Flame spread over acrylic cylinders in microgravity: effect of surface radiation on flame spread and extinction

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During the 1990s several combustion experiments involving cellulose and PMMA as burning fuels were conducted on the Space Shuttle varying the oxygen concentration up to 50% in two pressure levels of 1 and 2 atm (Solid Surface Combustion Experiments, SSCE). These pioneering experiments were among the first attempts to explore flame spread in a quiescent microgravity environment. Although several papers have been published on the flame spread rate over thin and thick fuels, digitizing the videos, previously stored in VHS media, and application of recently developed image analysis tools have allowed us to re-analyze those videos for further understanding of these unique experimental results. Specifically, this work explores the effect of surface radiation on flame spread and extinction, starting from a qualitative analysis of the experiments. The comparison with samples from the more recent BASS (Burning And Suppression of Solid fuels) investigation suggest that radiative effects for flat and cylindrical fuels can be quite different, and are affected by the oxygen concentration. A non-dimensional surface radiation number is proposed to capture geometric effects on radiation.

Nomenclature

L_g = diffusion length in gas-phase, m
r = cylinder radius, m
ρ = density, $\mathrm{Kg/m^3}$
c_g = specific heat (c_g for gas phase and c_s for solid phase), $\mathrm{kJ/(Kg\cdot K)}$
λ = thermal conductivity, $\mathrm{kW/(m\cdot K)}$
τ_h = thermal penetration depth, m
τ = fuel half-thickness, m
T_v = vaporization temperature, K
T_f = flame temperature, K
V_f = flame spread rate, $\mathrm{m/s}$
σ = Stefan-Boltzmann constant, $5.67\cdot 10^{-8}\,\mathrm{W/(m^2\cdot K^4)}$

I. Introduction

FLAME spread over solid fuels has been largely studied in the past decades to understand the fundamental nature of hazardous fire spread and the growth of small flames. An important factor to determine flame growth and heat transfer to solid fuels is flame spread rate, which indicates how fast a flame front moves along a virgin fuel. Flame spread rate is affected by several fuel characteristics, such as fuel thickness and geometry, and ambient conditions such as flow field around the flame, pressure and oxygen concentration. In microgravity, buoyancy does not affect the flow around the flame, and very small values of forced-flow velocity can be obtained (in the order of a few cm/s). This specific characteristic has allowed researchers to study basic combustion phenomena and validate computational models[1].

The importance of a specific mode of heat transfer depends on the burning conditions. For example, in opposed-flow flame spread, radiation becomes important when the external flow velocity is reduced to few cm/s.

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Bhattacharjee and Altenkirch investigated computationally the importance of gas-phase and surface radiation for thin fuels in this low flow regime in microgravity[2], and later compared them to the SCCE cellulosic fuels[3], concluding that surface radiation losses can lead the flame to extinction in a quiescent environment if the fuel thickness increases. These results were confirmed by the next missions of SSCE, where thick slabs of PMMA (Polymethyl-Methacrylate) were tested, revealing that flame spread was unsteady with eventual extinction[4,5].

Flames over thick slabs of PMMA are affected by additional conductive heat losses from the solid fuel to the sample holder, but this practical problem can be avoided using cylindrical samples, which have been largely considered by researcher also in theoretical and computational works for their importance in fire safety and combustion phenomena[6-9]. Cylindrical samples were tested in SSCE in a 50% oxygen atmosphere without forced flows, and the flames burnt the samples completely[8].

Cylindrical PMMA samples were also used in the more recent BASS-II investigation on the International Space Station (ISS), to study the effect of a forced flow and oxygen concentration on flame spread over multiple solid fuel geometries[11,12]. BASS-II is an extension of the previous BASS investigation, which has been fundamental for characterizing flames behavior in microgravity and test the flammability conditions of several materials[13]. Even though cylinders in BASS-II could burn at very low flow velocities – in the order of few cm/s – in both opposed and concurrent flows, when the forced flow was set to zero the flames were not able to spread and they eventually extinguished[14].

