COMBUSTION OF SOLID FUEL IN VERY LOW SPEED OXYGEN STREAMS

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1. Introduction

In reduced gravity, the combustion of solid fuel in low-speed flow can be studied. The flame behavior in this low-speed regime will fill a void in our understanding of the flow effect on combustion. In addition, it is important for spacecraft fire safety considerations. In this work, modeling and experimental work on low-speed forced-concurrent-flow flame spread are carried out. In addition, experiments on reduced-gravity buoyant-flow flame spread are performed.

2. Low Speed Forced Flow

2.1 Concurrent-Flow Flame Spread Model [1]

The model considers two-dimensional, steady flame spread in concurrent flow over a thin solid. Because of its thinness, the fuel bed can burn through. The flame could therefore reach a constant length provided that a . constant (and equal) flame tip velocity, pyrolysis front velocity, and fuel burnout rate, can be obtained in the low-speed concurrent flow environment.

The flame is assumed to be laminar because of its small size and low velocity. The gas-phase fluid mechanical treatment is more comprehensive than most works in the past. In the flame base region (where the upstream flow is seen first), streamwise heat and mass diffusion is included. This, together with finite-rate, gas-phase chemical kinetics, enables us to examine the question of flame stabilization and extinction. The elliptic treatment of this flame stabilization zone entails the full Navier-Stokes equations. On the other hand, to save computational time, a boundary layer approximation is employed in the downstream region. The two zones are coupled at an appropriate gas-phase location. They are also coupled indirectly through the solid by energy exchange. A simplified solid fuel model is used. The solid is assumed to be thermally thin and to pyrolyze according to a one-step Arrhenius law with no char and tar formation. A solid-surface radiative-loss term is included which becomes critically important in the low-speed flammability limit. Because of the coupling between elliptic and parabolic regions and between the gas and solid phases, the numerical solutions require many iterations and are computationally intensive; they are carried out using the Cray X-MP Supercomputer at the NASA Lewis Research Center.

Although the model has been formulated for a mixed forced and buoyant flow, extensive computations have been performed for purely forced flow only, using oxygen mole fraction and free-stream velocity as parameters. Fig. 1 gives all the points calculated and the extinction boundary. Some of the important results are summarized below.

- The extinction boundary consists of a quenching and a blowoff branch similar to those in stagnation-point flow [2] and in opposed-flow flame spreading [3]. The quenching limit is due to the surface radiative loss. Without radiative loss, the model predicts no low-speed limit. Fig. 2 shows the maximum computed flame temperatures. In all cases, the maximum temperature decreases with flow velocity, especially near the quench limit. The flame spread rate decreases monotonically with flow velocity, as expected (Fig.3).

- Flames quench at low speed by shrinking in size. Near-limit flames remain stabilized in the fuel burnout region, as shown in Fig. 4. This fixed stabilization is in contrast to flame blowoff at higher speed where the flame cannot be stabilized in the fuel burnout region. Extinction is reached when the flame is blown downstream. This illustrates one of the distinctions in flame extinguishment between quenching and blowoff. This difference becomes clear in a two-dimensional analysis but is obscure in one-dimensional stagnation-point flames. The reactivity contours shown in Fig. 4 resemble the visible blue flame seen in experiment (take $w=10^{-4}$ $g/cm^3/sec$ for example), which will be discussed in the next section.

Using finite-rate kinetics enables us to examine the integrated flux of fuel vapor crossing any vertical plane. Far downstream, the fuel-flux stops changing (because the reaction becomes frozen), providing a measure of fuel escaping the flame. The fraction of fuel not consummed in the flame increases dramatically at lower speeds because of the increased importance of flame-tip quenching. Additionally, the variation of escaped fuel vapor is not monotonic with flow velocity.

2.2 Forced Concurrent Flow Flame Spread Experiments [4]

Low-speed concurrent-forced-flow experiments were conducted at Lewis Research Center's 5-second drop tower using thin tissue paper Kimwipe) as the solid fuel. The relative flow was generated using a sample translation device in a total of twenty-seven drop tests. In these tests, the flow velocity was varied from less than 1 cm/s to 5 cm/s and the oxygen concentration in nitrogen (at normal atmospheric pressure) from 30% down to extinction. Color cine films were made of the flames.

