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 ($S_l$) 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 to 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 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 ($S_l$). 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 $S_l$, however, at μg self-induced convection obviously cannot be neglected.

As described by Williams, the basic approach to modeling $S_l$ 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

$$S_l = \frac{\rho \delta \dot{q}}{\rho \omega C_p T (T_f - T_m) \tau},$$

where $q$, $\rho$, $C_p$, $T$ and $\tau$ are the density, specific heat, temperature, fuel bed thickness and the subscripts $s$, $g$, $v$ and $a$ refer to the solid fuel, gas-phase, vaporization condition and ambient condition, respectively. $\delta$ is the length of the zone over which heat is transferred from the gas to the fuel surface; for opposed-flow flame spread $\delta$ is proportional to the convection-diffusion zone thickness $\frac{\alpha_s}{U}$ where $\alpha_s = \frac{\lambda_s \rho S}{\delta_p}$ is the thermal diffusivity, $\lambda$ 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 $q = \frac{\lambda (T_f - T_m)}{\delta}$, where $T_f$ is the flame temperature given by

$$T_f = \frac{(Q_f - L_v)}{C_{p,v} + (T_f - T_m)} + T_m;$$

$$S = \frac{\nu_{fu}}{\nu_{fu} M_{fu} + \nu_{ox} M_{ox}} \frac{v_{fu} M_{fu}}{v_{ox} M_{ox}}$$

where $Y$ is the mass fraction, $M$ the molecular weight, $v$ 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

$$S_l = A \frac{\lambda_s}{\rho \omega C_p \tau} \frac{T_f - T_v}{T_f - T_m},$$

where $A$ is a constant and $\lambda_s$ is the thermal conductivity of the solid fuel.
where \( \lambda \) is a constant for a fuel bed of fixed thickness. For thick fuels, the "exact" solution \( \lambda = 1 \). Note that steady spread is impossible even if \( q \) because this ideal \( S_f \) is independent of \( \lambda \). This is because, although the length of the preheat zone, thus the fuel surface area exposed to the flame, is proportional to \( \delta \), the net change in the total heat flux to the fuel bed is also proportional to \( \delta \); 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, \( \tau_n \) is the fuel bed half-thickness, whereas for thermally thick (effectively semi-infinite) fuels, where heat conduction through the solid fuel is important, \( \tau_n \) is the depth of thermal penetration into the solid fuel (\( \tau_n \)), which can be estimated by equating \( q \) to the heat flux within the solid fuel \( \lambda(T - T_\infty) \), where the subscript \( y \) refers to the direction normal to the fuel surface:

\[
\tau_n = \frac{\lambda(T - T_\infty)}{q} \Rightarrow S_f = \frac{q^2\delta}{\rho C_p \lambda(T - T_\infty)}
\]  

(4).

This result is identical to that determined by Tarifa and Torralbo 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 \( q = \lambda(T - T_\infty) / \delta \), as in thin fuels, the "exact" solution for \( S_f \) over thick fuels is obtained:

\[
\tau_n = \frac{\lambda(T - T_\infty)}{\lambda(T - T_\infty)} \Rightarrow S_f = S_f \lambda(T - T_\infty) \frac{q^2\delta}{\rho C_p \lambda(T - T_\infty)}
\]  

(5).

The transition from thermally thin to thermally-thick behavior occurs when \( \tau_n = \tau_n \). Note then that a given material may behave as thermally thin or thermally-thick depending on \( \tau_n \) and thus \( \lambda \).

Equation 5 shows that for thick fuels, \( S_f = U \) and thus suggests that \( S_f \) is indeterminate at \( \delta \) unless a forced flow is applied. The conventional view is that for quiescent \( \mu g \) conditions \( S_f \) must be unsteady and decreasing until extinction occurs due to radiative losses. An analysis based on unsteady heat conduction to the fuel bed predicts that the thermal penetration depth \( \tau_n = \sqrt{T_\infty} \) which results in \( S_f \) being 

(6).

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 \( \delta \) 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 \( \delta_s = \alpha_s U = \alpha_s S_f \). The heat flux per unit area to the fuel surface due to radiation can then be estimated as \( \Lambda \delta_s \), where \( \Lambda = 4Q_0(T_f^4 - T_{\infty}^4) \) is the radiant heat emission rate per unit volume, \( \sigma \) is the Stefan-Boltzman constant and \( \alpha_s \) is the Planck mean absorption coefficient. The combined effects of gas-phase radiation and thermal conduction is then given by \( q = \Lambda \delta_s + \lambda(T_f - T_{\infty})/\delta_s \). Combining this with \( \delta_s = \alpha_s S_f \) and Eqs. 4 lead to (assuming unit fuel bed emissivity):

\[
S_f = \left[ \frac{\Lambda \alpha_s^2}{\sqrt{\alpha_s \rho \mathcal{C}_p \lambda_s (T_f - T_{\infty}) - \lambda_s (T_f - T_{\infty})}} \right]^{1/2}
\]

(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, \( S_f \sim \Lambda \). 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 \( \alpha_s \sim P^{-1} \).