Bhattacharjee et al. indicated solid surface radiation as the responsible mechanism of unsteady flame spread and eventual quenching for thick PMMA slabs[12], and a non-dimensional radiation number was introduced to quantify these losses for thin fuels, starting from the scaling of an energy balance and its non-dimensionalization. A similar scale analysis used by Higuera and Linan for cylinders revealed that curved surfaces are less affected by surface radiation losses than flat ones[15]. Curvature also increases flame spread rates, as discussed in the detailed analysis of Delichatsios et al.[14], because of enhanced heat transfer in the gas phase and faster temperature rise of the solid fuel.

The importance of surface radiation in a quiescent environment is still not clear because of the peculiarity of the burning conditions; scale analyses, as well as numerical models, suffer from extremely small values of spread rate and flow velocity (resulting in extremely large diffusion length), and the limited oxygen available limits the reaction rate. In this work we investigate the importance of surface radiation on flame spread in the quiescent environment and different oxygen levels, to establish if the driving extinction mechanisms for flat fuels apply to cylindrical samples as well. By assuming gas and solid radiation equally important, we can simplify the heat balance at the flame leading edge and neglect the effect of soot in the gas phase which is harder to model and extrapolate from experiment videos[16]. A non-dimensional number that evaluates the importance of surface radiation in cylindrical geometry is still lacking.

Due to the large technological gap in image acquisition between SSCE (1990s) and BASS (2010s), the video quality of the cylinders burning in SSCE is much lower than the ones in BASS, but still enough to extrapolate important qualitative results. The videos were analyzed with a MATLAB code we developed, called *Flame Image Analyzer Tool*[17] (FIAT), where the flame can be automatically tracked with two methods: (i) luminance intensity (the only parameter used to track the flame after converting the frames from the RGB to the YCrCb space), and (ii) color filtering (the RGB color channels are manually filtered to isolate the region of interest).

Starting from the qualitative observation of the videos, we use scale analysis to study the physical mechanisms behind flame extinction in a quiescent environment, focusing on the importance of surface radiation.

II. Microgravity Experiments

During the 1990s, several experiments using cellulosic fuel (filter paper) and PMMA were performed on the Space Shuttle for the Solid Surface Combustion Experiment (SSCE), more than 15 years after the tests in Skylab[18]. SSCE explored the effect of oxygen concentration (up to 70%) and pressure levels (1, 1.5 and 2 atm) in a quiescent environment for flat thin and thick fuels. During STS-91, also two PMMA rods were burnt at 50% oxygen and 1 atm. Flames over cellulosic samples have been already discussed in the past[3] and will not be reported here; we focused instead on acrylic samples, and in particular on the cylindrical samples that can be better compared to the ones used in BASS. This investigation and its extension

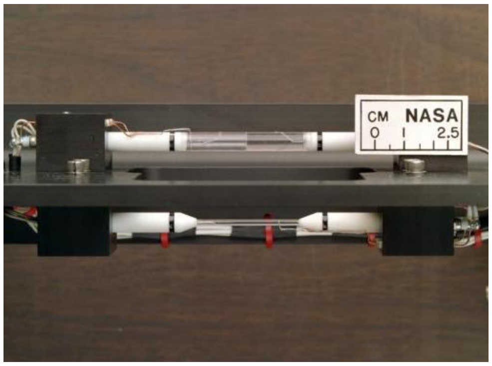

Figure 1. Picture of the two cylindrical samples tested in 1998.