While in most tests the leading edge of the fuel receded steadily as it was burnt following the ignition transient, the downstream flame tip propagation was unsteady. Flames grew in length (after the ignition transient) at higher oxygen concentrations and relative flow velocities, but shrunk at lower concentrations and velocities. In higher-speed flows, in normal gravity, flame length has always been observed to grow after ignition [5]. The shrinking flames observed in these microgravity tests could be quenching, but the slow evolution of the flame length in the 5 second test time did not allow enough time to observe their eventual fate. Alternatively, the small, slowly evolving flames may be indicative of near-steady configurations of flames in very-low-speed concurrent flows. Fig. 6 (the color photos are grouped together) shows a comparison of flames at approximately 5 cm/sec relative concurrent flow at three different oxygen concentrations. The shape of the 15% oxygen concentration case can also be compared favorably with the computed reaction contours (e.g. 10^{-4} $g/cm^3/sec$) shown in Fig. 4 for the same test condition.

The measured spread rates of the flame base, the leading edge of the fuel at which burnout occurs, are similar to the computed values shown in Fig. 3. However, spread rates at high oxygen concentrations and high relative-flow velocities are lower experimentally at the end of the drop while the rates at low oxygen concentrations and low relative-flow velocities are higher experimentally. These observations are consistent with the suggestion that the flames might not have had sufficient time to reach their final configuration in the available 5 seconds.

A flammability map, based upon the status of flames at the end of 5 seconds of microgravity, has been drawn and is similar to Fig. 1. No detailed comparison can be made because steady flames have not been achieved experimentally. It is clear that even for a thin fuel such as Kimwipes, which provide ample steady flamespread data in opposed-flow configurations, longer microgravity duration is needed to satisfactorily determine flame spread rates and extinction limits in concurrent flow.

3. Buoyant-Flow Flame Spread in Reduced-Gravity Experiments

Flame spread in buoyant flow under reduced-gravitational conditions has been observed using the NASA KC-135 aircraft flying parabolic trajectories at approximately 1/3rd, 1/6th, and 1/10th normal earth gravity levels. The test apparatus includes provisions for controlled ignition energy, color-schlieren flame imaging and three dimensional measurements of the local acceleration levels. Tests were conducted in O_2/N_2 mixtures from 18% oxygen down to extinction (of the same thin Kimwipe tissues used in our other tests) at normal and reduced pressures for upward (concurrent flow) flame propagation; and at normal pressure for downwaru (opposed flow) propagation.

3.1 Downward Flame Spread and Extinction

Schlieren images of flames spreading in buoyant, opposed flow showed steady propagation in oxygen concentrations below the normal-gravity flammability limit. At each oxygen concentration (18, 16, and 15% oxygen) spread rates decrease with increasing acceleration, though the difference between 1/10th g and 1/6th g is small. Tests conducted at 14% oxygen showed flame propagation at 1/10th g, and a blowoff extinction was observed during the aircraft pullout maneuver to approximately 2g. Flames at higher acceleration levels and 14% oxygen did not appear to survive the ignition transient. Fig. 5 shows a flammability map using acceleration level and normal-atmospheric-pressure oxygen concentration as parameters. The solid line gives the high-g blowoff boundary. The low-g extinction boundary, which cannot be determined accurately in the aircraft experiment, is indicated by the shaded curve. Fig. 7 shows schlieren images of the downward spreading flames at 15% oxygen at two reduced-gravity levels.

3.2 Upward Flame Spread

Schlieren images of flames spreading in buoyant, concurrent flows show propagation of flames down to normal-atmospheric-pressure oxygen concentrations of 12%, in both 1/6th and 1/3rd g. A single test at 1/10th g did not result in a propagating flame at 12% oxygen, while another at 14% did.

At normal atmospheric pressure, the upward spreading flames were characterized by thermal/flame plumes that become unsteady downstream of the flame stabilization zone. The tissue-paper fuel tended to curl, particularly in the normal pressure tests, disturbing the bottom of the flame. Fig. 8 a and b show two parts of an upward propagating flame at 15% oxygen in 1/6th g as they passed by the single schlieren window. In Fig. 8a, the unsteady/unstable plume is shown, while in Fig. 8b, the bottom of the flame is shown stabilized near the lowest point on the fuel surface.

