

REFLIGHT OF THE SOLID SURFACE COMBUSTION EXPERIMENT: OPPOSED-FLOW FLAME SPREAD OVER CYLINDRICAL FUELS¹

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Introduction

Although much has been learned about flame spreading at low gravity from recent experimental and theoretical efforts (see, e.g., refs. 1-3) understanding of the role of radiation heat transfer is limited. The difficulty lies in the fact that the modelling that must be done in concert with a limited number of low-gravity experiments to assist in interpretation of experimental results is complicated by several factors when radiation is involved. Although the process of radiative heat transfer is well described by the radiative transfer equation (RTE), the solution of the RTE itself is cumbersome, and almost always approximate due to, among other things, the three-dimensional nature of the radiative field, spectral and temperature dependence of properties, soot formation, turbulence-radiation interaction, and inhomogeneity of the medium.

The effort described here is a reflight of the Solid Surface Combustion Experiment (SSCE) (ref. 4), with extension of the flight matrix first and then experiment modification. The objectives of the reflight are to extend the understanding of the interplay of the radiative processes that affect the flame spread mechanisms.

Two experiments are scheduled for flight aboard the Space Shuttle using the existing SSCE chamber and electronics. In each experiment, thick PMMA is the fuel, the thick fuel being used for reflight because most "real fuels" are thick. One experiment is an extension of the SSCE PMMA experiment using exactly the same flat surface configuration used in previous SSCE flights but exchanging the dual sample configuration of the earlier experiments for a single long sample. The "long sample" configuration is chosen to allow observation of the predicted phenomena following ignition and flame spread, which for flat, thick fuel surfaces appears to be unsteady, leading eventually to flame extinction because of the influence of radiative processes (ref. 3).

The second experiment, and the one on which we concentrate here, is to utilize a cylindrical geometry, which provides a unique environment whereby the effects of finite flame width inherent in the flat surface experiments on the radiative field is eliminated. The problem is inherently two dimensional, not only from a hydrodynamic point of view but also the radiative field, and so approximations of dimensionality in applying radiation models are not needed.

Considerable work has been done over the past three decades on flame spread over a flat fuel bed placed in an opposing flow. Although the influence of parameters such as ambient oxygen level, pressure, fuel thickness, etc. are well understood, there are relatively few studies on the effects of fuel geometry, e.g., the cylindrical geometry considered here compared to the flat-surface geometry, an important parameter for practical applications.

Kosdon *et al.* (ref. 5) developed a similarity solution for flames over cylindrical fuels and compared the mass burning rate with experiments performed on cellulosic and birchwood samples. Fernandez-Pello and Santoro (ref. 6) studied downward flame propagation over PMMA cylinders with an emphasis on the determination of the mechanism of flame spread. They concluded that the dominant mode of heat transfer is a function of the fuel thickness, with the solid conduction playing a more dominant role for thicker fuels. Tewarson and Khan (ref. 7) studied the effects of flame spread rates for electrical cables, but in a concurrent flow configuration.

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Here we discuss the experiments to be conducted with cylindrical fuel samples in a quiescent, microgravity environment on future Space Shuttle flights, and the supporting modelling effort, which includes scaling, analytical, and numerical work. Some of the modelling results are compared among themselves and to available experimental results.

Reflight Experiments

The reflight experiments, as mentioned above, consist of two experiments using the existing SSCE chamber (ref. 4) and electronics. In each experiment, PMMA is the fuel. The first experiment is to exchange the dual sample configuration of the earlier experiments for the single long sample, 6.2 mm wide, 2.9 mm thick, and 59.9 mm long, to be burned in a test atmosphere of 50% O₂/ 50% N₂ at 1 atm. The sample will be exposed to the atmosphere on one 6.2 mm x 59.9 mm surface; the other surfaces will be insulated from the surroundings. Because the sample is expected to extinguish during the test (ref. 3), there are no provisions for quenching the sample. The sample will be ignited using the same resistively heated Kanthol wire energized for 5 seconds at 3.75 amps. Six thermocouples will be suspended above the sample at a height of 10 mm from the sample surface, spaced along the sample centerline. These thermocouples will provide a redundant measure of the flame spread progress and the change in the temperature field away from the flame leading edge, while avoiding the possible interference with the quenching process. The flame will be imaged using a video camera from one perspective and a cine camera from an orthogonal perspective.