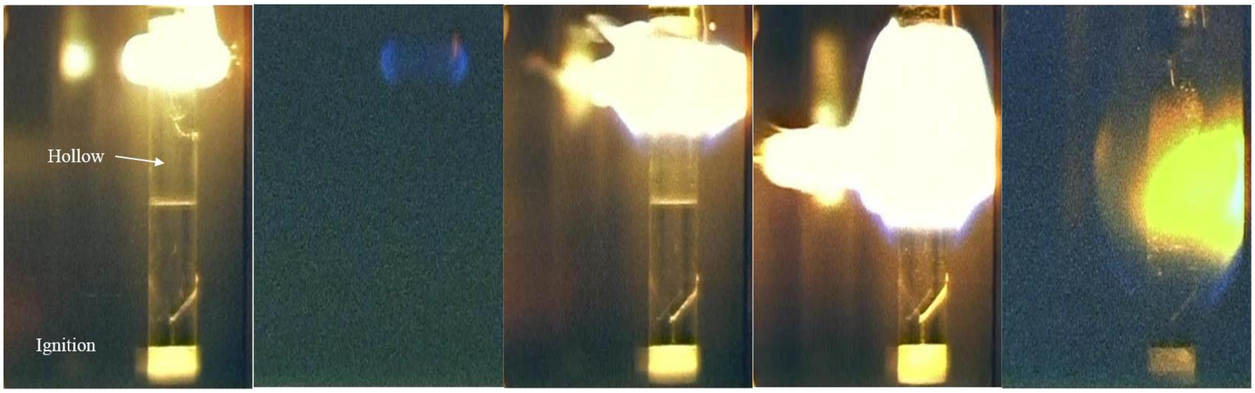

Figure 2. Frames of the SSCE video where a flame spreads over a cylinder (diameter of 6.4 mm) in a quiescent environment and oxygen concentration of 50%. Referring to the ignition time, the frames were captured at (starting from left to rigth): 0, 4, 21, 36, 66 s.

BASS-II provided a large amount of experimental data regarding flames burning in concurrent and opposed-flow[13], up to 55 cm/s, and both flat and cylindrical samples were used. The oxygen concentration in the BASS experiments varied in the range 15-22%, much lower than the one used in SSCE.

The two PMMA cylinders tested during SCCE are shown in Fig. 1, and were burnt in 1998 on STS-91, the last Shuttle-Mir Docking mission. The thicker cylinder (top one in Fig. 1) had a diameter of 6.4 mm and length of 40 mm, but the first half was hollow with an external thickness of 1 mm[10]. The thinner cylinder instead had a diameter of 2 mm with similar length (44 mm), and both samples were burnt with pressure of 1 atm with an oxygen concentration of 50%, inside of the 39L combustion chamber designed for SSCE[18].

The flat PMMA samples used in SSCE showed a tendency to extinguish in a quiescent environment also with high oxygen concentration, because of the high thermal losses through surface radiation related to the high vaporization temperature; however, the flames over the PMMA rods seem to spread steadily, even though the flame lengths grow for the entire experiment. Figure 2 shows frames at different time after ignition of the flame generated over the thicker cylinder, which was hollow in the first half. The flame gets bigger and bigger, but the speed of the flame leading edge is constant as can be interpolated from the flame front position during time as shown in the graph on the left of Fig. 3. The blue flame front was tracked with the color filtering method, starting from the initial flame right after the igniter went off (second frame from left in Fig. 2), and ending when it reached the end of the sample (about 90 s after ignition); when the main region of the flame reaches the fuel transition from hollow to full sections (between 40 and 50 s), it adjusts to the new thickness with strong changes in color and brightness, and the blue flame front basically becomes invisible in the video. The spread rates obtained from leading edge tracking with FIAT differ from the previously published values[10] of less than 10%, except for the full section of the bigger cylinder that is much lower (only 40% of the previously reported value). The flame over the thinner cylinder is so fast that only takes few seconds to spread along the 44 mm sample (about 8 s as shown in Fig. 3); even though the thin cylinder has the same fuel thickness of the hollow section of the thicker sample (1 mm), the flame spreads more than three times faster. Beside the absolute values of the spread rate, Fig. 3 shows that flames advance steadily, unlike the unsteady propagation on the thick slabs[4].

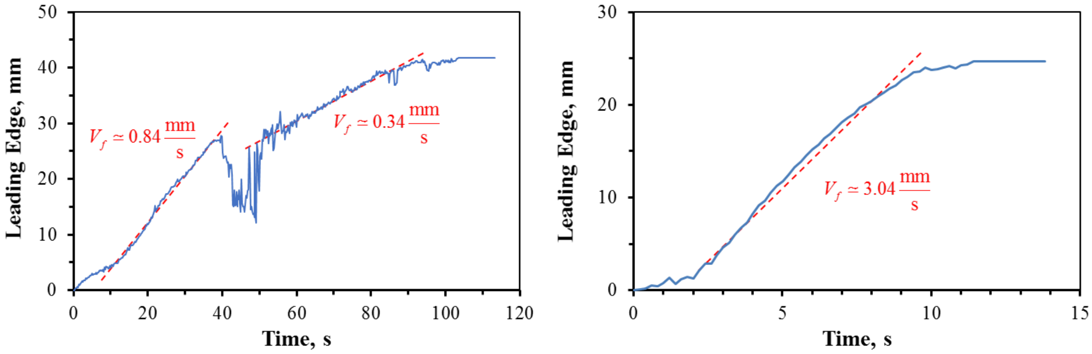

Figure 3. Position of the leading edge during time of the 6.4 mm cylinder (left), and 2 mm (right).

