

Diffusive and Radiative Transport in Fires Experiment: DARTFire¹

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Introduction

The physics of opposed-flow flame spread over solid fuels is reasonably well understood for the situation in which the incoming flow speed is much greater than the flame spread rate. The propagation process is dominated by forward conduction heat transfer, either through the gas or solid, and the gas-phase kinetics (ref. 1-3). The characteristics of the spread process can generally be divided into a thermal regime, i.e., a regime in which gas-phase kinetics can be considered infinitely-fast, the spread rate being dictated by conduction heat transfer, and a kinetic regime in which gas-phase chemical kinetics is important. For thin fuels in the thermal regime, the spread rate is independent of flow speed while for thick fuels it is proportional to the flow speed (ref. 1). In the kinetic regime, increases in flow speed cause a reduction in spread rate that eventually leads to flame extinction through flame blowoff (ref. 1-4).

Reductions of flow velocity in the thermal regime are limited by the flow induced by the Earth's buoyancy, on the order of several 10's of cm/s. In a microgravity environment, however, slower flows may be obtained, and the spread process enters into a new regime, the microgravity regime (ref. 5). The diffusional length scale in the gas, L_g , is approximately the thermal diffusivity of the gas divided by the incoming flow speed. Reductions in flow speed tend to increase this diffusional length, which increases the size of the flame and hence increases the importance of radiation. Qualitatively, the ratios of radiation loss from the flame, R_g , and radiation loss from the fuel surface, R_s , to conduction from the gas to the solid are (ref. 6):

$$R_g = \frac{4a_p \sigma}{\lambda_g} \left(\frac{T_f^4 - T_{env}^4}{T_f - T_v} \right) L_g^2; \quad R_s = \frac{\epsilon \sigma}{\lambda_g} \left(\frac{T_v^4 - T_{env}^4}{T_f - T_v} \right) L_g \quad (1)$$

and so the increase in L_g with a reduction in opposing flow speed results in an increase of the above ratios. For the speeds that may be encountered in a microgravity environment, the ratios are such that radiative phenomena are important. In Eq. (1), a_p is a Planck mean absorption coefficient, λ_g is the thermal conductivity of the gas, T_f and T_v are the flame and vaporization temperature, and T_{env} is a radiative environment temperature.

Recent results from the Solid Surface Combustion Experiment indicate that while for thin fuels radiation in a quiescent environment is important, and it causes a reduction in steady flame spread rates compared to the Earth-bound environment, for thick fuels, there appears to be no steady-state spread process in a quiescent environment (refs. 5,6). For thick fuels the possibility exists that, absent an opposing flow of sufficient strength to press the flame close enough to the fuel surface to allow the heated layer in the solid to develop, the heated layer fails to become "fully developed." The result is that the flame slows, and, because the incoming flow speed to the flame is the spread rate, there is an increase in the relative radiative loss from the flame, leading eventually to extinction. This potential inability of a thick fuel to develop a steady spread rate is not present for a thin fuel because the heated layer is the fuel thickness, which reaches a uniform temperature across the thickness relatively rapidly.

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The objectives of the DARTFire experiment are to investigate the transition from ignition to either flame propagation or extinction in order to determine the characteristics of those environments that lead to flame evolution. In addition, flame shapes and measured gas-phase field variables, spread rates, radiative characteristics, and solid-phase regression rates are compared with model prediction. Thick PMMA is the fuel, which is subjected to a low speed forced flow in the microgravity environment of a sounding rocket flight while certain of the fuel samples are subjected to a laser flux in order to control the radiative environment of the flames. It is the interplay of the radiative and diffusional processes that determine if the flames spread at a steady rate or if they evolve to extinction in low velocity flows. The low speed threshold below which steady spread would appear not to be possible may be delineated in the course of the experiments.

Experimental

DARTFire sounding rocket hardware is shown in Figure 1. The flow supply system accounts for the first (left) third of the 10 foot overall length. The twin flow tunnels and diagnostics take up the middle third, and the electronics the last (right) third. Two experiments are conducted simultaneously during the approximately 6 minute experiment.

The mirror twin flow tunnels support from 1-20 cm/s flow through each tunnel with 10 cm x 10 cm flow crosssection. Black PMMA samples, 2 cm long x 2 cm thick x 0.635 cm wide, are mounted in the floor of the duct 4 cm from the inlet flow straighteners.

