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Imposed Radiation Effects on Flame Spread over Black PMMA in Low Gravity

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Summary

The objective of this work is to determine the effect of varying imposed radiation levels on the flame spread and burning characteristics of PMMA in low gravity. The NASA Learjet is used for these experiments; it provides an environment of 10^{-2}g's for approximately 20 seconds. Flame spread rates are found to increase non-linearly with increased external radiant flux over the range studied. This range of imposed flux values is believed to be sufficient to compensate for the radiative loss from the flame and the surface.

Background

The importance of radiation on the flame spread process over thermally-thick fuels in normal gravity was discussed by de Ris [1], who derived an explicit expression for the flame spread rate as a function of ambient gas flow and gas-phase radiation. If radiation is negligible, then flame spread rates over thick fuels vary linearly with opposed flow velocity. The relation is not linear if radiation is important. Experiments of burning PMMA in normal gravity [2] at high opposed flow velocities found, away from blowoff, that approximately $V_f \propto V_g^{0.6}$ for 50% O_2 where V_f is flame spread rate and V_g is gas-phase velocity. Detailed numerical models [3] with surface radiative loss predict that the effect of radiation on flame spread over thick fuels is important regardless of the level of the opposing velocity, and that the ratio of radiation to conduction is of unit order throughout the range of flows.

In this work, low gravity experiments were conducted with imposed radiant heating of the solid fuel surface to examine the effects of radiation in low gravity. These are the first attempts at such experimental control and measurement in low gravity. Further experiments are planned on a NASA sounding rocket as part of an experimental program called DARTFire to study diffusive and radiative transport in flames in low gravity.

Hardware Description:

The NASA Lewis Learjet [4], which provides up to six low gravity trajectories per flight, was used to perform these tests. Each low gravity trajectory is approximately 20 seconds long. Two experimental racks were mounted within this aircraft, and the experiments were conducted by one or two on-board researchers.

The experiments were conducted in a 0.039 m³ chamber with two viewports. The sample was mounted in the center of the chamber to avoid conductive losses to the walls. The PMMA sample was insulated with Fiberfrax to minimize heat losses to the metal holder. The black PMMA sample was 2 cm long, 0.635 cm wide, and 2 cm deep. The sample was oriented vertically in the aircraft so that during normal gravity and elevated gravity, the flame spread is "downward", that is, in the direction of the gravitational vector. The atmosphere for all tests was 50% O_2 in N_2 at 1 atmosphere pressure.

The output of a laser diode at 810 nm was optically conditioned to provide a uniform flux set between 0-2 W/cm² ±6% over the entire surface of the sample. The laser performance was verified through a low-gravity calibration test to ensure that cooling in low gravity was sufficient to maintain diode performance.

Levels of flux were selected to globally offset the surface and gas-phase radiative losses The surface radiative loss was estimated to be 1 W/cm² based upon a measured fuel surface temperatures of 363 °C [5]. That value was doubled to estimate the imposed flux needed to offset the combined radiative losses based on the results of Bhattacharjee et al. [6], who showed the effect of gas-phase and surface radiative losses on flame spread rates were comparable.

A hot wire ignitor (28 W) was activated for 2 seconds to initiate flame spread in low gravity during the first trajectory. Based upon solid-phase length scales of 0.5 mm, and gas-phase residence times of no more than 2 seconds, stable flame spread uninfluenced by the ignition should be obtainable in the short trajectory. The sample was allowed to burn throughout the first trajectory, a high gravity recovery, and then a second trajectory. The laser was activated just prior to ignition during the low gravity portions of the test, but turned off during the high gravity recovery period between trajectories. By the second trajectory, the flame had stabilized over the entire surface of the PMMA and a stabilized flame in low gravity was studied.

A 16 mm color film camera recorded the side view of the flame spread process and subsequent stable flame. The top viewport was used to accommodate both the laser diode system and a spot radiometer imaging a 3-5 mm diameter spot in the center of the PMMA sample.

The radiometer was equipped with an 8-12 micron bandpass filter and calibrated with a black body to provide non-intrusive surface temperature measurements.[7] The radiometer's bandwidth was selected to be 8-14 microns so that most of the gas-phase species would be excluded from the reading. Soot and gas-phase vapors do contribute if present, but the energy carried in this bandwidth for expected flame temperatures of approximately 1500-1800 K is a small fraction of the emissive power emitted by the fuel surface. A surface mounted thermocouple (type K, 0.0076 cm diameter, 1.5 mm from the ignitor, along the centerline of the sample) was also utilized to confirm the validity of the radiometric measurement. Measurement error is estimated to be within 10 °C.

