including the extinction conditions, flame shape, time-dependent flame tip and base locations, and flicker frequency, have been measured for various fuels, including methanol, methane, heptane, and trioxane. For the liquid or solid fuels, the variation of the fuel mass loss rate with addition of inhibitor have also been measured. The fundamental kinetic work necessary for other parts of the project have been determined [1,2].

Carbon dioxide used on the ISS is relatively inefficient and requires high concentrations (15-20 vol.%) when injected into air. Therefore, the deployment and dispersion of the agent to achieve the critical concentration everywhere inside a cluttered compartment such as instrumentation racks require careful system design considerations. One approach for reducing the critical agent concentration and, thus the total amount of agent is to combine inert agents with effective chemical compounds. In this case, the overall reaction rate is lowered in part through the lower temperature caused by the inert and in part through radical recombination by the added catalytic agent. Figure 1 shows the variation of the fuel consumption rate in a methanol cup-burner flame with addition of CO_2, CF_3Br, or their blend. The result demonstrates that by blending 2.2% of CF_3Br, the critical CO_2 concentration required for suppression dropped to 1/3 of that of CO_2 alone. Figure 2 presents the effect of some very active chemical agents in cup-burner flames [3,4]. Although only a few hundred ppm of super-effective agents rapidly reduced the critical CO_2 concentration at suppression, material condensation prohibited further blending [4]. By using data from our experiments as well as those in the literature, the performance benefit (volume based, compared to CO_2), as shown in Figure 3, has been compiled to compare the effectiveness of various agents, ranging from inert up to highly chemically active, in a variety of flames, including cup-burner (Cup), counterflow diffusion (CF, 10 s^{-1}, 20 s^{-1}, 30 s^{-1} strain rate), and premixed flames (Pre, 10%, 30%, 45% laminar flame speed reduction). Some super-effective

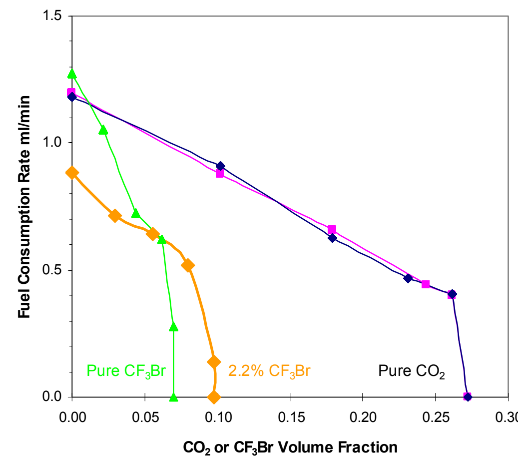

Figure 1 Methanol consumption rate (and extinction condition) in a cup burner with CO_2, CF_3Br, or their blend, added to the air stream.

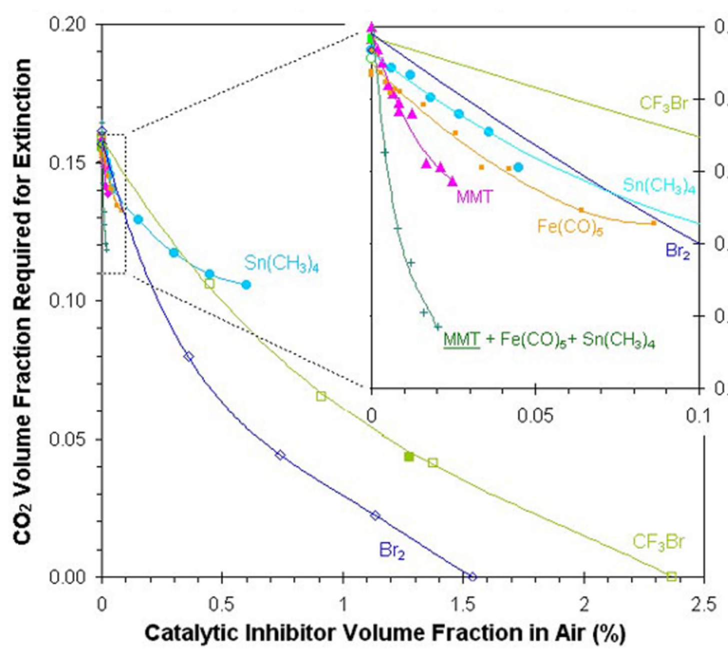

Figure 2 CO_2 volume fraction at extinction in a cup burner with added catalytic inhibitors.

agents are orders of magnitude more efficient.

