AIAA 2001-0467

RADIATION-DRIVEN FLAME SPREAD OVER THERMALLY-THICK FUELS IN QUIESCENT MICROGRAVITY ENVIRONMENTS

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Abstract

Microgravity experiments on flame spread over thermally thick fuels were conducted using foam fuels to obtain low density and thermal conductivity, and thus large spread rate (S_f) compared to dense fuels such as PMMA. This scheme enabled meaningful results to be obtained even in 2.2 second drop tower experiments. It was found 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. This is proposed to be 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.

Introduction

It is well known[1,2,3,4,5] that convection influences flame spread over solid fuel beds in numerous ways. Flame spread is typically classified as opposed-flow, where the direction of flame propagation is opposite that of the convective flow past the flame front, or concurrent-flow, where convection and spread are in the same direction. Downward flame spread at earth gravity (1g) is characterized by opposed flow since the upward buoyant flow is opposite the direction of flame spread, whereas upward flame spread is characterized as concurrent flow. At microgravity (µg) conditions, where buoyant convection is negligible, flame spread will necessarily be of the opposed-flow variety unless a forced flow is imposed, because the flame spreads toward the fresh atmosphere with a self-induced convection velocity equal to the spread rate (S_f). At 1g self induced convection can justifiably be ignored since buoyancy-induced flows are of the order of tens of cm/sec, which is much higher than S_f, however, at µg self-induced convection obviously cannot be neglected.

As described by Williams[2], the basic approach to modeling S_f is by equating the heat flux per unit area from the gas phase to the fuel surface (q) to the rate of increase in the enthalpy of the solid fuel, leading to

$$S_f = \frac{q\delta_g}{\rho_s C_{p,s}(T_v - T_\infty)\tau_s} \qquad (1),$$

where ρ, C_p, T and τ are the density, constant pressure specific heat, temperature, fuel bed thickness and the subscripts s, g, v and ° refer to the solid fuel, gas-phase, vaporization condition and ambient condition, respectively. δ_g is the length of the zone over which heat is transferred from the gas to the fuel surface; for opposed-flow flame spread δ_g is proportional to the convection-diffusion zone thickness[1] α_g/U where $\alpha_g \equiv \lambda_g/\rho_g C_{p,g}$ is the thermal diffusivity, λ the thermal conductivity and U the opposed flow velocity.

For the simplest case of flame spread over a thermally-thin fuel bed (in which there is no temperature gradient and thus no conduction within the fuel bed), heat transfer is purely by gas-phase conduction to the fuel bed and thus q ¯ $\lambda_g(T_f - T_v)/\delta_g$, where T_f is the flame temperature given by [1,6]

$$T_f = \frac{\left(Q_f - L_v\right)/C_{p,g} + (T_v - T_\times)}{1+S} + T_\times\ ; \qquad S \equiv \frac{\nu_{ox}M_{ox}}{Y_{ox,\infty}\nu_{fu}M_{fu}} \qquad (2),$$

where Y is the mass fraction, M the molecular weight, ν the stoichiometric coefficient, S the stoichiometric oxidant-to-fuel mass ratio, and the subscripts fu and ox refer to solid fuel vapors, and oxidant, respectively. This leads to

$$S_f = A\frac{\lambda_g}{\rho_s C_{p,s}\tau_s}\frac{T_f - T_v}{T_v - T_\infty} \qquad (3),$$

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à Professor, Department of Aerospace and Mechanical Engineering, Senior member AIAA where A is a constant. deRis[1] found an approximate solution for which A = ˆ2 and Delichatsios [7] found the "exact" solution A = „/4. Note that steady spread is possible even at µg because this ideal S_f is independent of U. This is because although the length of the preheat zone (thus the fuel surface area exposed to the flame) is proportional to δ_g and thus increases with decreasing U, the temperature gradient between the flame and the fuel surface is also proportional to δ_g thus the heat flux per unit area (q) decreases by the same amount, leading to no net change in the total heat flux to the fuel bed.