Flame Appearance

The flame under no external flux was a dim uniform blue with a very thin red (sooty) inner layer. Flame standoff distance was higher (2-3 mm) than normal gravity flames (1 mm). With 0.5 W/cm^2 imposed flux, the flame is all blue and dimmer. This was surprising because the radiant flux was expected to strengthen the flame.

When an external flux of 1 W/cm^2 was imposed, the flame developed a yellow region, and the luminous thickness of the flame increased. The yellow flame developed spurting flamelets believed to be associated with localized fuel vapor bubble ruptures on the pyrolyzing fuel surface. The flame became even more luminous, agitated, and thicker with 1.8 W/cm^2 flux. The fuel blowing and bubbling at the high incident flux, as evidenced by the increased frequency of the spurting flamelets, appear to be dominating the gas-phase fluid motions in the flame region despite g perturbations of 10^{-2} g. These g perturbations were estimated to produce local flow velocities on the order of 10 cm/s via the $g^{1/3}$ dependence [8].

Flame Spread With An Imposed Radiative Flux

Figure 1 plots the position-versus- time histories of the flame under 0, 0.5, 0.97, and 1.8 W/cm^2 external flux. Measurements began after the leading edge of the flame reached a steady-state configuration after ignition (a few seconds). The flame was typically a few mm from the ignitor at this point. The leading edge progresses steadily in low gravity. The slope of the curve is the spread rate. There is a rapid increase in spread rate as the acceleration level increases starting at relative times of approximately 18 seconds. During the pullout, the flame is exposed to gravity levels between 1.5 and 2 g's. Pullout spread rates are measured starting a few seconds after the pullout begins, to allow for transition.

The measured low gravity flame spread rates are included in the Figure 1 legend. The spread rate measurements are believed to be accurate to within 2% based upon repeatability of the no flux case. Care was taken to measure spread rates during portions of the trajectory that were free of large acceleration perturbations. These spread rates are plotted in Figure 2 as a function of radiant flux.

Spread rates increase nonlinearly as radiant flux increases in low g and during the high gravity pullout at the end of the low g trajectory even though the laser was deactivated at the end of the low gravity trajectory due to the elevated surface temperatures.

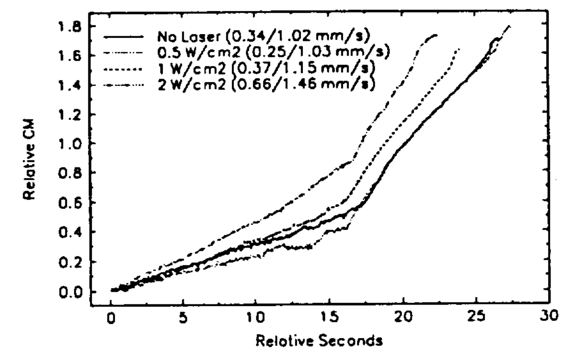

Figure 1 Flame position as a function of time during both the low gravity and pullout portions of the test.

Fuel preheating effects will be discussed later. The normal gravity flame spread rate measured in [2] is plotted in Figure 2 and agrees well with the pullout data for no radiative flux. This is due to the $g^{1/3}$ dependence [8] of buoyant flow, so that the increase in flow is only 20%. The data from [2] indicates that spread rates change little for these small changes in flow.

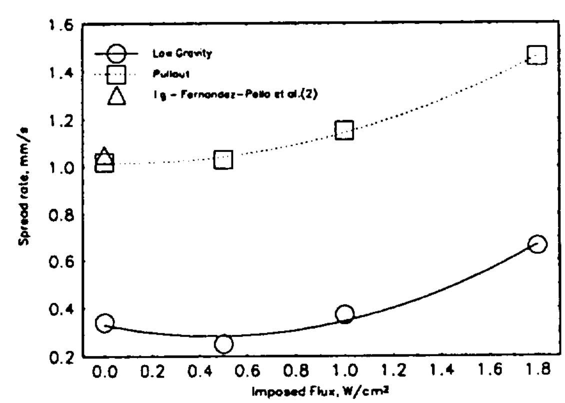

Figure 2 Measured spread rates for the low gravity and pullout portions of the tests.

It is surprising that the lower levels of imposed flux (0.5-1 W/cm^2) have so little effect on the flame spread rate. It is only at the highest flux levels (where radiative losses are believed to be fully countered) that we see an appreciable effect of the imposed flux on the flame spread, and here the spread rate agrees favorably with the extrapolated normal gravity value (0.66 mm/s vs 0.6 mm/s at 10 cm/s flow[2]).

Spot Radiometer Measurements

Since the spot radiometer was centered on the sample, typically the flame did not reach the spot within the first trajectory. Therefore, the radiometric data from the first trajectory can be used as an indication of the fuel heating due solely to the imposed radiant flux.