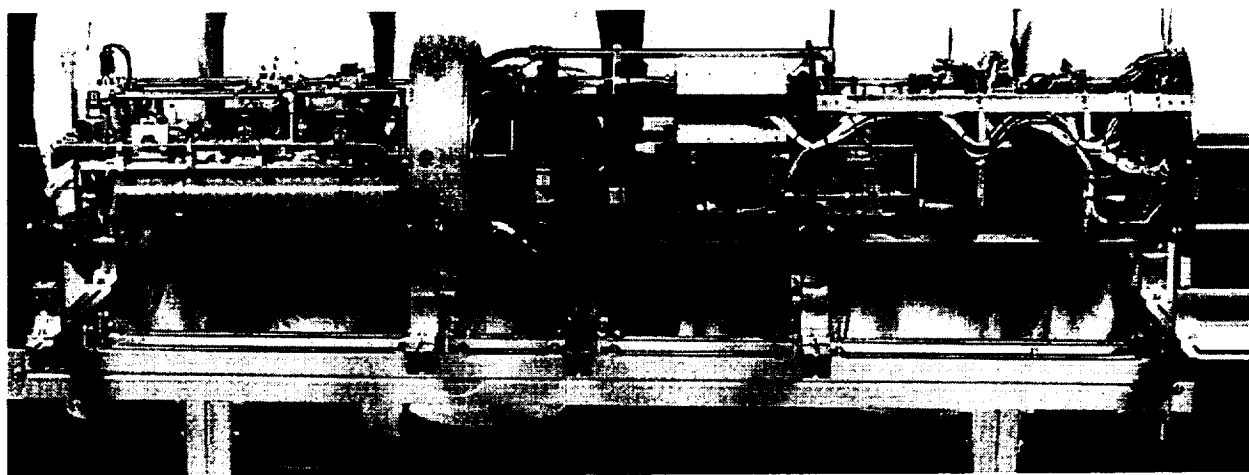


Figure 1. DARTFire sounding rocket hardware mounted on support rack. During launch, thick metal skins cover the payload.

A laser diode and associated lenses are mounted in the ceiling of one of the two ducts to provide an external radiant flux of up to 2 W/cm² onto the sample surface. The controlled external radiant flux allows the surface energy balance to be adjusted to compensate for radiant loss from the surface and gaseous species. The walls of the tunnels have windows for ultraviolet-visible and infrared imaging of the flame. These two primary diagnostic cameras are discussed below.

Other diagnostics include spot radiometers with a 6 mm diameter field of view to image the surface and gas-phase emissions over the spectral wavelength range of 8-14 μ m. A total of 6 gas-phase type R and solid-phase type K thermocouples are used to record flame temperatures, surface pyrolysis temperatures, and in-depth temperatures from each sample during the experiment.

The test matrix is shown in Table 1. For those experiments in which there was a laser flux, the sample was ignited with the laser on, the laser was turned off following spread to the middle of the sample, and then the laser was turned back on toward the end of the spread process. Measured spread rates, and spread rates computed from the modelling effort described below, are also shown. Three flights have been conducted to date. A fourth flight is being requested for later this year with the conditions of 70% O₂, either 1 or 5 cm/s flow, with no laser flux, and 50% O₂ at 1 cm/s with a laser flux of 1 W/cm² but with the ordering of when the flame is subjected to the laser irradiation reversed from previous flights, i.e., the flame will initially spread with the laser off, and when the flame is approximately half-way along the sample, the laser would then be turned on.

UV-Visible Imaging

A multispectral intensified array video camera is used to image the flame. This has increased sensitivity over film and therefore can enable direct visualization of radical species by incorporating appropriate filters. Color images are obtained by combining red, green, and blue filtered images to obtain a 24-bit color composite image of the flame as part of the post-mission image

Table 1

Flight Tunnel	Molar Oxygen Concentration, %	Bulk Flow Velocity, cm/s	Imposed Radiant Flux, W/cm ²	Meas V_f , mm/s Laser on/off	Model V_f , mm/s Laser on/off
1A	35	1	1	no ignition	
1B	50	1	0	- / 0.20	- / 0.10
2A	50	1	1	0.19/ 0.10	0.27/ 0.10
2B	50	5	0	- / 0.32	- / 0.31
3A	50	1	2	0.33/ 0.20	0.48/ 0.12
3B	50	10	0	- / 0.45	- / 0.47
4A (proposed)	50	1	1		
4B (proposed)	70	1 or 5	0		