Numerical simulations have been performed to investigate the flame structure of methane-air flames with added CO_2 [5-8], CF_3H, and $Fe(CO)_5$ [4]. Figure 4 shows the temperature contours for flames in 1*g* with a CO_2 volume fraction of 0.05 and 0.145 (the suppression limit). The computation has revealed that the suppression of cup-burner flames occurs via a blowoff process (in which the flame base drifts downstream) rather than the global extinction phenomenon typical of counterflow diffusion flames.

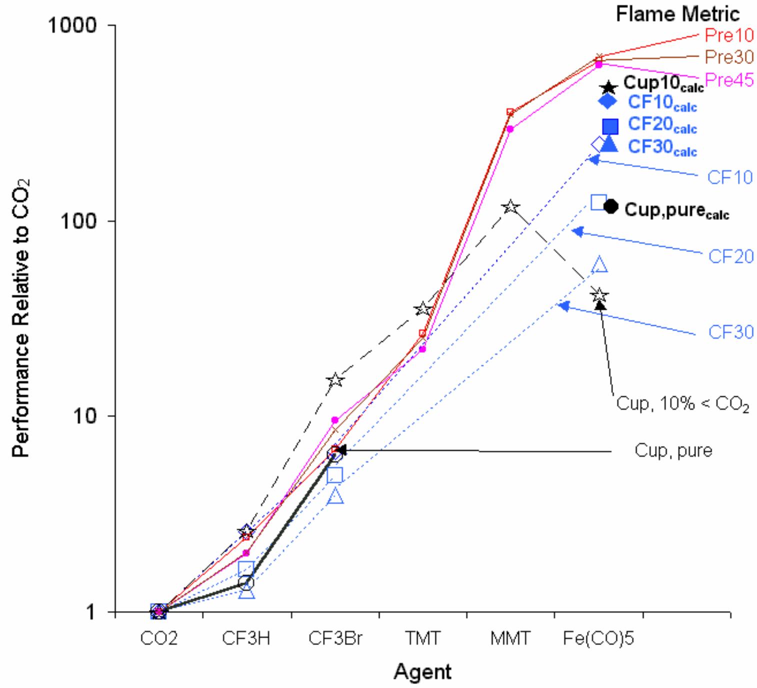

Figure 3 Performance comparison for a several agents assessed with a variety of flame metrics.

Figure 5 shows the structure of the flames in 0*g* for X_{CO_2} = 0 and X_{CO_2} = 0191 (the suppression limit) [6,8]. The calculations for the zero-gravity flames show:

- the flame flicker (~ 10 Hz at 1*g*) is eliminated for gravity levels below 0.5 *g*.
- with lower gravity, flame diameter increases, the tip opens, and the edge of the flame base becomes vertical.
- the flame tip opening is calculated to be due to radiative losses, which become more important at lower gravity as the lack of convective mixing reduces the local reaction rate.
- The extinction process (a gradual edge blow-off with increasing CO_2 volume fraction in the air) is similar in 0*g* to that in 1*g*.
- the extinction condition for CO_2 addition is about 32 % higher in 0*g* than in 1*g*.
- at the extinction CO_2 volume fraction, elimination of the radiation losses creates a stable flame.

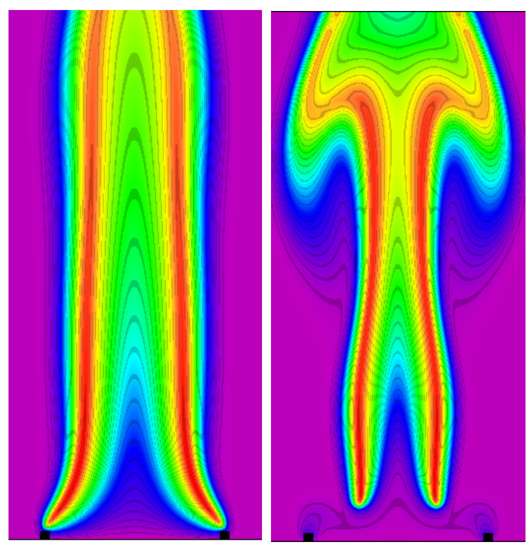

Figure 4 Calculated temperature contours in a 1*g* cup-burner methane flame with X_{CO_2} = 0.05 (left) and 0.145 (right) in the air stream.

The calculations were used to examine the importance of radiation transport in the 0g flames. Figure 6 shows the variation of the heat-release rate and radiative heat loss across the flame at 20 mm above the burner. As the gravity force was reduced, the radiative heat loss maintained a same level, while the heat-release rate decreased significantly due to diffusion-limited reactant fluxes into the flame zone. As a result, the net heat release decreased, thus leading to extinction in the downstream locations. Figure 7 shows the variation of the temperature and axial velocity with height up the flame, calculated with and without the influence of radiation. The figure clearly indicates the decreased temperature in the 0*g* flames, which is not so dramatic in the 1*g* flames.