Figure 3 plots average heating rate read by the radiometer during the first trajectory prior to the approach of the flame. These heating rates are approximately 0.3, 2.0, 3.2, and 5.3 °K/second for laser power inputs of 0, 0.5, 0.97, and 1.8 W/cm².

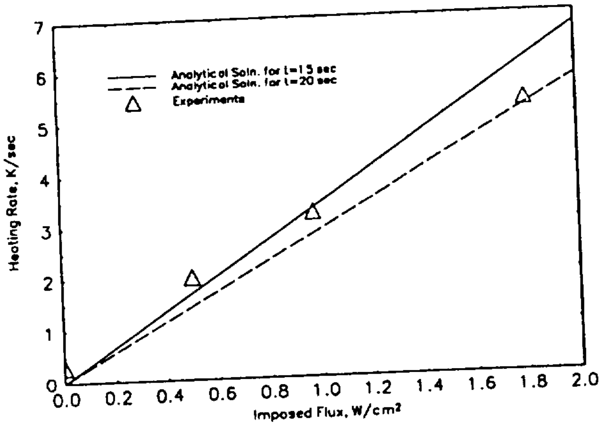

Figure 3 Comparison of radiometrically measured surface heating rates to theoretical heating rates at 15 and 20 seconds.

These rates were derived from the slopes of the blackbody temperature-time lines shown in Figure 4 after ignition. The rates of surface temperature increase also agree well with calculated heating rates shown for 15 and 20 seconds using the solution to the unsteady solid-phase conduction problems with an imposed surface flux [9]. This analytical solution for the surface temperature is

$$T_{surface} = \frac{R_i\, t}{\rho c\, l} + \frac{R_i\, l}{k}\left[\frac{1}{3} - \frac{2}{\pi^2}\sum_{n=1}^{\infty}\frac{(-1)^n}{n^2}\cos(n\pi)e^{\frac{-\alpha n^2\pi^2 t}{l^2}}\right]$$

where $T_{surface}$ is in K, R_i is the imposed radiant flux in W/cm², t is time in seconds and l is thickness of the slab in cm.

Figure 4 shows the actual radiometer effective black body data for each test. The bump in the temperature at six seconds corresponds to ignition. The ignition ball is typically large and sooty, so the 20 °C bump is believed to be due to the transient presence of hot gas-phase soot passing through the radiometer field of view. The first trajectory occurs from 5-25 seconds, and it is the slope of this data that provides the heating rate. The laser is deactivated at the end of the low g trajectory. The readings quickly rise after approximately 25 seconds, when the flame reaches the spot on the surface the radiometer is viewing. The black body temperatures reach a nearly steady level during the pullout and pullup into the 2nd trajectory. The second trajectory starts at approximately 60 seconds. The laser is then re-activated. Blackbody temperatures reach steady-state quickly during the second trajectory. Readings for no laser flux are nominally 395 °C, whereas for the 0.5, 0.97 and 1.8 W/cm² fluxes the blackbody temperatures read 385 °C, 410 °C and 423 °C, respectively. Contributions from soot and vapors are estimated to be no more than 10 °C for the steady flame, so there is a clear increase in fuel surface temperatures with increasing imposed flux.

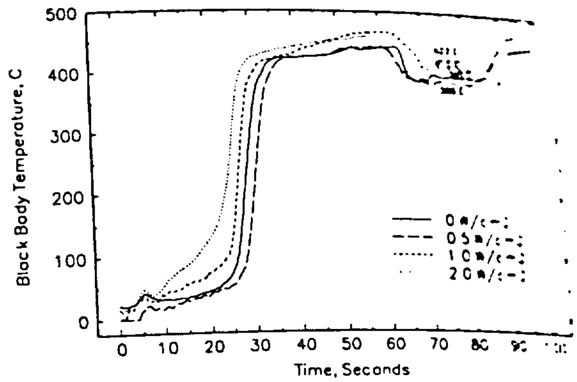

Figure 4 Radiometer readings during entire flight for each flux level with two low gravity trajectories. The first trajectory starts at approximately time=0, the second starts at time=60 seconds.

Comparison of Radiometer with Surface Thermocouple

A surface thermocouple trace is shown in Figure 5 with the radiometer signal for a direct comparison between a surface thermocouple reading and the spot radiometer reading. The surface thermocouple was located 1.5 mm from the ignitor wire so the flame would pass over the sample within the short trajectory.