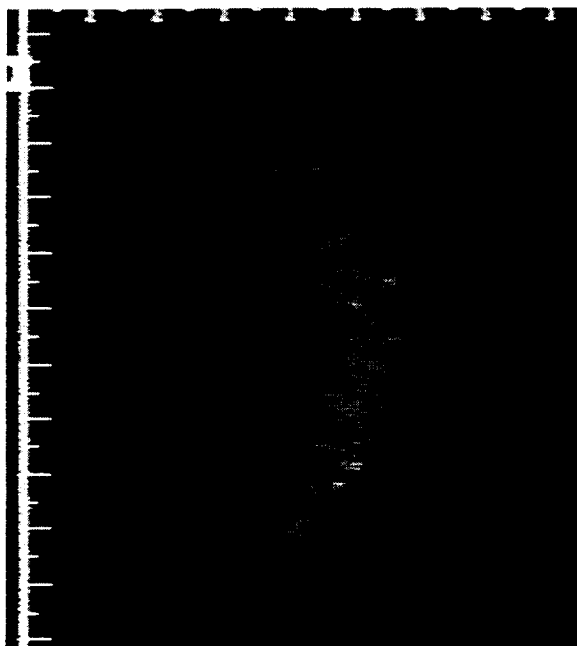


Figure 2a: Reconstructed color image of flame from test 2A. Ticks are 0.5 mm.

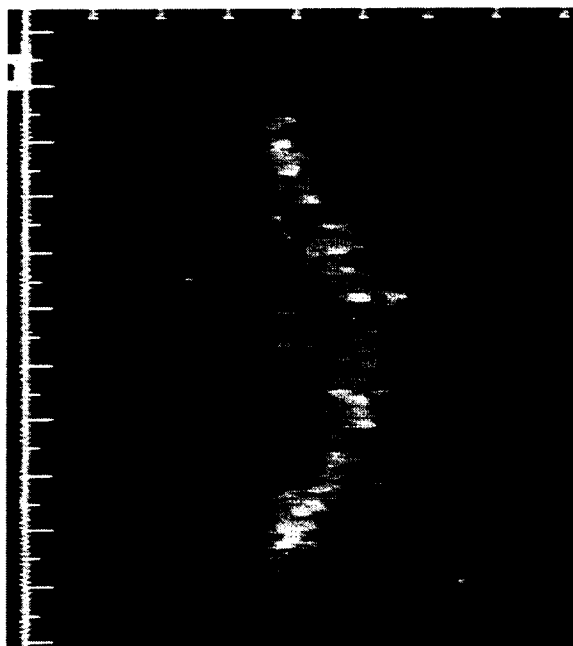


Figure 2b: OH chemiluminescent image from same time as color image. Ticks are 0.5 mm.

processing. An example of this is shown in Figure 2a. The chemiluminescence of OH and CH radicals in the reaction zone is imaged through 20 nm bandwidth OH and CH filters at 310 nm and 430 nm, as shown in Figure 2b. The camera utilizes peak mode to avoid saturation of the bright flames against the dark background, and it optimizes exposure time for each filter image independently.

Infrared Imaging

Infrared emission from the gaseous combustion products is also monitored during the DARTFire experiment. A multispectral PtSi detector camera (Inframetrics, Inc. Model Infra-Cam PtSi FPA (256x256 pixel array)) was modified to include a 6-filter internal wheel. Filters include $1.87\mu\text{m}$ (H_2O), 2.7 and $4.3\mu\text{m}$ (CO_2), $3.4\mu\text{m}$ (MMA vapor), $4.8\mu\text{m}$ (CO), and soot at $1.6\mu\text{m}$ where the gas is "clear." Infrared imaging has provided an immense quantity of data regarding the species fields in the experiment. CO_2 and H_2O images are shown in Figure 4. Blackbody calibration of each filter provides an effective blackbody temperature for each video grey level.

Data Treatment

The side-view of the flame as it spreads across the fuel is captured by the infrared video camera. The rotating filter wheel with six filters having different bandwidths (two for CO_2 bands, one for H_2O band, one for MMA band, one for soot and one for total radiation) in front of the camera lens produces alternating frames of six different kinds. The video data are digitized frame by frame, and the frames are sorted and reassembled according to the filter numbers resulting in six separate digital video images of the flame.