For thermally thin fuels, τ_s is the fuel bed half-thickness, whereas for thermally thick (effectively semi-infinite) fuels, where heat conduction through the solid fuel is important, τ_s is the depth of thermal penetration into the solid fuel (τ_p), which can be estimated by equating q to the heat flux within the solid fuel = $\lambda_{sy}[(T_v\text{-}T_\circ)/\tau_p]$, where the subscript y refers to the direction normal to the fuel surface:

$$\tau_p = \frac{\lambda_s(T_v - T_\infty)}{q} \Rightarrow S_f = \frac{q^2\delta_g}{\rho_s C_{P,s}\lambda_s\left(T_v - T_\infty\right)^2} \quad (4).$$

This result is identical to that determined by Tarifa and Torralbo[8] and deRis[1] for a prescribed externally-imposed radiative source, so the present approach is considered valid. If heat transfer to the fuel bed occurs via conduction and thus q ¯ $\lambda_g(T_f - T_v)/\delta_g$ as for thin fuels, the "exact" solution for S_f over thick fuels[1] is obtained:

$$\tau_s = \frac{\lambda_{sy}\delta_g(T_v - T_\infty)}{\lambda_g(T_f - T_v)} \Rightarrow S_f = U\frac{\lambda_g\rho_g C_{p,g}}{\lambda_s\rho_s C_{p,s}}\left(\frac{T_f - T}{T_v - T_\infty}\right)^2 \quad (5).$$

The transition from thermally thin to thermally-thick behavior occurs when τ_s ¯ τ_p. Note then that a given material may behave as thermally thin or thermally-thick depending on δ_g and thus U.

Equation 5 shows that for thick fuels, $S_f \sim U$ and thus suggests that S_f is indeterminate at µg unless a forced flow is applied. The conventional view[9], is that for quiescent µg conditions S_f must be unsteady and decreasing until extinction occurs due to radiative losses. An analysis[9] based on unsteady heat conduction to the fuel bed predicts that the thermal penetration depth $\tau_s \sim (\alpha_s t)^{1/2}$ which results in $S_f \sim t^{-1/2}$, where t is the time lapse from ignition. Indeed, this scaling indicates that in a sense all fuel beds are thermally thin at µg, because S_f will always decrease over time and thus τ_p will increase until it reaches τ_s. Computations and space experiments by Altenkirch and collaborators[9,10] support these assertions.

In this work we show that this inability to obtain steady spread over thick solid fuel beds in a quiescent µg environment no longer applies when heat is transported from the flame to the fuel bed by radiation in addition to or instead of conduction. While Altenkirch and collaborators *al.*[9,10] did consider radiative loss from the flame, they did not consider that the radiative transfer from the flame to the fuel bed could increase the instantaneous S_f or lead to steady spread. We derive a semi-quantitative prediction for S_f that is used to motivate µg experiments, which in turn demonstrate the validity of the proposed mechanisms of flame spread with flame radiation. Additionally, the transition from thermally thick to thermally-thin behavior is demonstrated as the fuel bed thickness is decreased, in a manner consistent with the proposed mechanisms.

As evidence of the importance of radiative transfer from the flame front to the fuel bed, we consult our prior thin-fuel experiments[11] on the effects of diluent type (which affects the radiative properties of the atmosphere) on S_f. Experiments in radiatively inert N_2, He or Ar diluents showed the conventional behavior where S_f is lower and the minimum flammable O_2 concentration is higher at µg because U is lower, thus δ and radiative loss are higher. In contrast, for radiatively active CO_2 and SF_6 diluents, the opposite behavior is observed. This was attributed to (1) the increased radiative emission from CO_2 or SF_6, which increases the net heat flux to the fuel bed and (2) reabsorption of this radiation, which reduces the radiative heat loss. (Diluent type also affects the Lewis numbers of the atmosphere but these effects were shown to be of lesser importance.)