III. Discussion

The experimental cases are not enough to establish if the flames over the two cylindrical samples of SSCE were completely steady, but the energy balance and a scale analysis can be used to study the importance of surface radiation. Delichatsios et al.[19] compared flat and cylindrical fuels, and they showed that the heat transferred from the flame to the virgin fuel is enhanced due to curvature by a factor of:

$$f_{\mathrm{cyl}} = \frac{\mathrm{c}\left(L_g/r\right)}{\ln\left(1+\mathrm{c}\,\dfrac{L_g}{r}\right)} \tag{1}$$

Where c is a constant which value depends on the burning conditions, e.g. 1.8 for natural convection and 3.2 for microgravity[19]. The value of the constant is not relevant for the scaling in the present study, so it will be set equal to 1.

We can evaluate the effects of radiative heat transfer on cylindrical fuels starting from the energy balance in a flame-centered control volume as the one in Fig. 4. Neglecting surface radiation, only the conductive term in the gas phase and the vaporization term in the solid phase are responsible of flame spread[20]:

$$V_f \rho_s c_s \left(T_v - T_\infty\right)\pi\left(r^2-\left(r-\tau_h\right)^2\right) \sim \lambda_g\left(T_f - T_v\right) f_{\mathrm{cyl}}\, 2\pi r \tag{2}$$

Therefore, the spread rate in the thermal regime can be obtained solving Eq. (2):

$$V_{f,\mathrm{th}} \sim f_{\mathrm{cyl}}\left(1-\frac{\tau_h}{2r}\right)^{-1}\frac{\lambda_g}{\rho_s c_s \tau_h}\left(\frac{T_f-T_v}{T_v-T_\infty}\right) = f_{\mathrm{cyl}}\left(1-\frac{\tau_h}{2r}\right)^{-1}\frac{\lambda_g}{\rho_s c_s \tau_h}F \tag{3}$$

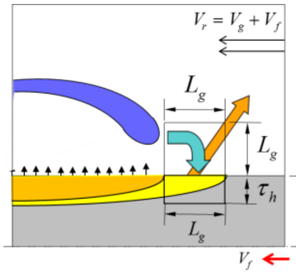

Figure 4. Control volume used for the energy balance in Eq. (2) and (9).

The thermal penetration depth τ_h in Eq. (3) can be substituted with the sample radius when the fuel is thermally thin ($\tau_h = r$), or with the expression following from the boundary condition of conduction on the fuel surface for thermally thick cylinders ($\tau_h = \lambda_s L_g / \left(\lambda_g F\right)$). Scaling the gas phase thermal length as $L_g \sim \alpha_g / V_r \sim \alpha_g / \left(V_f + V_g\right) \sim \alpha_g / V_g$, and the thermal diffusivity as $\alpha_g \sim \lambda_g / \rho_g c_g$, we get:

$$V_{f,\mathrm{th,thn}} \sim 2 f_{\mathrm{cyl}} \frac{\lambda_g}{\rho_s c_s r} F \tag{4}$$

$$V_{f,\mathrm{th,thk}} \sim f_{\mathrm{cyl}}\left(1-\frac{\lambda_s}{\rho_g c_g V_g 2rF}\right)^{-1}\frac{\lambda_g \rho_g c_g}{\lambda_s \rho_s c_s} V_g F^2 \tag{5}$$

Eq. (4) and (5) are analogous to de Ris' spread rate expressions for thin and thick flat fuels. As observed and proved by Delichatsios et al.[19], the spread rate over thick cylinders tends to the asymptotic value for thick flat fuels, because $f_{\mathrm{cyl}} \to 1$ for $r \to \infty$ (flat surfaces can be thought as curved surfaces with infinite radius), whereas spread rate over thin fuels results more than doubled with respect of similar thin flat fuels.