Now consider two images at two different bands, I_1 and I_2 , taken within one rotation of the filter wheel. The maximum time gap between these frames can be about 0.01 s (the wheel rotates at 60 Hz). The flame spread rate being on the order of 0.1 to 1.0 mm/s , the maximum displacement is about 0.01 mm between two images, which is insignificant. Suppose the signal recorded at a particular point in the flame is s_1 and s_2 corresponding to the bands I_1 and I_2 of CO_2 . Using the calibration curve of the camera and filter transmittance, the ratio of the band intensities i_1 / i_2 can be obtained from s_1 and s_2 .

In terms of bandwidth A_1 and A_2 (ref. 7), $i_{b1} / i_{b2} = A_2 i_1 / A_1 i_2$, which can be solved for temperature if A_1 and A_2 are known. From a representative theoretical flame, A_1 and A_2 can be obtained using a narrow-band radiation program such as RADCAL (ref. 8). The temperature calculated from the blackbody intensity ratio can be used to refine the calculation of A_1 and A_2 . The final temperature though will be a function of CO_2 concentration of the theoretical flame.

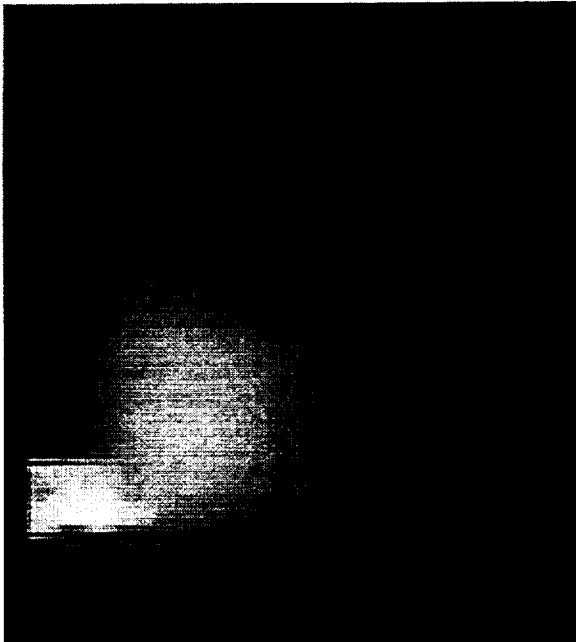


Figure 3a: $1.87\mu\text{m}$ band H_2O image from test 2A. Approximately same time and scale as Fig. 3.

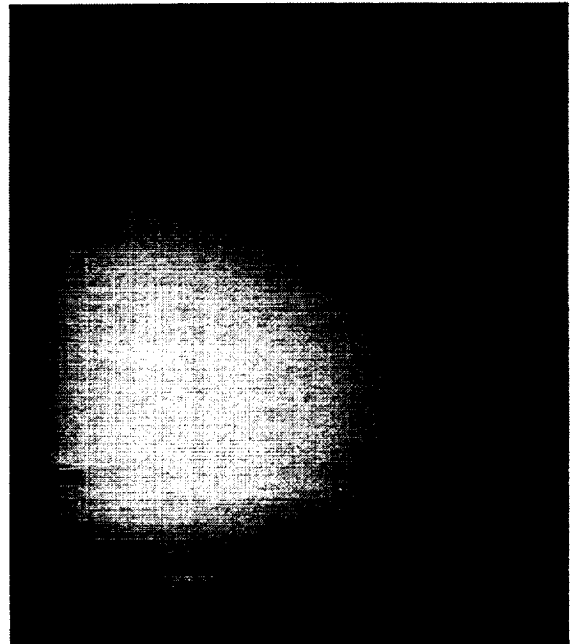


Figure 3b: $4.3\mu\text{m}$ band CO_2 image from test 2A. Approximately same time and scale as Fig. 3.

A check on the theoretical prediction of the CO_2 concentration can be made by utilizing the surface temperature measurements. At a point on the fuel surface, A_2 / A_1 can be evaluated experimentally from the blackbody intensity ratio, because the temperature and the intensity ratios are both known. For a given temperature RADCAL can accurately predict the concentration of CO_2 from the value of A_2 / A_1 .

