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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:

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

where U is the buoyant or forced convection velocity, λ, ρ, 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 $S_f \sim U$, 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,

$$S_f = \frac{q^2 \delta}{\rho_s C_{P,s} \lambda_s (T_v - T_\infty)^2} \qquad (2),$$

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 δ in both the directions parallel to and perpendicular to the fuel bed, where δ is presumed to be the convective-diffusive zone thickness $\delta \sim \alpha_g/U = \alpha_g/S_f$ and $\alpha_g = \lambda_g/\rho_g C_{p,g}$ is the thermal diffusivity. The heat flux per unit area to the fuel surface due to radiation is estimated as $\Lambda\delta_g$, where $\Lambda = 4\sigma a_P(T_f^4 - T_v^4)$ is the radiant heat emission rate per unit volume, σ is the Stefan-Boltzman constant and a_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):

$$S_f = \left[\frac{\Lambda \alpha_g^2}{\sqrt{\alpha_g \rho_s C_{P,s} \lambda_s}\,(T_v - T_\infty) - \lambda_g (T_f - T_v)}\right]^{1/2} \qquad (3)$$

Equation (3) predicts that without gas-phase radiation, no steady spread is possible ($S_f = 0$) and with gas-phase radiation, steady spread with $S_f \sim \Lambda^{1/2}$ 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_f can be much higher for fuels with low $\rho_s C_{P,s} \lambda_s$. This led us to use polyphenolic foam (used in floral arranging) having low ρ and λ 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).

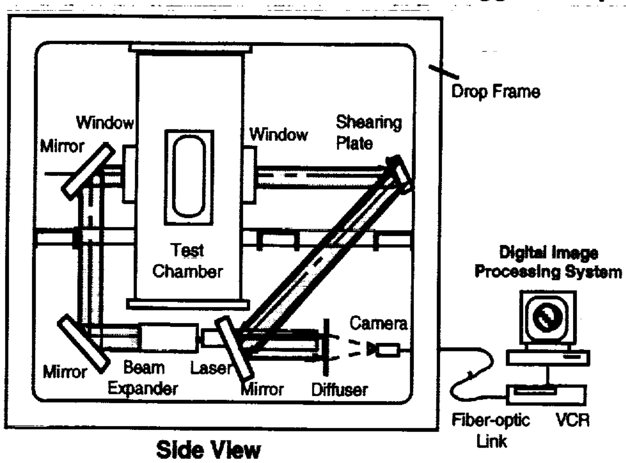

Figure 1. Schematic of drop frame and camera apparatus. The fuel bed is mounted inside the chamber parallel to the plane of the page.

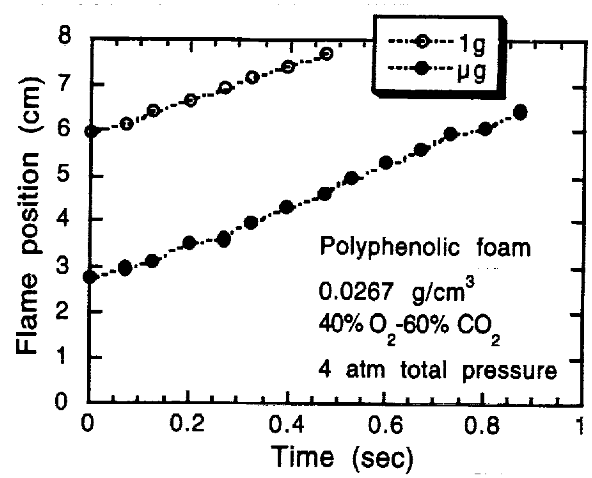

Figure 2. Position of spreading flames as a function of time in a 40%% O_2 - 60% CO_2 mixture at 4 atm at earth gravity and g.

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.