Approximate analysis of flame spread over thick fuels with radiative transfer

In this section we present an approximate model of how flame-generated radiation transmitted to the fuel surface could affect spread rates for thick fuel beds. When radiative heat transfer to the fuel bed is significant, S_f as given by Eqs. 1 and 4 are still valid, but Eqs. 2 and 5 must be modified. For flame-generated radiation, q_r is coupled to the spread process itself, and depends strongly on the spectral properties of the gas. As a first estimate, in this analysis we consider optically thin radiation, where no reabsorption occurs and the spectral properties can be lumped into a single parameter.

For our estimate of S_f over thick fuel beds, the flame front is assumed to be an isothermal volume of optically-thin radiating gas at temperature T_f with dimension δ_g in both the directions parallel to and perpendicular to the fuel bed. We make this choice because for optically-thin radiation, there is no length scale for radiation and thus the thermal thickness of the flame front conditions is still determined by the convective-diffusive zone thickness δ_g ¯ $\alpha_g/U = \alpha_g/S_f$. The heat flux per unit area to the fuel surface due to radiation can then be 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 $q = \Lambda\delta_g + \lambda_g(T_f{}^\circ - {}^\circ T_v)/\delta_g$. Combining this with $\delta_g = \alpha_g/S_f$ and Eqs. 4 lead to (assuming unit fuel bed emissivity):

$$S_f = \left[\frac{\Lambda\alpha_g^2}{\sqrt{\alpha_g \rho_s C_{P,s} \lambda_s \left(T_v - T_\infty\right) - \lambda_g\left(T_f - T_v\right)}} \right]^{1/2} \tag{6}$$

This result yields a number of interesting predictions, the most important of which are that without gas-phase radiation, no steady spread is possible ($S_f = 0$) and with gas-phase radiation, $S_f \sim \Lambda^{1/2}$. Thus, increasing gas-phase radiation should increase S_f. Of course, the heat loss rate also increases, but the ratio of heat loss to heat generation will remain roughly constant. Equation 6 also shows that pressure effects are important and could increase or decrease S_f since $\Lambda \sim P$ and $\alpha_g \sim P^{-1}$.

Equation 6 is only valid when the denominator is positive, *i.e.*, when the thick fuel flame spread parameter $\Gamma \equiv (\rho_g C_{P,g}\lambda_g/\rho_s C_{P,s}\lambda_s)((T_f - T_v)/(T_v - T_\circ))^2 < 1$, which is virtually always the case - though for very low density fuels, its value is close to unity. Equation 6 shows that in a given atmosphere S_f can be much higher for fuels with low $\rho_s C_{P,s}\lambda_s$. This leads us to propose the use of polymeric foams with low ρ_s and λ_s to study thick-fuel flame spread in short-duration drop tower tests as precursors to space experiments using more quantifiable fuels with larger $\rho_s\lambda_s$, e.g. PMMA.

A factor not considered in this discussion is that radiative transfer to the fuel bed will also increase T_f, as analyzed by deRis[1], though using representative values of the thermodynamic and transport parameters the predicted effect is not strong enough to affect the above conclusions. It does, however, make the impact of radiative transport slightly stronger than that shown here.

Experimental apparatus

In order to test for the proposed possibility of steady flame spread over thermally-thick fuels in quiescent μg environments, a set of μg experiments was conducted in the NASA Glenn 2.2 second drop tower facility, and comparison tests were performed in the same apparatus with the same test conditions at earth gravity.

The experiments were performed in our flame spread apparatus (Fig. 1) that has been described previously,[11] so only a brief description is given here, emphasizing the changes made for this study. A 20 liter chamber is filled with the desired atmosphere by a computer-controlled partial pressure gas mixing system. This chamber is rated for working pressures from vacuum up to 10 atm. The fuel samples are typically 10 cm wide and 11.5 cm long and are held between aluminum quenching plates on both sides in order to inhibit edge-burning effects. Before each test, a fan inside the vessel is operated to ensure mixing of the components of the atmosphere. After allowing time for settling of convection currents, the samples are ignited by a 30 gage Kanthal wire to which 28 VDC is applied. This wire is imbedded in a nitrocellulose membrane that is glued onto the fuel surface. For most cases, the samples can be ignited at 1g then dropped at an appropriate time so that the μg portion of the test would be within the field of view of the cameras, however, some CO_2-diluted atmospheres at low O_2 concentrations support flame spread only at μg, hence in these cases the samples must be ignited at μg. The igniter is controlled and the radiometer data (described below) are collected by a microcontroller-based data acquisition and control system.