The second experiment takes advantage of the reduction in dimensionality of the radiation environment provided by a cylindrical sample. Two samples will be burned in this test, both in 50% O₂/ 50% N₂ (see Figure 1). The first sample will be 44 mm long and 6.4 mm in diameter. The first half of the sample length will be hollow with a 1.0 mm wall thickness, the other half length solid. This single sample provides examples of both a "large diameter," thin fuel and a large diameter, thick fuel. The second sample is 40 mm long and 2.0 mm in diameter, and solid, to provide a "small diameter," thin fuel. Both samples will be ignited using the same Kanthol wire ignitor. The thin wall, large diameter sample section is expected to burn at a steady rate in the 50% O₂ test atmosphere, while the thick sample section is expected to spread to extinction. The small diameter sample is also expected to burn at a steady rate.

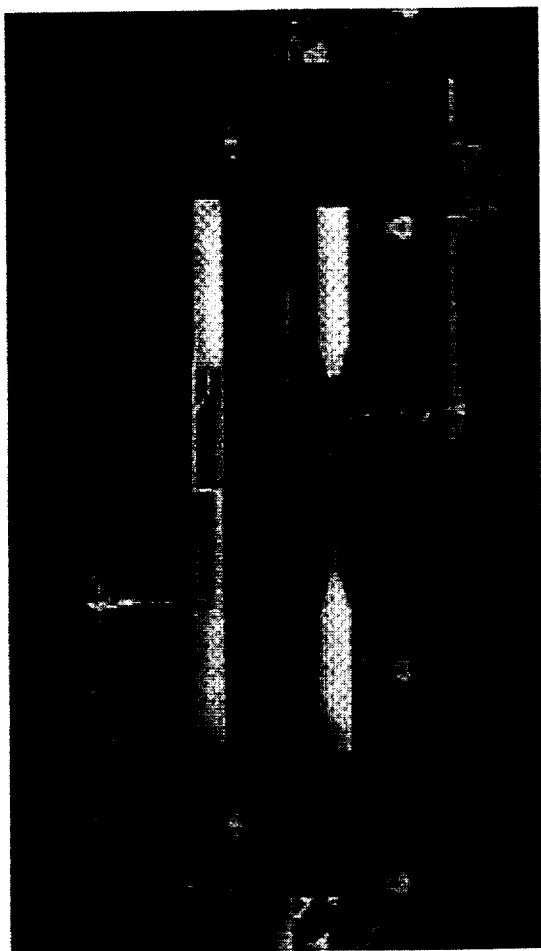


Figure 1 Cylindrical PMMA samples. Upper sample is 2.0 mm in diameter. Lower sample is 6.4 mm in diameter; right side is hollow, left side solid.

Modelling Formulation

The mathematical formulation is patterned after the flat surface formulation (refs. 2,3) except for the global-balance radiation model, which is reformulated for the cylindrical geometry. The numerical solution employs the finite-volume formulation of Patankar (ref. 8) for the hydrodynamic calculations and the TTNH formulation of Grosshandler (ref. 9) for line-of-sight radiation calculations with the species, CO₂, H₂O, and MMA vapor. The computational code has been validated by comparing the numerical result with analytical solutions available for simpler models.