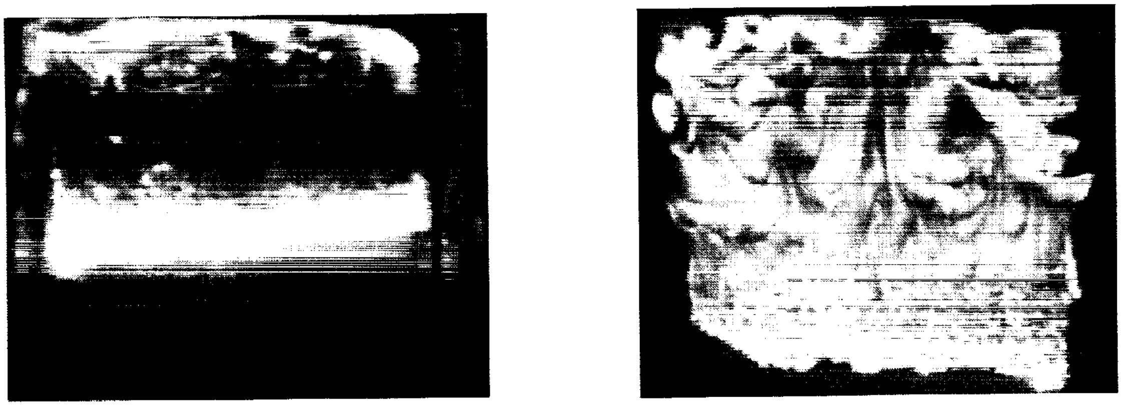

Figure 3. Images of flame spread over a thick solid fuel bed in a 40% O_2 - 60% CO_2 mixture at 4 atm. Flame spreads from top to bottom. Width of samples is 10 cm. Left: microgravity (bright band in the lower part of image is the flame front.) Right: earth gravity.

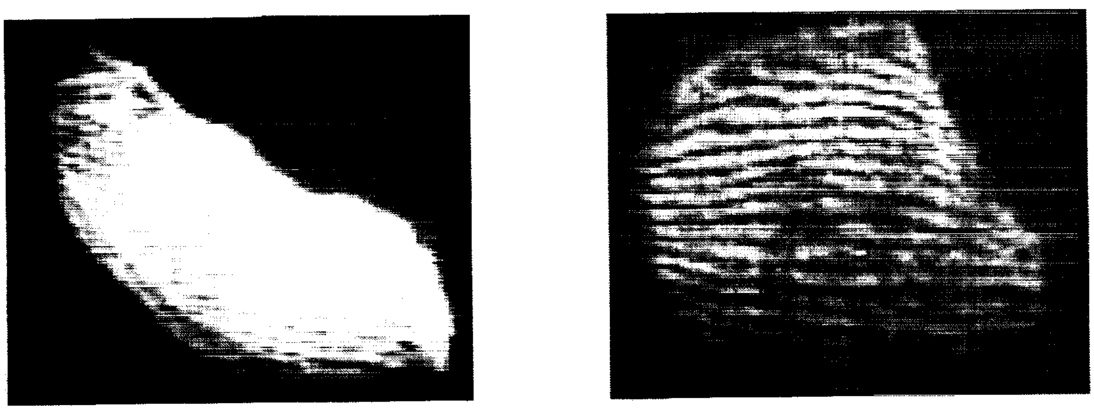

Figure 4. Side-view interferometer images of flame, same conditions as Fig. 3. Width of images is 5 cm. The upper black region is the combustion products. Left: microgravity. Right: earth gravity.

Figure 5 shows that, as was also seen in prior tests using thermally-thin fuels [3], for thick fuels the quiescent g S_f can be higher than its 1g (downward) counterpart for CO_2-diluted atmospheres but not N_2-diluted atmospheres. Figure 6 shows that a transition from S_f increasing rapidly with pressure (P) to S_f nearly independent of P at P ~ 5 atm. While the cause of this transition is uncertain, it may be due to a transition from radiation dominated by optically-thin behavior to optically-thick behavior. Figure 7 shows that S_f becomes less dependent on fuel bed thickness as thickness increases, indicating the approach to the thermally-thick limit. The transition thickness is about 2 mm for the case shown. Figure 8 the radiative emission from a O_2 - CO_2 atmosphere test at g, which are the only cases tested where the back radiometer showed significant flux. This is because only in this case is there substantial emission, absorption and re-emission, which is the only means to obtain substantial radiative flux to the back radiometer. O_2 - N_2 atmospheres (not shown) do not exhibit this behavior at all [4], and even for O_2 - CO_2 atmospheres this was seen only at g where δ is larger and thus the total radiative flux is greater.

