COMPARISON OF CARBON DIOXIDE AND HELIUM AS FIRE EXTINGUISHING AGENTS FOR SPACECRAFT

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The effects of radiation heat transfer in microgravity compared to convection heat transfer in earth gravity for opposed-flow (downward) over thermally-thick fuel using low density foam fuel were investigated. Microgravity experiments on flame spread over thermally-thick fuels were conducted using foam fuels to obtain low density and thermal conductivity, and thus large flame spread rate compared to dense fuels such as PMMA. And thereby valid microgravity results were obtained even in 2.2 second drop-tower experiments not to mention for the longer duration tests in Zero Gravity Facility. Contrast to the conventional understanding, it was found that steady flame spread can occur over thick fuels in quiescent microgravity environments, especially when radiatively-active diluent gases such as CO_2 were employed. This is proposed to result from radiative heat transfer from the flame to the fuel surface, which could lead to steady spread even when the amount of the heat transfer via conduction from the flame to the fuel bed is negligible. Radiative effects are more significant at microgravity conditions because the flame is thicker and thus the volume of radiating combustion products is larger as well.

These results suggested that helium may be a better inert or extinguishment agent on both a mass and a mole bases at microgravity even though CO_2 is much better on a mole bases at earth gravity, and these are relevant to studies of fire safety in manned spacecraft, particularly the International Space Station that uses CO_2 fire extinguishers. CO_2 may not be as effective as an extinguishing agent at µg as it is at earth gravity in some conditions because of the differences in spread mechanisms between the two cases. In particular, the difference between conduction-dominated heat transport to the fuel bed at earth gravity and radiation-dominated heat transport at µg indicates that radiatively-inert diluent such as helium could be preferable in µg applications. Helium may be a superior fire suppression agent at µg on several bases. First, helium is more effective than CO_2 on a mole basis (thus pressure times storage volume basis) at µg, meaning that the size and weight of storage bottles would be smaller for the same fire-fighting capability. Second; helium is much more effective on a mass basis (by about 11 times) at µg. Third; helium has no physiological activity, unlike CO_2 that affects human respiration. Fourth, as compared to N_2 or CO_2, is not very soluble in water and thus has fewer tendencies to cause bloodstream bubble formation following rapid spacecraft cabin depressurization.

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Motivation

- Flame spread over solid fuels; a useful means of understanding more complex two-phase non-premixed flames

- Radiation is substantial, especially at reduced gravity – important in fire modeling in manned spacecraft

- Benefits of this research

  - Spacecraft fire safety - ISS will use CO_2 fire extinguishers, but flames spread *faster* at reduced gravity with CO_2 diluent due to radiative heating of fuel!

  - He has lots of advantages over CO_2 in ISS, at reduced gravity

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Flame spread model for opposed flow with radiation