Scaling

Consider the control volume near the leading edge of the flame shown in Figure 2 in flame-fixed coordinates with the oxidizer approaching the flame at a velocity

$V_r = V_g + V_f$ and the fuel at V_f , where V_g is a known opposing flow velocity, and V_f is the desired spread rate. Assuming negligible blowing in the preheat

region, V_r is the only velocity scale leading to the following gas-phase diffusion/conduction length scales.

$$L_{gx} \approx \frac{\alpha_g}{V_r}, \quad L_{gy} \approx \sqrt{\alpha_g \frac{L_{gx}}{V_r}} = \frac{\alpha_g}{V_r}, \quad \text{Thus: } L_{gx} \approx L_{gy} \approx L_g = \frac{\alpha_g}{V_r}. \quad (1)$$

For flat surfaces in the thermal regime the solid is preheated primarily through gas phase conduction (refs. 10,11). Assuming the same mechanism for the cylindrical geometry, the solid-phase length scales can be expressed as follows, where R is the solid cylinder radius.

$$L_{sx} \approx L_{gx} = \frac{\alpha_g}{V_r}, \quad L_{sy} \approx \min\left(R, \sqrt{\alpha_s \frac{L_{sx}}{V_f}}\right) = \min\left(R, \sqrt{\frac{\alpha_s \alpha_g}{V_f V_r}}\right) \quad (2)$$

Taking into account the radial variation of surface area, the conduction heat flux from the gas to the solid phase at the fuel surface can be scaled as:

$$\dot{q}''_{gsc} = \gamma \dot{q}''_{gsc, cart}, \quad \text{where,} \quad \dot{q}''_{cart} = \lambda_g \frac{T_f - T_v}{L_g}, \quad \gamma = \frac{L_g/R}{\ln\left(1 + \frac{L_g}{R}\right)} \quad (3)$$

The total heat flow from the gas phase to the preheating zone of the solid phase is expended in the sensible heating of the solid from T_∞ to T_v as it approaches the flame with a velocity V_f in the flame-fixed coordinates.

$$\rho_s c_s V_f (T_v - T_\infty) \cdot \left[\pi R^2 - \pi (R - L_{sy})^2 \right] \approx 2\pi R \dot{q}''_{gsc} \quad (4)$$

Therefore,

$$V_f \approx \frac{\gamma}{\left(1 - \frac{L_{sy}}{2R}\right)} \frac{\lambda_g}{\rho_s c_s L_{sy}} \frac{(T_f - T_v)}{(T_v - T_\infty)} \quad (5)$$

The thermally thin and thick limits are obtained by combining Eqs. (5) and (2).

$$V_{f, thin} \approx 2\gamma \frac{\lambda_g}{\rho_s c_s R} \frac{(T_f - T_v)}{(T_v - T_\infty)}, \quad V_{f, thick} \approx \frac{\gamma^2}{\left(1 - \frac{1}{2R} \sqrt{\frac{\alpha_s \alpha_g}{V_{f, thick} V_r}}\right)^2} \frac{V_r \lambda_g \rho_g c_g}{\lambda_s \rho_s c_s} \left(\frac{T_f - T_v}{T_v - T_\infty} \right)^2 \quad (6)$$

Note that while the thick formula is a transcendental equation, the thin formula, when compared to the corresponding flat surface formula (ref. 12), indicates that the spread rate is at least twice as fast for thin cylindrical fuels compared to flat surface fuels in the thermal regime.

Results and Discussion

Spread rates, computed for cylindrical fuels of different radii in a downward spread configuration under atmospheric conditions, are compared with experimental results (ref. 6,13) and prediction from Eq. (5) in Figure 3. The computational predictions agree reasonably well with the experimental spread rates. Finite-rate kinetics are known (ref. 14) to have a significant effect at 21% O₂. The scaling formula, built with the assumption of infinite-rate kinetics, understandably overpredicts the spread rate. However, it captures the nature of the variation of V_f with the fuel radius. In calculating V_f from Eq. (5), a recently developed (ref. 14) expression for an equivalent opposing flow velocity has been used for V_r .

Computational spread rates in a thermal regime configuration, $V_g = 40$ cm/s, O₂ level 50%, for both flat and cylindrical fuels are presented in Figure 4. Corresponding predictions from Eq. (5) are plotted in Figure 5. The radius of the cylindrical fuel and the half-thickness of the flat fuel are both referred to as τ . The cylindrical spread rate in the thin regime is at least twice as fast as the corresponding flat case as anticipated. For the cylindrical thin fuel, however, the computational results to date are not grid-independent.