The surface thermocouple senses the approach of the flame during the first trajectory and heats up to a nearly constant surface temperature of around 400 C prior to the end of the trajectory, which occurs at approximately 21 seconds. Although not shown, the temperature stabilizes in the pullout to 440 °C, in agreement with the radiometric data during the pullout. The radiometer looks at the surface of the fuel after the flame has stabilized over the surface, and enters low gravity. As the flame enters low gravity during the second trajectory the radiometric reading drops about 50 °C. The steady low g reading of 395 °C agrees well with the thermocouple reading of 400 °C.

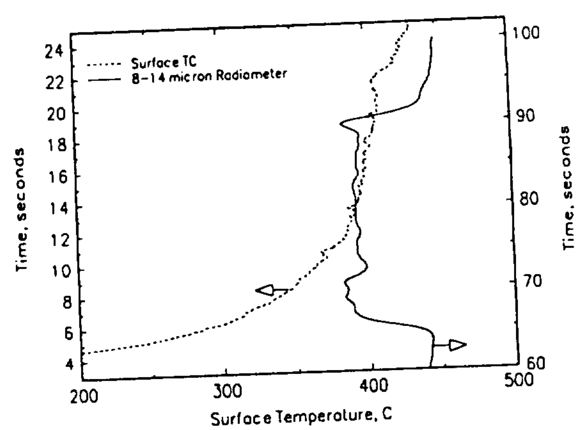

Figure 5 Comparison between thermocouple reading and radiometer reading for in imposed flux..

Discussion

Flame spread controlling mechanisms in low gravity have been attributed to radiative loss from the flame and surface [6], or oxidizer mass transport limitations in the absence of convection [8], or really a combination of both. With the imposition of external flux values sufficient to compensate for the combined radiative losses from the flame and the surface, spread rates comparable to extrapolated normal gravity spread rates are recovered. Weaker levels of imposed flux (ie 0.5-1 W/cm^{2}) appear to have a little to no effect on the flame spread. This was unexpected and is currently not understood.

Previous studies of external radiant effects on flame spread in normal gravity air observed that downward flame spread rates over PMMA are a power law function of the temperature difference between fuel pyrolysis temperature and fuel temperature prior to the arrival of the flame spreading in air [5]. As shown in Figure 6, the pullout flame spread data does have a similar dependence with temperature differences varying from 280-380 °C (since this data is for 50% O_2, spread rates are higher than air). The low gravity data shows a strong variation in

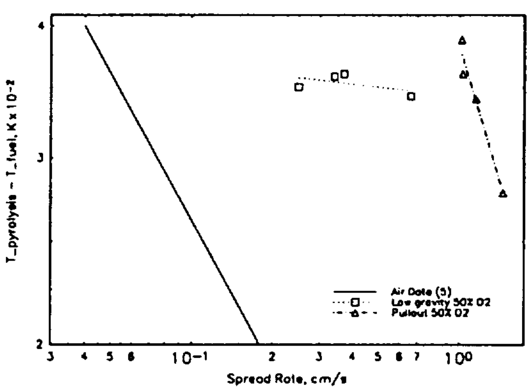

Figure 6 Power law relationship between flame spread rate and ($T_{pyrolysis}$ - T_{fuel}). Slopes of air data [5] and pullout data are qualitatively similar, but low gravity data do not correlate.

spread rate with fuel preheating, but the range of temperature differences is smaller - 335-360 °C. The slope of this data is very different, for as-yet undetermined reasons.

Physical effects of the external radiant flux are evident in the flame appearance. The fuel blowing velocity is increased as evidenced by 1) the increased sputtering of sub-surface bubbles during pyrolysis and 2) the increased fuel surface temperatures with imposed flux. The radiometric data indicates that the fuel surface pyrolysis temperatures are increasing with increasing flux. For Arrhenius kinetics, fuel pyrolysis rates increase exponentially with surface temperature, so a small increase in pyrolysis temperatures corresponds to large increases in fuel pyrolysis rates.

The sputtering effect characteristic of normal gravity PMMA pyrolysis is largely absent in low gravity with no imposed flux. At the highest flux levels in low gravity, however, sputtering is so dramatic that it appears to induce flows on the order of those from the estimated g perturbations of the aircraft, (i.e. 10 cm/s). This increased and non-uniform blowing must affect the ambient flow environment and the fuel/oxidizer mixing, but what role this has in the flame spread process is not clear. A dramatic case of this type of non-uniform burning was observed aboard Skylab [10], where a piece of nylon burned unexpectedly for more than 10 minutes in a completely quiescent environment prior to extinguishment by venting to vacuum.

In summary, these preliminary results provide some insight and have produced many new questions regarding the effect of radiation on flame spread in low gravity. It is recognized that the data is quite limited, and more tests are needed to verify these trends and help explain some of the questions raised by these results.

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