U + S_f

Ambient
temperature : T_∞

δ

S_f

y

Flame front

x

$\delta = \alpha_g/(U+S_f)$

δ

$q\delta W \Rightarrow q = \lambda_g(T_f - T_v)/\delta_g + \Lambda\delta_g$

Vaporization temperature : T_v

τ_s τ_p

Conductive heat
transfer through
the fuel bed

$\lambda_s\delta W(T_v - T_\infty)/\tau_p$

Rate of enthalpy
increase of fuel bed

S_f

$= \rho_s S_f W \tau_s C_{p,s}(T_v - T_\infty)$

Ambient
temperature : T_∞
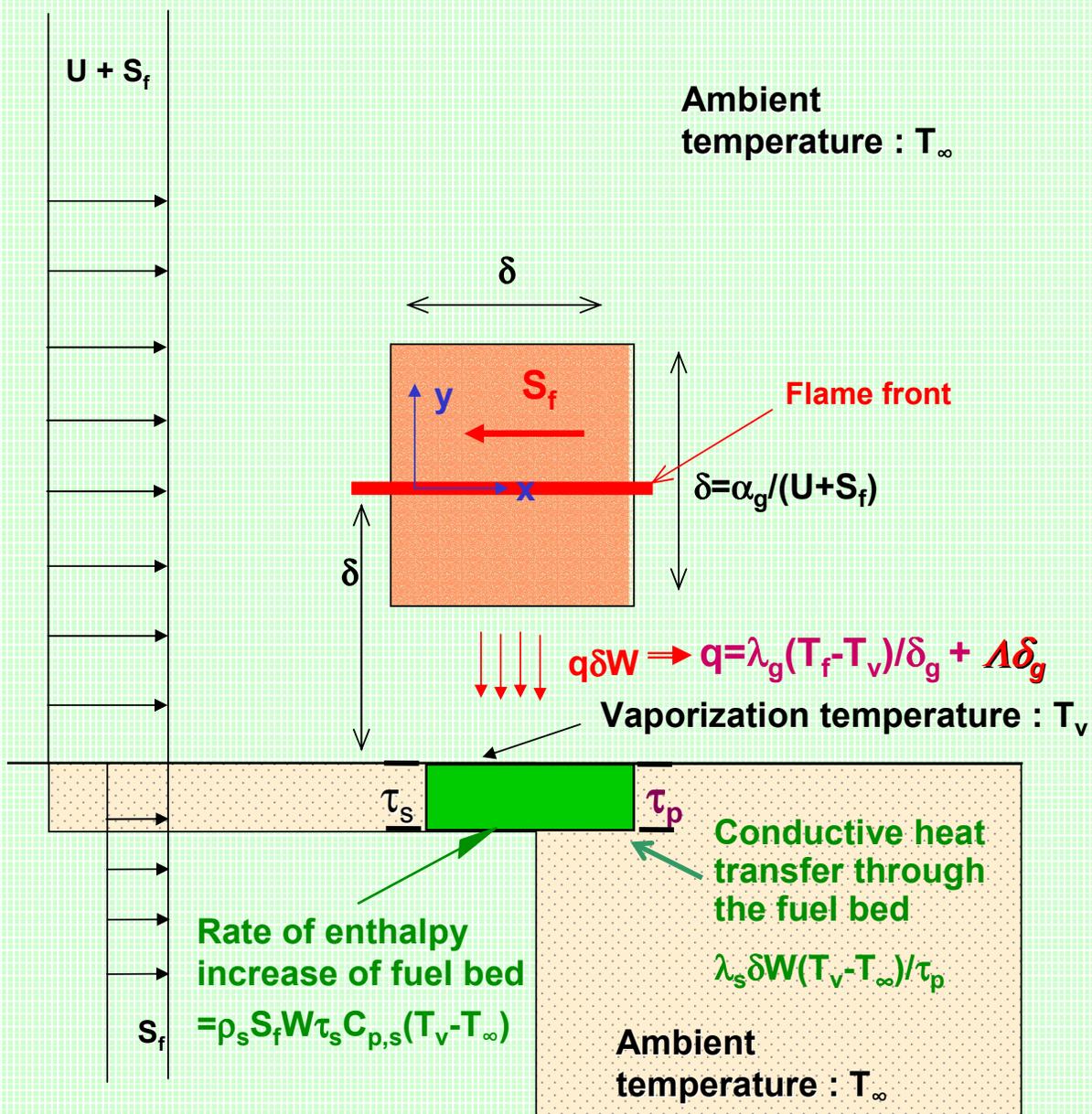
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Theoretical background

- Equating heat generation from fuel with heat conduction through the gas q *(= heat transferred to fuel bed per unit area)*

- de Ris (1969): Radiative transfer from external source to fuel bed leads to steady spread over thick fuel bed even if U = 0

- Estimation of radiative flux from the flame to fuel bed leads to combined effects of conduction and radiation because hot gases such as CO_2 and SF_6 radiate by themselves:

- $q = \lambda_g (T_f - T_v)/\delta_g$, $+ \Lambda\delta_g$, Λ = radiative emission per unit volume

- $\delta_g = \alpha_g/S_f$ assume U=0

- Substitute into the equation

$$S_f \sim \frac{q^2 \delta_g}{\rho_s C_{p,s} \lambda_s (T_v - T_\infty)^2}$$

$$S_f = \left[\frac{\Lambda \alpha_g^2}{\sqrt{\alpha_g \rho_s C_{P,s} \lambda_s}(T_v - T_\infty) - \lambda_g(T_f - T_v)} \right]^{1/2}$$