Computational results for which the radiation computation was frozen at one particular condition are presented for a quiescent microgravity environment in Figure 6. Because the radiative field in Figure 6 was not computed for each configuration

separately, the results are qualitative. Results for hollow cylinders are included. The thickness of the cylindrical shell and the half-thickness of the flat fuel are both referred to as τ . For a given radius, spread rate over a hollow cylinder (with the interior cavity filled with insulation) decreases with increasing thickness and merges with the results from $\tau = R$ for cylinders, i.e., solid cylinders with no cavity. For both flat surfaces and solid cylindrical surfaces the spread rate continues to decrease as the fuel thickness increases until no steady-state solution can be found indicating the possibility of extinction after a critical fuel thickness. This is understandable in that in the absence of any imposed flow, the thickness of the heated layer in the solid is approximately,

from Eq. (2), $L_{sy} = \frac{\sqrt{\alpha_s \alpha_g}}{V_f}$. As the spread rate decreases, a progressively thicker layer of fuel is heated by the flame, which

in turn reduces the spread rate further as evident from Eq. (5). As this layer is developing, the mass diffusional scale in the gas grows while radiation losses keep the flame from growing in size such that eventually, oxygen diffusion into the flame is insufficient to sustain it and extinction occurs (ref. 3). Unsteady numerical computation for spread over a PMMA cylinder of 5 cm radius and 2 mm wall thickness in a quiescent microgravity environment is shown in Figure 7 in which flame position as a function of time is presented. The spread rate continually decreases until the flame reaches a location at which it continues to burn for a substantial amount of time without forward progress while radiation losses depress the flame temperature over time. Eventually, the flame leading edge, actually the peak heat flux from the gas to the solid, retreats, and the flame extinguishes.

Summary

The cylindrical geometry provides an attractive geometry for investigating the influence of radiation on flame spread in a quiescent microgravity environment because it eliminates the three dimensional effects inherent in the flat surface geometry of finite width. Simple analyses based on energy balances along with numerical modelling of the spread process indicate that spread rates over the cylindrical surface are faster than for the flat surface for the same sample thickness, i.e., radius. The unsteady behavior observed for thick, flat surface fuels is anticipated in the cylindrical geometry as well. Space Shuttle experiments are planned to delineate the unsteady effects observed in earlier SSCE experiments for both flat and cylindrical surfaces.

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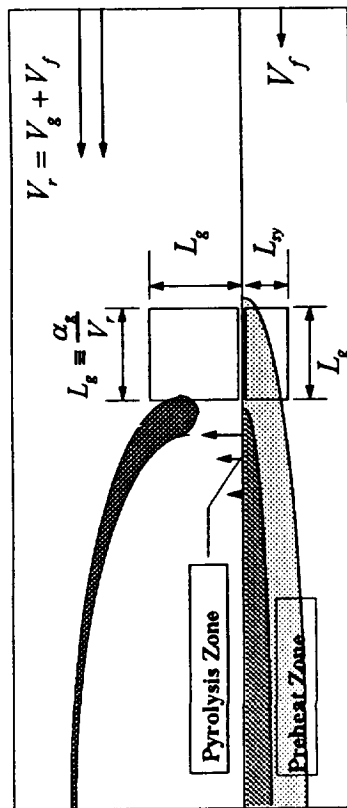


Figure 2 Schematic of the flame with a control volume at the leading edge showing various length scales.