The flame-spread process is imaged using two CCD cameras whose signals are connected via fiber-optic cables to ground-based S-VHS video recorders. The video records provide information on the spread rate and flame shape. One camera is positioned with its viewing axis in the plane of the fuel sample so that it images the flame front. Another CCD camera is located with its viewing axis orthogonal to the plane of the fuel sample so that it could image laser shearing interferograms of the flames from a side view. In the laser shearing interferometer,[12] the laser beam was expanded and passed through the test section, then reflected off the front and rear surfaces of a shearing plate (an optical-quality glass flat with parallel faces). By adjusting the beam expander so that the beam is slightly convergent or divergent, an interferogram is obtained. The fringe displacement in the shearing interferogram is proportional to the density gradient rather than density difference between the test image and a reference image as in conventional interferometry. The interferogram was projected on a ground glass screen and recorded via the CCD camera.

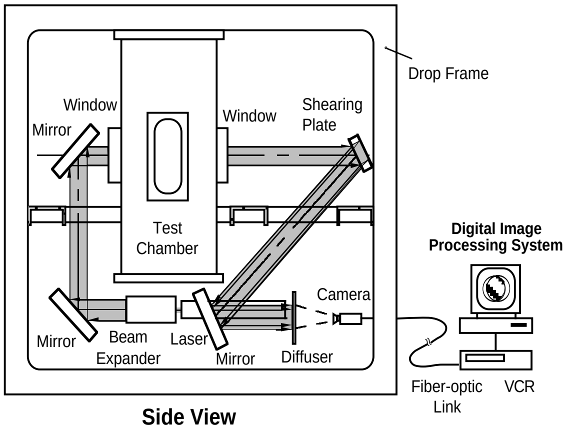

Figure 1. Schematic of drop frame and camera apparatus. The fuel bed is mounted inside the chamber parallel to the plane of the page.

Narrow-angle wall-mounted thermopile-type radiometers are used to determine the net emission reaching the radiometer along its line-of-sight, which is an important prediction of the radiation model. Two types of radiometers were used: (1) a front-side radiometer viewing a hole in the fuel bed, which measures only the gas-phase contribution to the outward radiative flux, and (2) a back-side radiometer that viewing the same hole in the fuel bed, which measures the inward gas-phase radiative heat flux.

The standard fuel for fundamental thick-fuel combustion experiments has been poly-methylmethacrylate (PMMA) which has a thick-fuel spread rate parameter $\lambda_s\rho_sC_{P,s}(T_v-T_\infty)^2$ of about 3.3 x 10^{10} J^2/m^4s. This relatively large value leads to rather slow flame spread, e.g. about 0.006 cm/sec in air at 1 atm. This is far too low to observe steady-state spread (if it exists) in short-duration drop-tower experiments.

What is needed is a thick fuel material for which $\lambda_s\rho_sC_{P,s}(T_v-T_\infty)^2$ is small enough that information might be obtained in short-duration μg experiments that would aid in the design of later space experiments using more readily quantifiable fuels such as PMMA. For this purpose, after evaluating numerous candidate materials, we have chosen polyphenolic foams which have values of $\lambda_s\rho_sC_{P,s}(T_v-T_\infty)^2$ that are 2 to 3 orders of magnitude smaller than PMMA because of the foams have much lower thermal conductivity (λ_s) and density (ρ_s) than PMMA. The polyphenolic foams were chosen primarily because they have lower sooting tendency and negligible melting or dripping tendency compared to other foams such as polystyrene or polyurethane. Of course all foams contain trapped gas, however, the density of the foams we employed is still at least 20 times that of air, so that even if all the trapped gas were air, this air provides a negligible contribution to the overall stoichiometry. The permeability of the foam (typically 10^{-7} m^2) is such that the flow through the porous media can be neglected.