Equation 6 is only valid when the denominator is positive, \( i.e. \), when the thick fuel flame spread parameter \( \Gamma = (\rho \mathcal{C}_p \rho_s \alpha_s)/(\rho \mathcal{C}_p \lambda_s ((T_f - T_{\infty})/((T_f - T_{\infty}))) < 1 \), 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 \( \rho \mathcal{C}_p \alpha_s \). This leads us to propose the use of polymeric foams with low \( \rho_s \) and \( \lambda_s \) to study thick-fuel flame spread in short-duration drop tower tests as precursors to space experiments using more quantifiable fuels with larger \( \rho \mathcal{C}_p \lambda_s \), e.g. PMMA.

A factor not considered in this discussion is that radiative transport 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 shown here.

**Experimental apparatus**

In order to test for the proposed possibility of steady flame spread over thermally-thick fuels in quiescent \( \mu g \) environments, a set of \( \mu g \) 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 \( \mu g \) 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 \( \mu g \), hence in these cases the samples must be ignited at \( \mu g \). 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.
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 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 polymethylmethacrylate (PMMA) which has a thick-fuel spread rate parameter \( \lambda_p C_p (T - T_0)^2 \) of about \( 3.3 \times 10^{10} \text{ cm}^2 / \text{sec} \). 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 behavior from 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).

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 need 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 \( \mu \)g. 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 \( \mu \)g. From these tests, it can be seen that in \( \text{O}_2-\text{CO}_2 \) atmospheres, steady flame spread is possible over thick fuels at quiescent \( \mu \)g conditions when gas-phase radiation effects are significant. Figure 4 shows that, as was also seen in the thin fuel tests, for thick fuels the quiescent \( \mu \)g spread rate is higher than its \( 1g \) counterpart for \( \text{CO}_2 \)-diluted atmospheres but not \( \text{N}_2 \)-diluted atmospheres. Figure 4 also shows that, as expected, the spread rate increases with increasing \( \text{O}_2 \) concentration.

What is needed is a thick fuel material for which \( \lambda_p C_p (T - T_0)^2 \) is small enough that information might be obtained in short-duration \( \mu \)g 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 \( \lambda_p C_p (T - T_0)^2 \) that are 2 to 3 orders of magnitude smaller than PMMA because of the foams have much lower thermal conductivity \( \lambda_p \) and density \( \rho_p \) than PMMA. The polyphenolic foams were chosen primarily because they have lower heating tendency and negligible melting or dripping tendency compared to other foams such as polysyrene 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 \( 10^{-6} \) atm cm/s such that the flow through the porous media can be neglected.
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. Bright band in the lower part of the images is the flame front; upper bright band is from the ignition source. (b) Earth gravity.

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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.

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

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

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The only case where the back-side radiometer shows substantial response is for the O$_2$ - CO$_2$ atmosphere at $\mu g$. 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 $\mu g$ where $\delta$ 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 $\mu g$ than at $\mu g$ for both CO$_2$ and N$_2$ atmospheres.

Figures 4 a - 2 show, respectively, the radiative characteristics of flame spread in O$_2$ - N$_2$ mixtures at 1g, O$_2$ - N$_2$ mixtures at $\mu g$, O$_2$ - CO$_2$ mixtures at 1g and O$_2$ - CO$_2$ mixtures at $\mu g$. These results confirm our hypotheses concerning radiative transfer as well as the

Figure 7. Effect of fuel bed density on spread rate over thick and fuels beds at $\mu g$ 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 9. Radiative flux characteristics of flames spreading over polyphenolic foam fuel. (a) 40% O$_2$ - 60% N$_2$, earth gravity.

Figure 10. Radiative flux characteristics of flames spreading over polyphenolic foam fuel. (a) 45% O$_2$ - 55% N$_2$, 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 ($S_i$) 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 $\mu g$ than at $1 g$ despite the absence of convection at $\mu g$, 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 $\mu g$ than at $1 g$, indicating that the $\mu g$ 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 $1 g$ vs. radiation-dominated heat transport at $\mu g$ indicates that radiatively-inert diluents such as helium could be preferable in $\mu g$ applications.

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