The distinction between thermally thin and thick limits fades away in a quiescent environment ($V_g = 0$), because the penetration depth is defined with the time scale related to the flame spread rate, which is small compared to forced flow velocities when they are present; in other words, defining the penetration depth as[4,19]:

$$\tau_h \sim \sqrt{\alpha_s t} \sim \sqrt{\alpha_s L_g / V_f} \quad \to \quad \tau_h \sim \sqrt{\alpha_s \alpha_g} / V_f \tag{6}$$

Considering first very thin PMMA cylinders, we could substitute Eq. (4) in Eq. (6) to get a relation between thermal depth and radius, that is:

$$\tau_h \sim \frac{\sqrt{\alpha_s \alpha_g}\,\rho_s c_s}{2 f_{\mathrm{cyl}} \lambda_g} r \tag{7}$$

From Eq. (7) we can see that the penetration depth is directly proportional to the fuel radius, and the proportionality factor is constant except for f_{cyl}. This term, however, does not influence Eq. (7) significantly, because in a quiescent environment it becomes:

$$f_{\text{cyl,q}} = \frac{\dfrac{\alpha_g}{V_f r}}{\ln\left(1+\dfrac{\alpha_g}{V_f r}\right)} \tag{8}$$

The spread rate V_f depends on f_{cyl} again, but it is also known that large variations in V_f in Eq. (4) are due by the inverse proportionality with r; therefore, the product $V_f r$ can be considered almost constant, or at least a secondary effect in Eq. (7). Therefore, larger radii in Eq. (7) cause the penetration depth to increase as well, and the direct proportionality between the two suggests that in a quiescent environment cylinders can be considered thermally thin (no temperature gradient along thickness) unless the product $V_f r$ causes large variations of the cylindrical factor. In other words, the flame has enough time to heat up the thickness before proceeding along the virgin fuel, on the contrary of what happens with an external flow. Flame spread rate still decreases with thickness, as proven by the spread rates of SSCE, but both sample diameters act like thin fuels and flames spread at a constant rate.

The situation is different when we include the surface radiation term in the energy balance of Eq. (2):

$$V_f \rho_s c_s \left(T_v - T_\infty\right)\pi 2 r \tau_h \left(1-\frac{\tau_h}{2r}\right) + \varepsilon\sigma\left(T_v^4 - T_\infty^4\right) 2\pi r L_g \sim \lambda_g \left(T_f - T_v\right) f_{\text{cyl}} 2\pi r \tag{9}$$

This equation can be normalized and solved for the spread rate V_f; introducing the non-dimensional terms $\eta_f = V_f / V_{f,\text{th}}$ and $\eta_g = V_g / V_{f,\text{th}}$ ($V_{f,\text{th}}$ is obtained from Eq. (3)), we can rewrite Eq. (9) as:

$$\left(\eta_f + \eta_g\right)\left(\eta_f - 1\right) + \Re \sim 0 \tag{10}$$

Where:

$$\Re = \left(1-\frac{\tau_h}{2r}\right)\frac{\varepsilon\sigma\tau_h}{\lambda_s}\frac{\Omega^2}{f_{\text{cyl}}^2 F^2}\frac{T_v^4 - T_\infty^4}{T_v - T_\infty}, \quad \Omega^2 = \frac{\lambda_s \rho_s c_s}{\lambda_g \rho_g c_g} \tag{11}$$

$\Re$ is the so-called radiation number, and it is equivalent to the one obtained for flat fuels by Bhattacharjee et al.[20], except for the geometrical factor $1-\tau_h/2r$ and $1/f_{\text{cyl}}^2$. It should be noticed that no assumptions have been made on fuel thickness; this dependence is included in the length scale τ_h, which depends on the flow conditions as illustrated above.

