FIRE SUPPRESSION IN LOW GRAVITY USING A CUP BURNER

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Longer duration missions to the moon, to Mars, and on the International Space Station increase the likelihood of accidental fires. The goal of the present investigation is to: (1) understand the physical and chemical processes of fire suppression in various gravity and O2 levels simulating spacecraft, Mars, and moon missions; (2) provide rigorous testing of numerical models, which include detailed combustion-suppression chemistry and radiation sub-models; and (3) provide basic research results useful for advances in space fire safety technology, including new fire-extinguishing agents and approaches.

The structure and extinguishment of enclosed, laminar, methane-air co-flow diffusion flames formed on a cup burner have been studied experimentally and numerically using various fire-extinguishing agents (CO2, N2, He, Ar, CF3H, and Fe(CO)5). The experiments involve both 1g laboratory testing and low-g testing (in drop towers and the KC-135 aircraft). The computation uses a direct numerical simulation with detailed chemistry and radiative heat-loss models. An agent was introduced into a low-speed coflowing oxidizing stream until extinguishment occurred under a fixed minimal fuel velocity, and thus, the extinguishing agent concentrations were determined. The extinguishment of cup-burner flames, which resemble real fires, occurred via a blowoff process (in which the flame base drifted downstream) rather than the global extinction phenomenon typical of counterflow diffusion flames. The computation revealed that the peak reactivity spot (the reaction kernel) formed in the flame base was responsible for attachment and blowoff of the trailing diffusion flame. Furthermore, the buoyancy-induced flame flickering in 1g and thermal and transport properties of the agents affected the flame extinguishment limits.

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Fire Suppression in Low Gravity Using a Cup Burner

Background
- Longer duration missions to Mars, the moon, or aboard the International Space Station increases the likelihood of fire events.
- NASA's fire safety program of manned space flights is based largely upon controlling the materials flammability and eliminating ignition sources.
- This project investigates fire suppression in the reduced-gravity environment.

Objectives
- Understand physical/chemical processes of fire suppression in various gravity and O₂ levels simulating spacecraft, Mars, and moon missions.
- Provide rigorous testing of analytical models, which include comprehensive combustion and suppression chemistry.
- Provide basic research results useful for advances in space fire safety technology, including new fire-extinguishing agents and approaches.

Approach
- **Experiment:**
  - Using a cup burner, which resembles real fires, measure the critical extinction mole fraction of fire suppression agents for selected fuels.
  - Determine physical/chemical effects of agents on flame structure/suppression processes.
- **Computation:**
  - Simulate unsteady fire suppression phenomena in various flames using a 2D code with detailed chemical reaction and radiation models.

Diagnostics:
- Particle image velocimeter (PIV)
- Mach-Zehnder interferometer (MZI)

Parameters:
- **Fuel:**
  - Gas: CH₄, C₂H₆, C₃H₈
  - Liquid: n-C₇H₁₆, CH₃OH
  - Solid: trioxane (3(CH₂O)), PMMA
- **Oxidizer:**
  - O₂/Ar mixture
  - Oxygen mole fraction: 0.21 – 0.3
- **Velocity:**
  - 3 – 20 cm/s
- **Agent:**
  - CO₂, N₂, Ar, CF₃H (HFC-23), C₃F₇H (HFC-227ea), CF₃Br
  - Water Mist, Inert/Water Mist, Microencapsulated Water
- **Gravity:**
  - µg, lunar (1/6 g), Martian (1/3 g), 1g
- **Pressure:**
  - 0.7 – 1 atm

Numerical Simulations (1g)
- Suppression of cup-burner flames occurs via blowoff rather than global extinction typical of counterflow diffusion flames.
- Flame flicker (~11 Hz) ceases at < 0.5 g.
- Heat-release rate decreases with reducing g, while radiative heat loss remained const.

Numerical Simulations (low-g)
- 5.0% CO₂ in Air
- 14.5% CO₂ in Air
- 10.05% CF₃H in Air
- 10.1% CF₃H in Air

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Agent Effectiveness
- The effectiveness of a fire-extinguishing agent depends upon the flame characteristics.

Phosphorus is:
- $3 \times$ better than CF$_3$Br in counterflow* flames
- $17 \times$ better than in premixed** flames
- but $\frac{1}{2}$ as good as in cup burner

** Korobeinichev et al. HOTWC 2000 p. 164.

- Performance advantage of chemically active agents over CO$_2$: variation with flame type.

Flame Flicker in 1g
- Flame flicker affects suppression processes and the flickering frequency varies with CO$_2$ content and co-flow velocity

Conclusions
- Suppression of cup-burner flames occurs via blowoff rather than global extinction typical of counterflow diffusion flames.
- Performance of agents is highly dependent upon the flame characteristics.
- Chemical agents reduce concentration (and amount) of inert agent required for suppression.
- Flame flicker (~11 Hz) affects suppression processes and ceases at $< 0.5$ g.
- Flame tip opens in low g due to radiative heat loss.
- Critical CO$_2$ concentration in 0g is ~32% higher than in 1g.

Key findings from numerical work
- Form vorticies in 1g
- Extinguish due to flame base de-stabilization
- Have tips that open in 0-g (due to radiation losses)
- Flicker at ~11 Hz in 1-g, but as g decreased, flicker decreased (below 0.5 g, don’t flicker).
- Require 32% more CO$_2$ to extinguish in 0g than in 1g.