Image data for OH and CH from the Xybion camera may be used to infer relative OH distributions and flame location (ref. 9). Ultimate comparison to computed flame position and structure requires a more detailed model of the gas-phase combustion chemistry in which intermediates such as OH are computationally tracked (refs. 9,10).

Modelling

The mathematical formulation for the forced, opposing flow configuration is patterned after earlier formulations (refs. 5,11). The numerical solution employs the finite-volume formulation of Patankar (ref. 12) for the hydrodynamic calculations and the TTNH formulation of Grosshandler (ref. 8) for line-of-sight radiation calculations with the species, CO_2 , H_2O , and MMA vapor. The computational code has been validated by comparing the numerical result with analytical solutions available for simpler models. Both steady and unsteady versions of the numerical code are available, but for the results reported here, only the unsteady version was used.

Spread Rate Results

Spread rates increase with increasing flow speed, both experimentally and computationally, and the modelling predicts relatively well the dependence of spread rate on incoming oxidizer flow velocity. The laser flux increases the spread rate, consistent with previous observations for downward spread at normal gravity (ref. 13). For the fuel that is preheated with the laser prior to flame arrival, when the laser is turned off, the spread rate decreases, but to a value higher than what it is under identical flow conditions without preheating. The effect of the laser preheating appears to be to increase the fuel temperature near the surface in the solid, which results in the increased spread rate (ref. 13). The experimental spread rate reported for experiment 1B appears to be higher than expected, i.e., it is equivalent to the spread rate for the same flow conditions but with a laser flux of 1 W/cm^2 from experiment 2A, although it might be expected to be slightly less than the result from experiment 2A with the laser off consistent with modelling results. The proposed flight matrix point was selected in part to investigate the repeatability of the experiments, particularly at the 1 cm/s flow speed, so as to determine the veracity of the spread rate measurement in experiment 1B.

In previous opposed-flow results for spread over PMMA (ref. 3) in an Earth-bound apparatus, three flame spread regimes were identified, one at "low flow velocities" in which the spread rate is independent of opposing flow, low velocity here being approximately below 90 cm/s for $50\% \text{ O}_2$, a regime in which the spread rate is proportional to the flow speed to a power, the thermal regime, and one in which the spread rate decreases with increasing flow speed until blowoff occurs. The low velocity regime occurs because of the influence of buoyancy induced flow, absent in the DARTFire experiment so that the thermal regime may be extended to lower flow velocities. In the thermal regime, the dependence of spread rate on incoming flow speed, U_∞ , is, from ref. 3, approximately $V_f \propto U_\infty^{0.43}$, above about 90 cm/s up to where the kinetic regime appears at about 450 cm/s . This dependence from the experimental and computational results in Table 1, excluding experiment 1B, persists down to an opposing flow speed of about 5 cm/s , at which point the dependence of V_f on U_∞ increases to about $V_f \propto U_\infty^{0.62}$. The change in the dependence signals the onset of radiative processes, which as the flow speed is reduced further, eventually lead to the unsteady spread behavior that leads to extinction observed in quiescent, microgravity flame spread experiments.

The unsteadiness and ultimate spread to extinction is, as mentioned above, due to the effects of radiation. Increased radiation causes the flame to shrink in size, the flame finds itself in a region of decreasing presence of oxygen, and the distance through which oxygen must diffuse to reach the flame, being unaffected by radiation, grows in time until eventually the oxygen supply to the flame is insufficient to sustain it, and the flame extinguishes. Transition from the classical thermal regime of flame spread over thick PMMA for $50\% \text{ O}_2$ to the microgravity regime in which radiation is important and will lead to extinction in a quiescent environment appears to occur for flows on the order of 5 cm/s . This threshold opposing flow should be a function of oxygen concentration.

Summary

A low velocity, opposed-flow, flame spread experiment designed for execution on a sounding rocket has been described. Early results of infrared and ultraviolet-visible imaging using video cameras and narrow band filters have been described along with planned digital image data reduction. Measured and computed spread rates show that the classical thermal regime for flame spread over thick PMMA persists, for 50% O₂, down to about 5 cm/s, at which point a transition to a microgravity regime in which radiation eventually leads to extinction in at least a quiescent environment. The microgravity regime of flame spread is then distinct from the thermal and kinetic regimes previously identified.

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