While smoldering combustion of foam materials has been widely studied in microgravity experiments, we are unaware of the use of foams for flaming combustion at microgravity. We emphasize that the current use of foams is motivated primarily by the needed to maximize S_f and minimize the time scales so that drop tower experiments can be employed.

Experimental results

Figure 2 shows examples of direct images of spreading flames at 1g and μg. From these images the effect of buoyancy can be seen. Figure 3 shows examples of the progress of flame spread (flame position vs. time) at 1g and μg. 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 μg conditions when gas-phase radiation effects are significant. Figure 4 shows that, as was also seen in the thin fuel tests[11], for thick fuels the quiescent μg S_f can be higher than its 1g (downward) counterpart for CO_2-diluted atmospheres but not N_2-diluted atmospheres. Figure 4 also shows that, as expected, the spread rate increases with increasing O_2 concentration. Figure 5 shows that a rather sharp transition in flame spread behavior from S_f increasing rapidly with pressure to S_f nearly independent of pressure is found at a pressure of about 5 atm. While the cause of this transition is uncertain, it might be due to a transition from radiation dominated by optically-thin behavior to optically-thick behavior. Moreover, the μg spread rate becomes less dependent on thickness as thickness increases as shown in Fig. 6. This shows the approach to a thick fuel regime. The transition thickness is about 2 mm for the case shown. Figure 7 shows that spread rate decreases with fuel density for these polyphenolic foams, at least for large density, in a manner similar to that predicted by Eq. 3 (spread rate inversely proportional to density). For small densities, it was found that the foam behaved in a very different behavior, primarily due to the formation of stringy soot structures (not shown) that did not occur for higher density fuels. From the interferometer images shown in Fig. 8, it can be seen that, as expected, the flame is thicker at microgravity than at earth gravity, indicating that the flame at microgravity has more volume and thus can transfer more radiation to fuel bed.

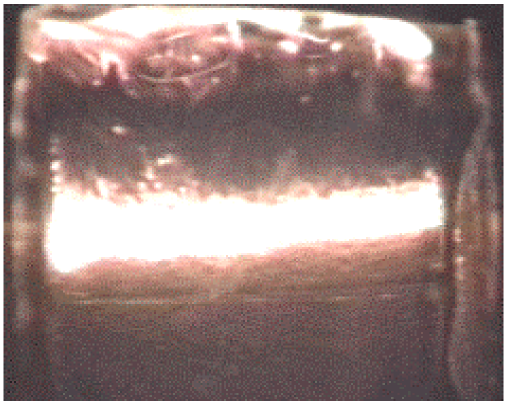

Figure 2. Image of flame spread over a thick solid fuel bed at μg. Width of fuel bed is 10 cm. Flame spreads toward the bottom of the image. Bright band in the lower part of the images is the flame front; upper bright band is from the ignition source.
(a) Microgravity.

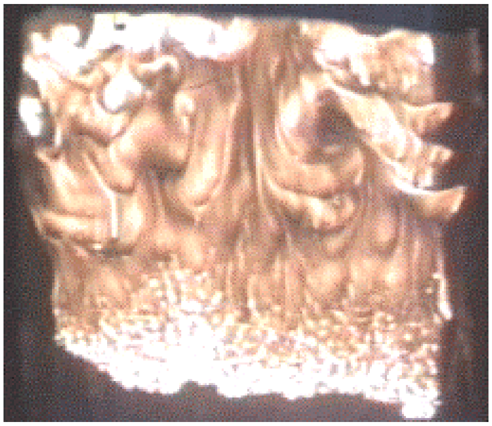

Figure 2. Image of flame spread over a thick solid fuel bed at μg. Flame spreads toward the bottom of the image. (b) Earth gravity.