FUTURE PLANS

Experiments for flame shape and extinction will be conducted in low-*g* for comparison with the modeling results and 1*g* experimental results. The model will be used for more detailed examination of both the present 1*g* results and the 0*g* results (to be obtained). Further 1*g* results will be obtained for a wider variety of inhibitors.

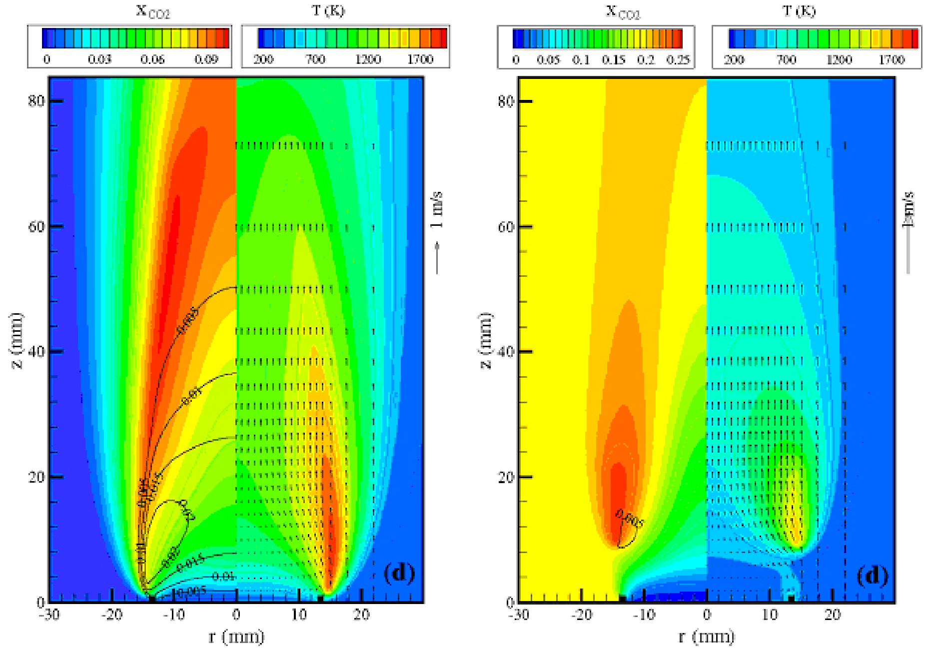

Figure 5 Calculated velocity, temperature (right), CO2, and H2 mole fractions (left) in 0*g* flames. (a) X_{CO_2} = 0, (b) X_{CO_2} = 0.191.

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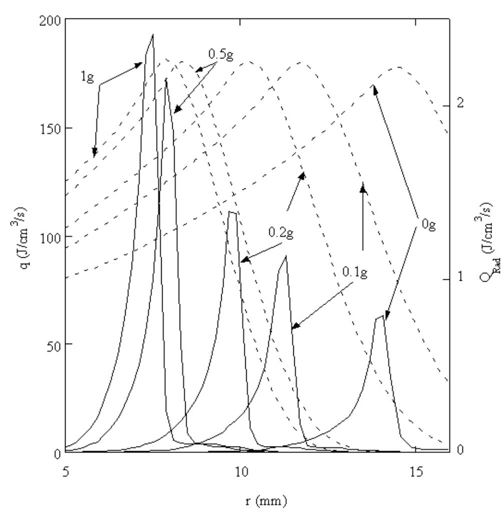

Figure 6 Heat-release rate (solid) and radiative heat loss (dashed) at 20 mm above the burner.

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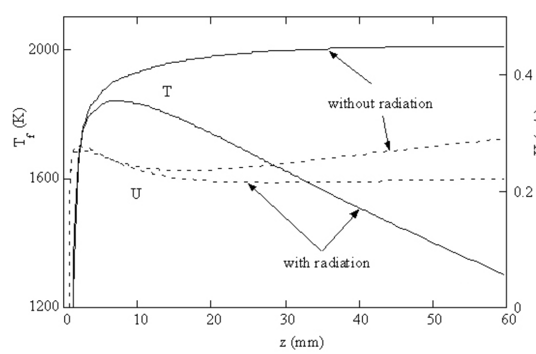

Figure 7 Variation of temperature and axial velocity with height along 0*g* flame.