TRANSPORT AND CHEMICAL EFFECTS ON CONCURRENT AND
OPPOSED-FLOW FLAME SPREAD AT MICROGRAVITY

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INTRODUCTION

Flame spread over flat solid fuel beds is a useful means of understanding more complex
two-phase non-premixed spreading flames, such as those that may occur due to accidents in
inhabited buildings and orbiting spacecraft. The role of buoyant convection on flame spread is
substantial, especially for thermally-thick fuels. With suitable assumptions, deRis [1] showed
that the spread rate ($S_f$) over thick fuels is given by:

$$S_f = \frac{U \lambda_g \rho_g C_{p,g}}{\lambda_s \rho_s C_{p,s}} \left( \frac{T_f - T_v}{T_v - T_\infty} \right)^2$$  \hspace{1cm} (1),

where $U$ is the buoyant or forced convection velocity, $\lambda$, $\rho$, $C_p$ and $T$ are the conductivity,
density, specific heat and temperature, and the subscripts s, g, v and refer to the solid fuel, gas-
phase, vaporization condition and ambient condition, respectively. Equation (1) indicates that
that for thick fuels $S_f \approx U$, and thus suggests that $S_f$ is indeterminate at $g$ (since $S_f = U$) unless
a forced flow is applied. (In contrast, for thermally thin fuels, the ideal $S_f$ is independent of $U$ [1].)
The conventional view [2], as supported by computations and space experiments, is that for
quiescent $g$ conditions, $S_f$ must be unsteady and decreasing until extinction occurs due to
radiative losses. However, this view does not consider that radiative transfer to the fuel surface
can enhance flame spread. While Eq. (1) presumes no radiation, deRis [1] also showed that when
radiation from a prescribed radiative flux per unit area ($q$) dominates heat transfer to the fuel bed,

$$S_f = \frac{q^2 \delta}{\rho_s C_{p,s} \lambda_s (T_v - T_\infty)^2}$$  \hspace{1cm} (2),

indicating that conductive transfer from the flame to fuel bed is not required for steady spread.

In this work we suggest that radiative transfer from the flame itself, not just from an
external source, can lead to steady flame spread at $g$ over thick fuel beds. As a first estimate, we
assume the flame to be an isothermal volume of optically-thin radiating gas at temperature $T_f$
with dimension $\delta$ in both the directions parallel to and perpendicular to the fuel bed, where $\delta$ is
presumed to be the convective-diffusive zone thickness $\delta = \alpha_g / \alpha_f = \lambda_g / \rho_g C_{p,g}$ is
the thermal diffusivity. The heat flux per unit area to the fuel surface due to radiation is
estimated as $\Lambda \delta$, where $\Lambda = 4\sigma_\text{ap}(T_f^4 - T_v^4)$ is the radiative heat emission rate per unit volume, $\sigma$ is
the Stefan-Boltzman constant and $\alpha_p$ is the Planck mean absorption coefficient. The combined
effects of gas-phase radiation and thermal conduction is then given by $q = \Lambda \delta + \lambda_g (T_f - T_v) / \delta$.
Substituting this into Eq. (2) leads to (assuming unit fuel bed emissivity):

$$S_f = \left[ \frac{\Lambda \alpha_g^2}{\sqrt{\alpha_g \rho_g C_{p,g} \lambda_s (T_v - T_\infty) - \lambda_g (T_f - T_v)}} \right]^{1/2}$$  \hspace{1cm} (3)

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Equation (3) predicts that without gas-phase radiation, no steady spread is possible \((S_f = 0)\) and with gas-phase radiation, steady spread with \(S_f = \Lambda^{1/2}\) is possible. Hence, the goal of this study is to determine if flame-generated radiation can in fact lead to steady spread over thick fuels at \(g\).

**EXPERIMENTAL APPARATUS**

Experiments were conducted in a 20 liter combustion chamber as shown in Fig. 1. \(O_2-N_2\) and \(O_2-CO_2\) atmosphere were employed since they have very different radiative properties - \(CO_2\) radiates strongly whereas \(N_2\) does not radiate, and thus for \(O_2-N_2\) atmospheres only the combustion products, not the ambient atmosphere, radiate. Equations 1 and 3 indicate that \(S_f\) in a given atmosphere \(S_e\) can be much higher for fuels with low \(\rho C_P \lambda\). This led us to use polyphenolic foam (used in floral arranging) having low \(\rho\) and \(\lambda\) to study flame spread in short-duration drop tower tests. The samples were ignited by an electrically-heated Kanthal wire imbedded in a nitrocellulose sheet attached to the fuel surface. The flames were imaged via CCD cameras whose signals are connected via fiber-optic cables to ground-based S-VHS video recorders. A shearing interferometer was used for the side view since the flames were sometimes too dim for direct video. Thermopile-type radiometers were used to determine flame radiation; a "front" radiometer viewed a hole in the flame side of the fuel surface, and a "back" radiometer viewed the non-burning side of the hole. By viewing a hole, interference from surface radiation was eliminated.

**RESULTS**

Figure 2 shows examples of the progress of flame spread (flame position vs. time) at \(1g\) and \(g\). The slope of these plots gives the spread rate; a straight line indicates a constant spread rate and thus steady spread. From these tests, it can be seen that that in \(O_2-CO_2\) atmospheres, steady flame spread is possible over thick fuels at quiescent \(g\) conditions when gas-phase radiation effects are significant, as suggested by our model (Eq. 3).

**Figure 1.** Schematic of drop frame and camera apparatus. The fuel bed is mounted inside the function of time in a 40%\(\%\) \(O_2\) - 60% \(CO_2\) mixture at 4 atm at earth gravity and \(g\).

**Figure 2.** Position of spreading flames as a function of time in a 40%\(\%\) \(O_2\) - 60% \(CO_2\) mixture at 4 atm at earth gravity and \(g\).

Figure 3 shows example images of spreading flames at \(1g\) and \(g\). From these images the effect of buoyancy can be seen at \(1g\). Figure 4 shows example side-view images obtained using the interferometer. As expected, the flame is thicker at \(g\) than \(1g\), indicating that \(g\) flames have more volume and thus more radiation to fuel bed.
CONCLUSIONS

Our results indicate that, in contrast conventional understanding, steady spread can occur over thick fuels in quiescent microgravity environments, especially when a radiatively active diluent gas such as CO₂ is employed. We propose that this is due to radiative transfer from the
flame to the fuel surface. Additionally, the transition from thermally thick to thermally thin behavior with decreasing bed thickness is demonstrated. It was found that foam fuels enabled steady spread to be obtained over thermally thick fuels at $g$ even in short-duration drop tower experiments. These results are being used to define a space flight experiment called Radiative Enhancement Effects on Flame Spread (REEFS) planned for the International Space Station in the Combustion Integrated Rack facility.

![Figure 5. Effect of $O_2$ concentration on $S_f$ over thick solid fuel beds at $g$ and earth gravity.](image)

![Figure 6. Effect of pressure on $S_f$ over thick solid fuel beds at $g$ and earth gravity.](image)

![Figure 7. Effect of fuel bed thickness on $S_f$ over thick solid fuel beds at $g$ and earth gravity.](image)

![Figure 8. Radiative flux characteristics of a flame spreading over a thick solid fuel bed at $g$ in a 40% $O_2$ - 60% $CO_2$ mixture at 4 atm.](image)

**REFERENCES**