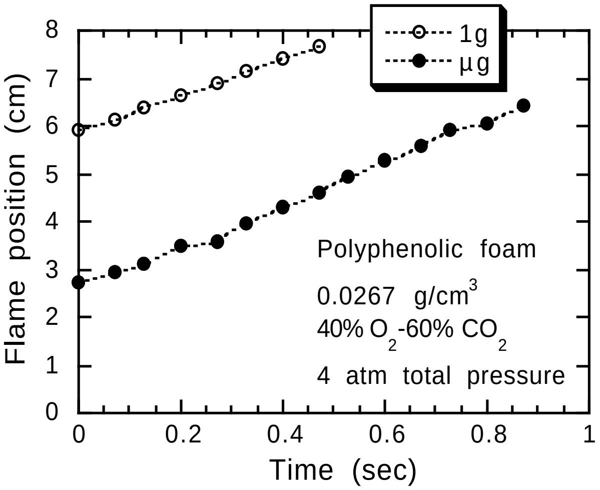

Figure 3. Position of spreading flame as a function of time.

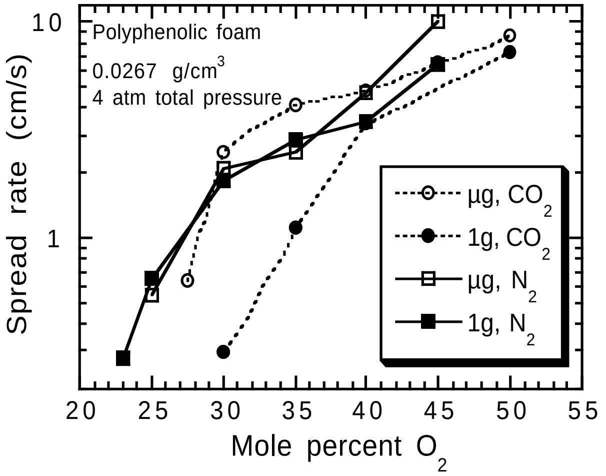

Figure 4. Effect of oxygen concentration on spread rates over thick solid fuel beds at μg and earth gravity.

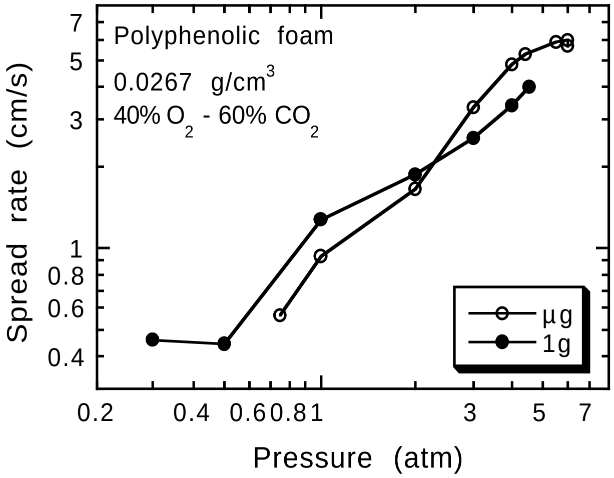

Figure 5. Effect of pressure on spread rate over thick solid fuel beds at μg and earth gravity.

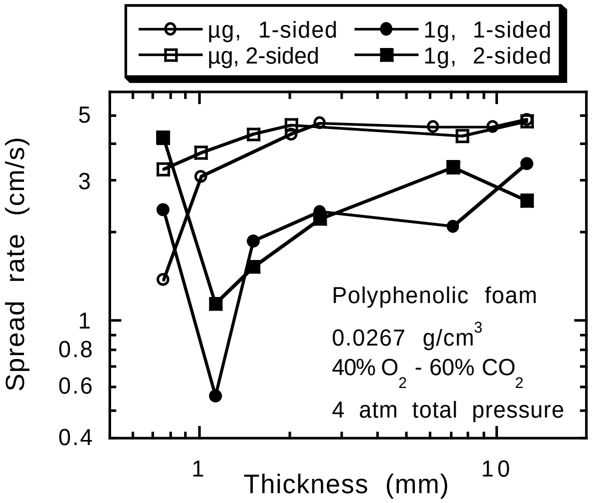

Figure 6. Effect of fuel bed thickness on spread rate over thick solid fuels bed at μg and earth gravity.