To show how the two extra terms in the cylindrical radiation number influence its value, we consider a flat sample with the same thickness as the radius of the thicker cylindrical PMMA sample, which was 1 mm in the hollow section and 3.2 mm ($\tau_h = r$ in the latter case). Using the properties listed in Table 1[21], and the experimental values of the spread rate obtained with FIAT to calculate f_{cyl} (the diffusion length in the gas phase would otherwise be hard to determine in a quiescent environment because of the dependence on the small velocity scale V_f), we can calculate the radiation numbers for flat and cylindrical geometries:

$$\begin{aligned} &\Re_{\text{flat}} = 40.02; \quad \Re_{\text{cyl}} = 0.68 \qquad (\tau = 1\text{mm}) \\ &\Re_{\text{flat}} = 128.08; \quad \Re_{\text{cyl}} = 0.33 \qquad (\tau = 3.2\text{mm}) \end{aligned} \tag{12}$$

The radiation number of the flat geometry is one order of magnitude larger than the respective cylindrical in the case of $\tau_h = 1$ mm, and even more in the case of $\tau_h = 3.2$ mm, indicating that surface radiation is very important in flame extinction over flat samples, while it might not play an important role in the cylindrical geometry. Using the spread rate values from Altenkirch et al.[10], the radiation numbers do not change significantly, $\Re_{\text{cyl}} = 0.48$ for $\tau_h = 1$ mm, and $\Re_{\text{cyl}} = 0.70$ for $\tau_h = 3.2$ mm. For simplicity, we assumed $\varepsilon = 1$, because a lower value would just reduce the radiation numbers without changing the order of magnitude between the two geometries. The flame temperature was calculated at equilibrium at www.thermofluids.net, resulting in $T_f \simeq 2800\ \mathrm{K}$, whereas $T_v \simeq 650\ \mathrm{K}$ and $T_\infty = 300\ \mathrm{K}$.

Table 1. PMMA and gas property values.

Property	Symbol	Unit	PMMA	Gas phase
Density	ρ	$\mathrm{kg/m^3}$	1190	0.518
Specific heat	c	$\mathrm{kJ/(kg \cdot K)}$	1.465	1.183
Thermal conductivity	λ	$\mathrm{W/(m \cdot K)}$	0.18	0.052

When oxygen concentration is lower, for example 21% as in some of the BASS-II experiments, the only thermodynamic parameter that changes significantly is the flame temperature ($T_f \simeq 2300\ \mathrm{K}$ at equilibrium), and the relative radiation numbers are $\Re_{\mathrm{cyl}} = 0.81$ for $\tau_h = 1\ \mathrm{mm}$, and $\Re_{\mathrm{cyl}} = 1.19$ for $\tau_h = 3.2\ \mathrm{mm}$. It should be noticed that these values are calculated to compare the effect of a possible variation of oxygen concentration on surface radiation, therefore the values of f_{cyl} were considered the same as before although the spread rate would tend to zero. Higher values of f_{cyl} imply lower surface radiation, suggesting that extinction over cylindrical surfaces is not driven by solid radiation as for flat fuels, but other mechanisms such as gas-phase radiation might be responsible for that. The surface radiation losses seem not to change much.

IV. Conclusions

The review of old videos from SSCE suggested that flames over cylindrical fuels could spread steadily in a quiescent environment even though flames over flat fuels (under similar environment) slowed down with eventual extinction. By using more advanced video processing tool, we calculated the average spread rate from the analysis of the flame leading edge tracking, and established that flame spread rate is quite steady in cylindrical geometry and shows no signs of slowing down (until the flame reaches the end of the sample). To explore the difference between the two geometries quantitatively, we use scaling arguments to develop a non-dimensional radiation number that incorporates the geometric effect on surface radiation. Our findings include the following. (i) In a quiescent environment cylindrical fuels behave as thermally thin because the thermal penetration depth increases in step with an increase in cylinder radius since diffusion length is inversely proportional to spread rate. (ii) Cylindrical surfaces are less affected by surface radiation than flat surfaces because of the curvature, which decreases the radiation number (measure of heat losses). The ratio of the radiating surface area to the flame area is indeed about one in a flat geometry while it is much lower in a cylindrical geometry (especially, for very thin samples or large flames). (iii) The effect of oxygen concentration is included in the radiation number, but a comparison between the burning conditions of SCCE and BASS shows that surface radiation losses might not be responsible of extinction for cylindrical fuels, in contrast with the behavior of flat fuels. An accurate analysis of gas-phase radiation, including the presence of soot, is needed to evaluate its importance at extinction.

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