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Experimental setup

- μg experiments; 2.2 second drop tower facility & Zero gravity facility were used
- Fuel
  - Problem with conventional thick fuels
    - Low S_f (e.g. PMMA ~ 0.006cm/sec in air,1atm):
    - Time scale ~ α/S_f^2 too large for drop towers
    - Length scale ~ α/S_f possibly too large even in space
  - Need very low $\rho_s\lambda_s C_{p,s}$ - use foams
  - Also high pressure - ρ_s higher, Q/V higher
- Polyphenolic foam; used in floral arranging, density : 0.029 g/cm^3
- Polyurethane foam; used in packing, density : 0.03 g/cm^3

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Diluent gas effect on S_f

polyphenolic foam
4 atm total pressure
0.027g/cm^3

Flame spread rate (cm/sec)

Oxygen mole concentration (%)

- ug CO$_2$
- ug N$_2$
- 1g CO$_2$
- 1g N$_2$

polyphenolic foam
4 atm total pressure
0.027g/cm^3

Flame spread rate (cm/sec)

Oxygen mole concentration (%)

- ug-CO$_2$
- ug-He
- 1g-CO$_2$
- 1g-He
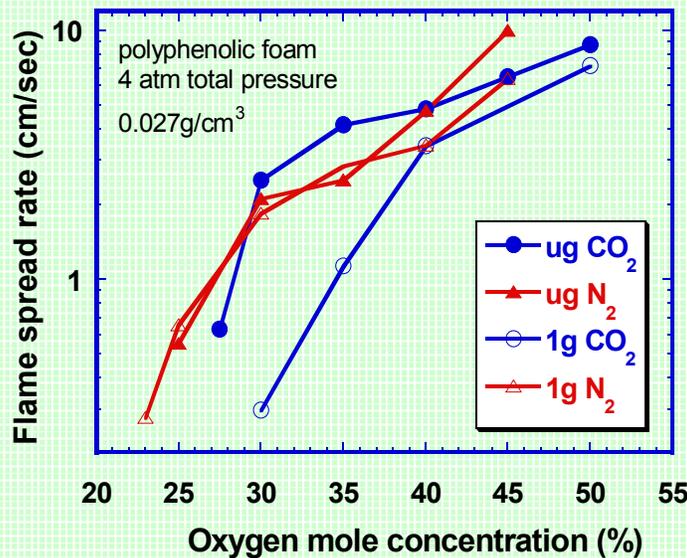
- For CO$_2$, S_f at μg is higher than at 1g, especially with CO$_2$ diluent & low O$_2$ concentrations, whereas for N$_2$ diluent, similar S_f

- At μg, S_f can be higher in CO$_2$ than N$_2$ at the same % O$_2$
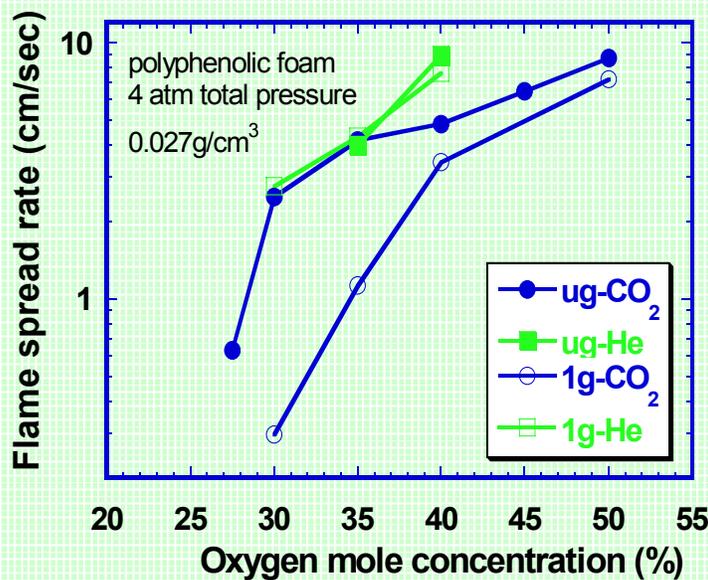
- He and CO$_2$ diluent shows similar S_f for fixed O$_2$ mole concentration even

  though mole based $C_p(CO_2) > C_p(He)$, $\lambda_g(CO_2) < \lambda_g(He)$ - T_f thus S_f is higher in He than CO$_2$ diluent;