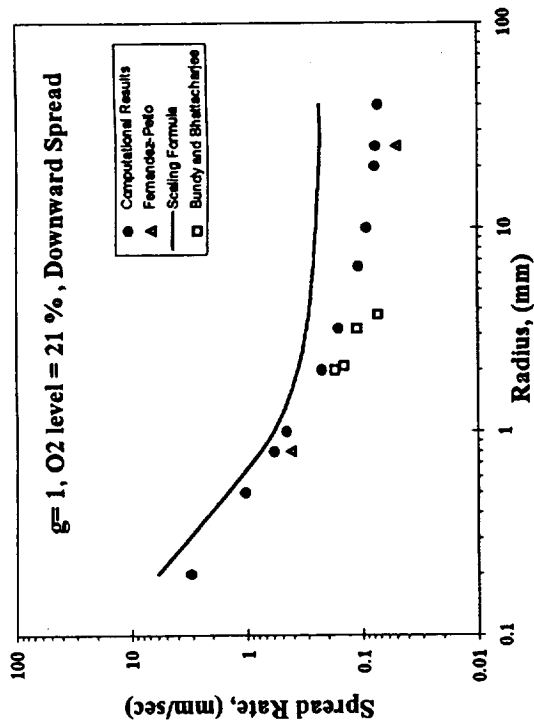


Figure 3 Comparison of computational, experimental, and scaling results for downward spread over cylindrical fuels under atmospheric conditions.

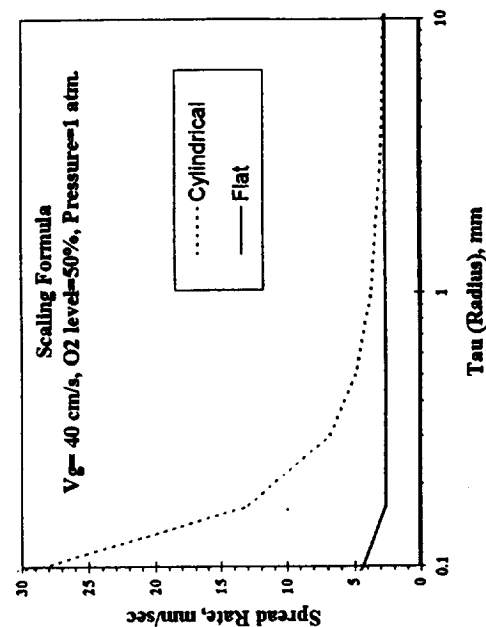


Figure 5 Spread rates predicted from scaling in the thermal regime.

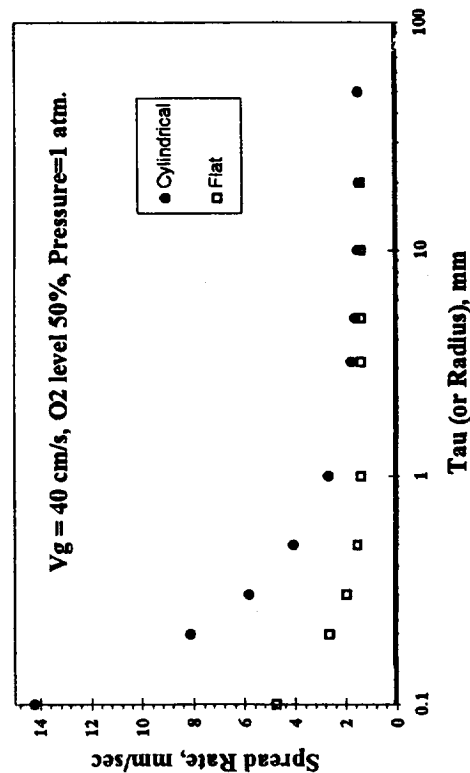


Figure 4 Computational spread rates for spread over flat and cylindrical fuels in the thermal regime.