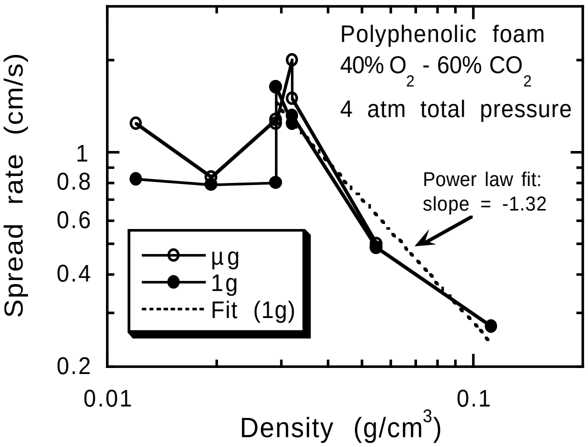

Figure 7. Effect of fuel bed density on spread rate over thick solid fuels beds at µg and earth gravity.

Figure 8. Image of Interferometer from the side of the fuel, and the upper black region represent the thick volume of the flame. (a) Microgravity

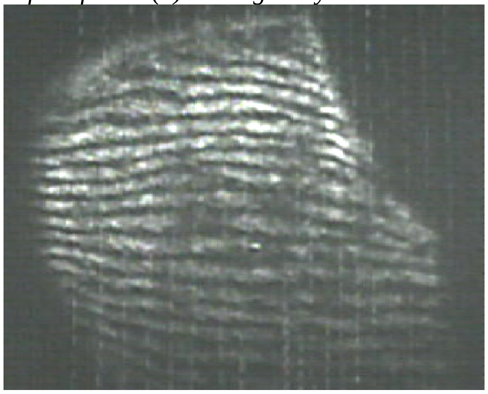

Figure 8. Image of Interferometer from the side of the fuel, and the upper right black region is smaller than that of the microgravity. (b) Earth gravity

Figures 9 a - d show, respectively, the radiative characteristics of flame spread in O_2-N_2 mixtures at 1g, O_2-N_2 mixtures at µg, O_2-CO_2 mixtures at 1g and O_2-CO_2 mixtures at µg. These results confirm our hypotheses concerning radiative transfer as well as the validity of our approach for testing these hypotheses. The only case where the back-side radiometer shows substantial response is for the O_2 - CO_2 atmosphere at µg. This is likely 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 backside radiometer. O_2 - N_2 atmospheres do not show this behavior at all, and even for O_2 - CO_2 atmospheres this is seen only at µg where δ is larger and thus the total radiative flux is greater. This is indeed confirmed in Fig. 9, which shows that the peak radiative flux is greater at µg than 1g for both CO_2 and N_2 atmospheres.

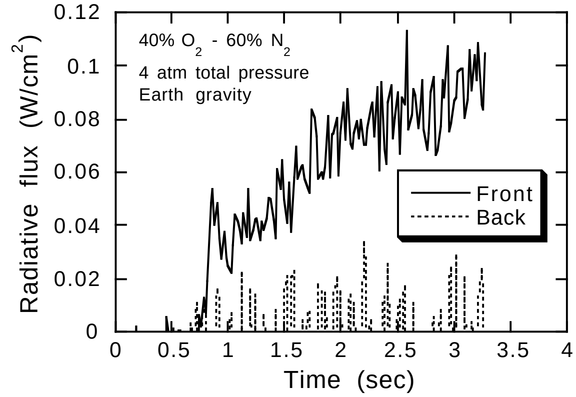

Figure 9. Radiative flux characteristics of flames spreading over polyphenolic foam fuel. (a) 40%% O_2 - 60% N_2, earth gravity.

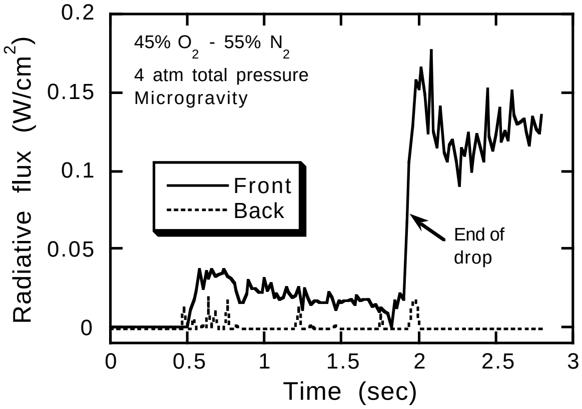

Figure 9. Radiative flux characteristics of flames spreading over polyphenolic foam fuel. (b) 45%% O_2 - 55% N_2, microgravity.