- MOF (min. O$_2$ fraction) at 1g similar, but He has higher MOF at μg

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Helium and CO$_2$ comparison, μg
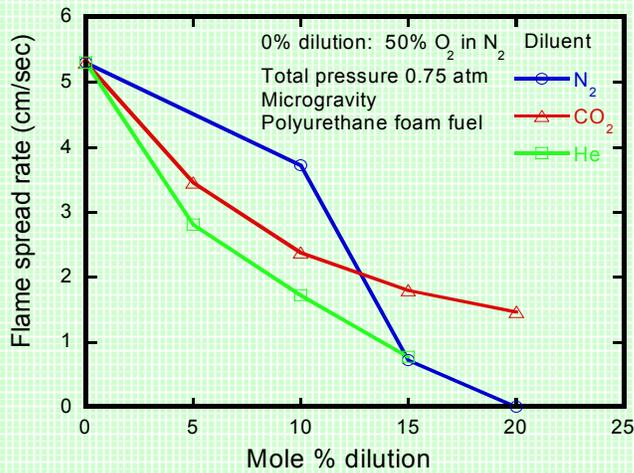
He shows slower S$_f$ than CO$_2$ diluted case at 0.75 atm, 50%O$_2$-N$_2$ of 0%dilution which is close to the space environment, μg
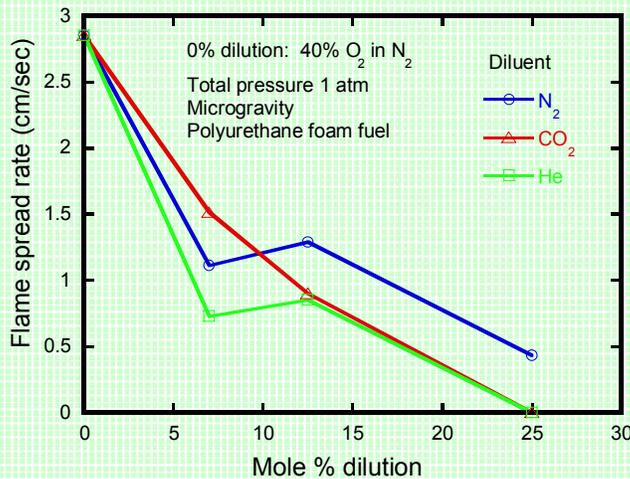
The trend between He and CO$_2$ as an extinguisher or inert agent shows reverse as pressure increases; CO$_2$ shows higher S$_f$ than He at 0.75 atm but lower S$_f$ at 2 atm
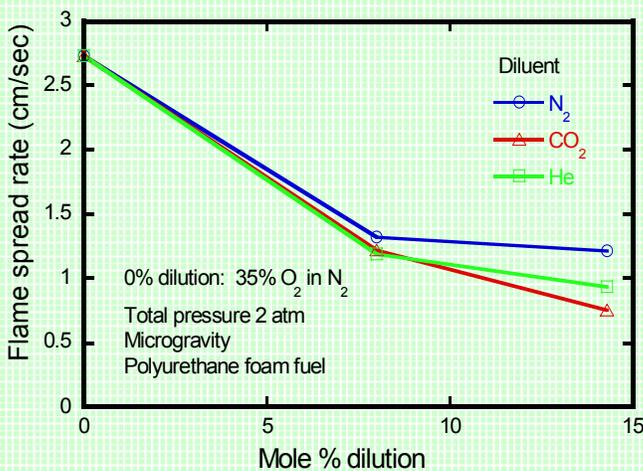
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Helium and CO$_2$ comparison, 1g
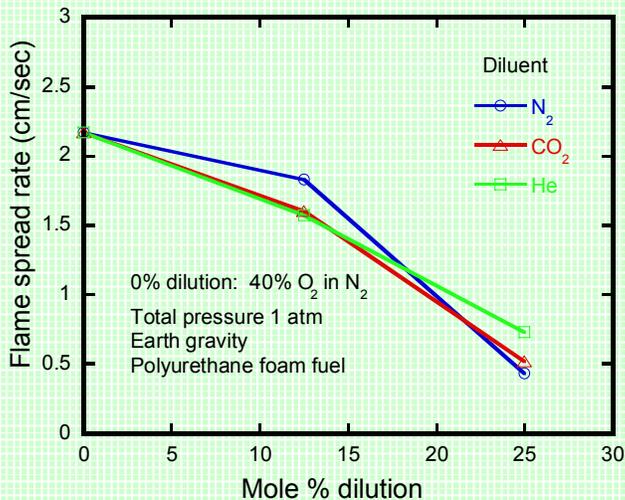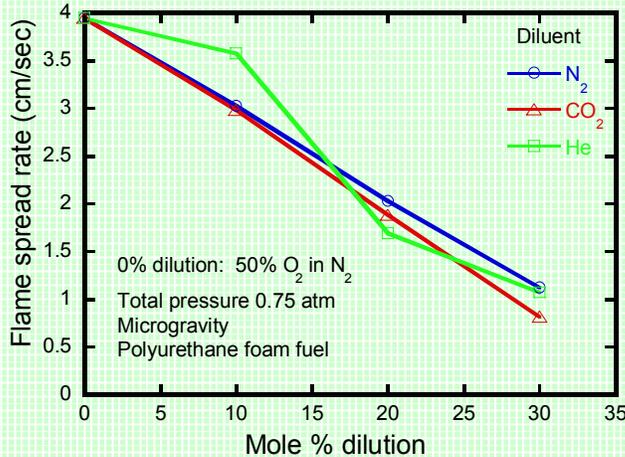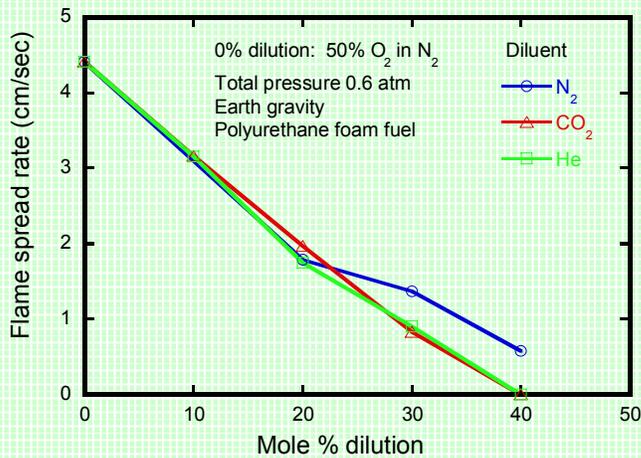
- **At 1g, CO$_2$ shows lowest S$_f$ or similar**