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 CO_2 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.

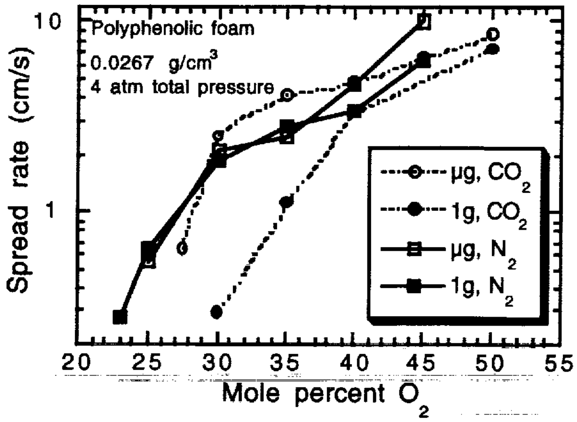

Figure 5. Effect of O_2 concentration on S_f over thick solid fuel beds at g and earth gravity.

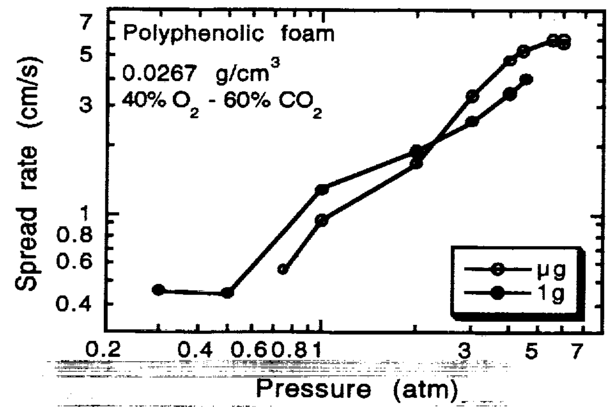

Figure 6. Effect of pressure on S_f over thick solid fuel beds at g and earth gravity.

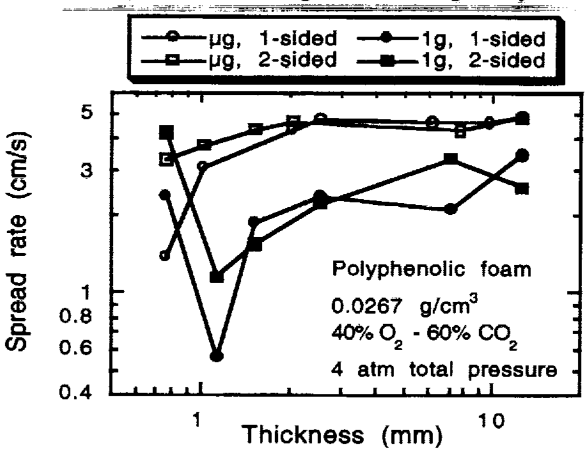

Figure 7. Effect of fuel bed thickness on S_f over thick solid fuel beds at g and earth gravity.

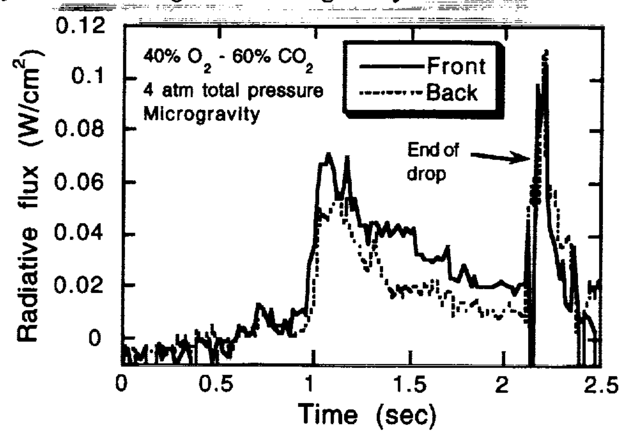

Figure 8. Radiative flux characteristics of a flame spreading over a thick solid fuel bed at g in a 40%% O_2 - 60% CO_2 mixture at 4 atm.

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