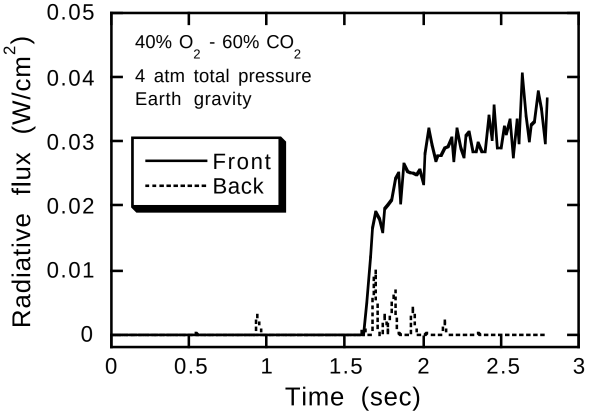

Figure 9. Radiative flux characteristics of flames spreading over polyphenolic foam fuel. (c) 40%% O_2 - 60% CO_2, earth gravity.

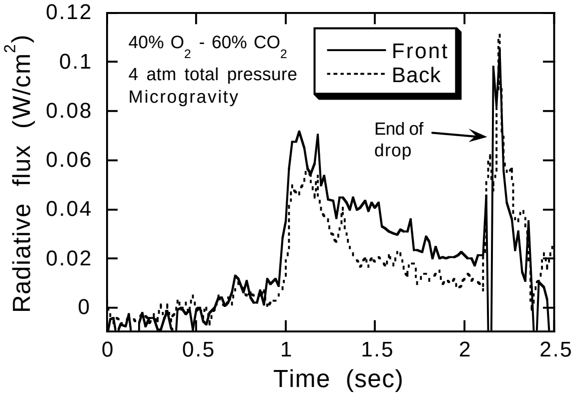

Figure 9. Radiative flux characteristics of flames spreading over polyphenolic foam fuel. (d) 40%% O_2 - 60% CO_2, microgravity.

Summary and Conclusions

Microgravity experiments on flame spread over thermally thick fuels were conducted using foam fuels to obtain low density and thermal conductivity, and thus large spread rate (S_f) compared to dense fuels such as PMMA. This scheme enabled meaningful results to be obtained even in 2.2 second drop tower experiments. It was found that, in contrast conventional understanding, steady spread could occur over thick fuels in quiescent microgravity environments, especially when a radiatively active diluent gas such as CO_2 is employed. In some cases with CO_2 diluent the spread rate was actually higher at µg than at 1g despite the absence of convection at µg, which without radiative transfer is expected to preclude the possibility of steady spread. This was shown to be due to radiative transfer from the flame to the fuel surface. This assertion is consistent with measurements of the radiatively fluxes to and from the fuel bed. This conclusion was also supported by interferometer images showing that the flames where much thicker at µg than 1g, indicating that the µg flames can radiate more heat to the fuel bed even to the point of overwhelming the conductive heat flux. Additionally, the transition from thermally thick to thermally thin behavior with decreasing bed thickness was demonstrated, at a typical fuel bed thickness of 2 mm.

These results 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 microgravity 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 1g vs. radiation-dominated heat transport at µg indicates that radiatively-inert diluents such as helium could be preferable in µg applications.

Acknowledgments

This work was supported by the NASA Glenn Research Center under grants NAG3-1611 and NCC3-671. The authors are grateful to our grant monitors, Drs. Sandra Olson and Suleyman Gokoglu, for many helpful discussions and technical support. We also thank the FEANICS team and the NASA-Glenn 2.2-second drop tower support staff for their help in coordinating and supporting the µg experiments.

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