- **He has more effects at μg**

- **1) Lewis No. effect; high Le $\rightarrow$ lower T$_f$ $\rightarrow$ lower S$_f$ (Zhang, *et.al.*, 1992)**

- **2) He; high $\lambda_g \rightarrow \alpha_g$ $\rightarrow$ thicker flame $\rightarrow$ more heat loss**

- **3) He; radiatively non-participating**

  - **No re-absorption**

  - **No re-radiation**

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Conclusion

- Drop-tower experiments show
    - S_f at μg in O_2-CO_2 sometimes *faster* than O_2-N_2 or O_2-He with same %O_2
    - At high %O_2 & low pressure, the addition of CO_2 diluent results in faster S_f than He at μg, but not at 1g.
- Results due to
    - Re-absorption and re-radiation of emitted radiation in O_2-CO_2 vs. no re-absorption and no re-radiation in O_2-N_2
    - Thicker flames (more volume $\Rightarrow$ more radiation) at μg
- Radiative preheating of the fuel bed by the gas is significant and re-absorption effects can prevent massive heat losses (thus extinction) in radiatively-active atmospheres at μg
- *He may be better extinguishing agent at μg than CO_2*
    - Same efficiency per mole (advantage for storage bottle mass & volume)
    - Much better per unit mass
    - **No physiological impact** (CO_2 affects human respiration)
    - Helium is **not soluble in water thus less tendency to cause bloodstream bubble formation** following cabin depressurization
    - Relevant to fire safety in manned spacecraft, specially ISS which uses CO_2 fire extinguisher

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