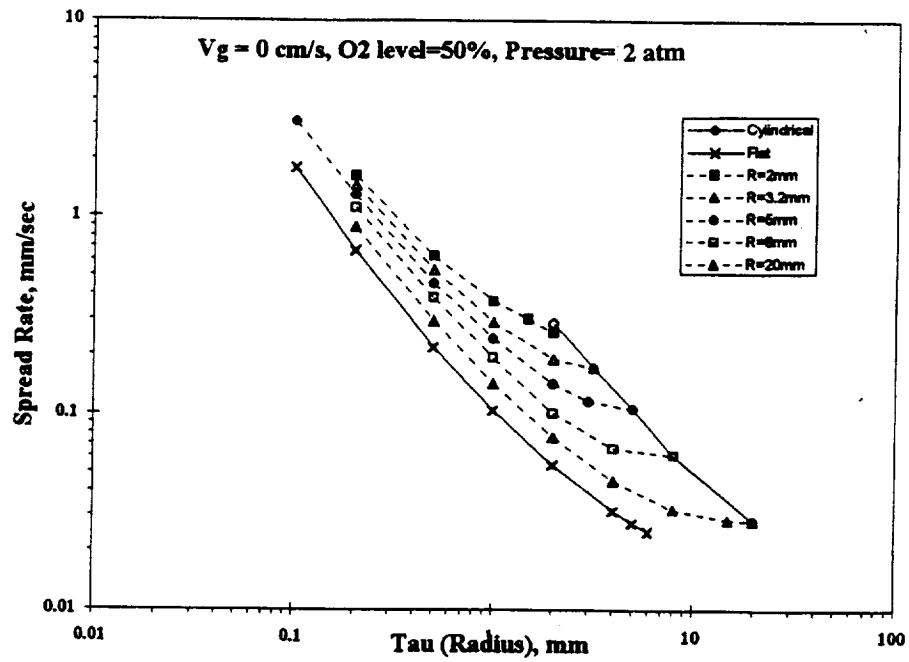


Figure 6 Computed spread rates over cylindrical and flat surfaces in a quiescent microgravity environment. For "large" thickness no steady-state solutions are found. Radiation is not computed for each configuration but is frozen for one and impressed on the others.

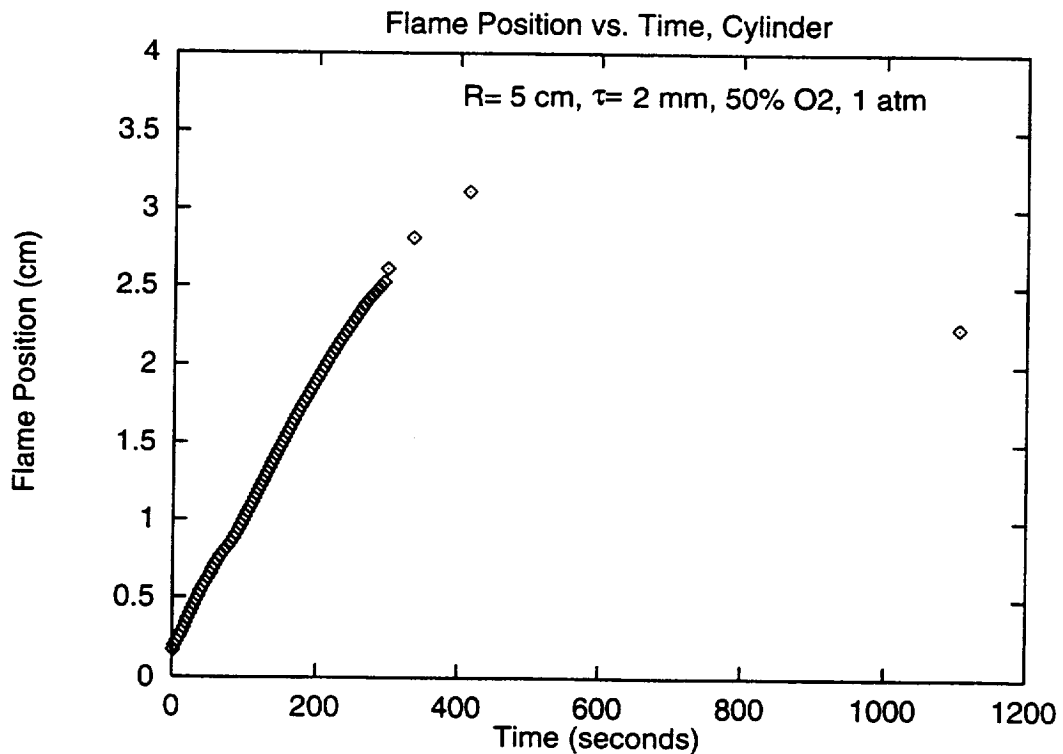


Figure 7 Computed flame position as a function of time for a "thick" cylinder with radiation computed as part of the solution as opposed to being impressed on the conditions as are the frozen radiation computations of Figure 6.