Tests were conducted at reduced pressure and showed the existence of low-pressure limits. In the small number of tests conducted, the pressure limits were not determined with precision. At reduced pressure the flame plumes were more laminar and the fuel deformed more slowly during burning. Fig. 8c shows the downstream plume of a 15% oxygen, 0.5 atmosphere pressure flame at 1/6th g. Below, in Fig. 8d, the stabilized bottom of the same flame is shown.

4. Future Plans

Although surface radiative loss is included in the current model and has proven to be important in low-speed flows, gaseous radiation has been neglected. In stagnation point flow, gas radiation is found to alter the low-speed quenching limit for one-dimensional stationary flames. In concurrent flow gaseous radiation is likely to be more important because the flame is longer. Comparison with experiment also shows that without gas radiation the model overpredicts the flame length. The inclusion of gaseous radiation in the model is the logical next step and will complete our understanding of radiative effects on flame spreading over solid fuels in low speed flows. At the same time thermally-thick solid fuel needs to be treated in the theory (presently, we have dealt with thermally-thin fuel only). The new elements that need to be added will include solid-phase heat transfer, fuel geometry change and an unsteady flame growth process.

Experimentally we will also begin to test thicker fuels in low-speed flows. Because of the limitations of microgravity time in ground-based facilities, steady state is not expected, even were burnout possible. In order for the results to be useful, a controlled ignition process will be extended to thick fuels. The ignition transient experiments and related modeling will lead to a rational design of a space-based experiment required to obtain concurrent-flow flame spreading data in the very low-speed regime.

Because of the flammability limit data we have obtained for both low-speed forced flow and buoyant flow in reduced gravity, we also hope to contribute to the reevaluation of flammmability test methods for spacecraft materials.

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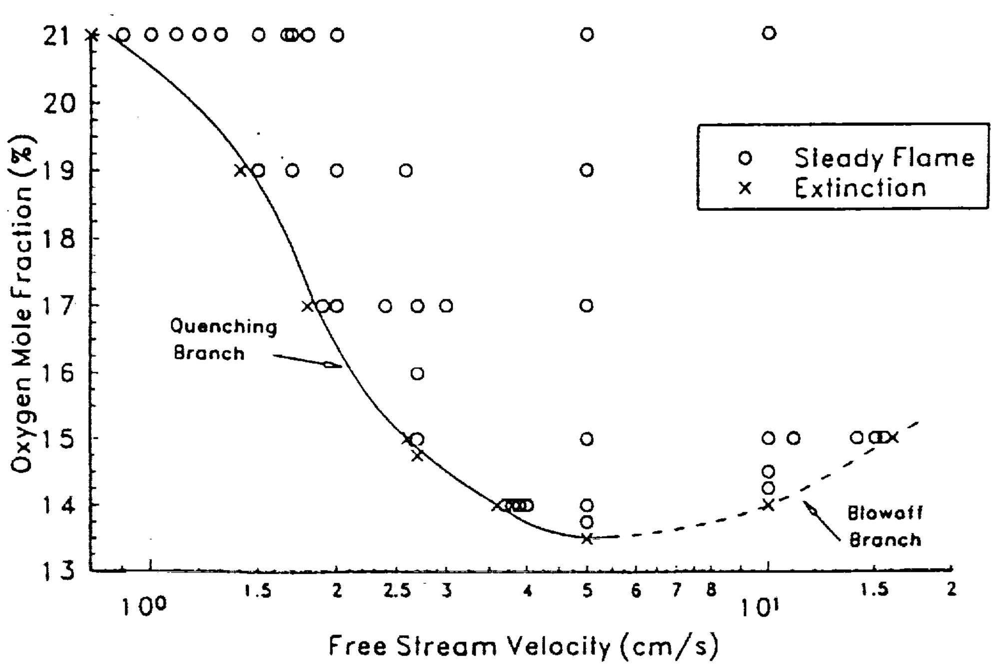

Fig. 1 Extinction Boundary of a Thin Solid Fuel in Concurrent Flow

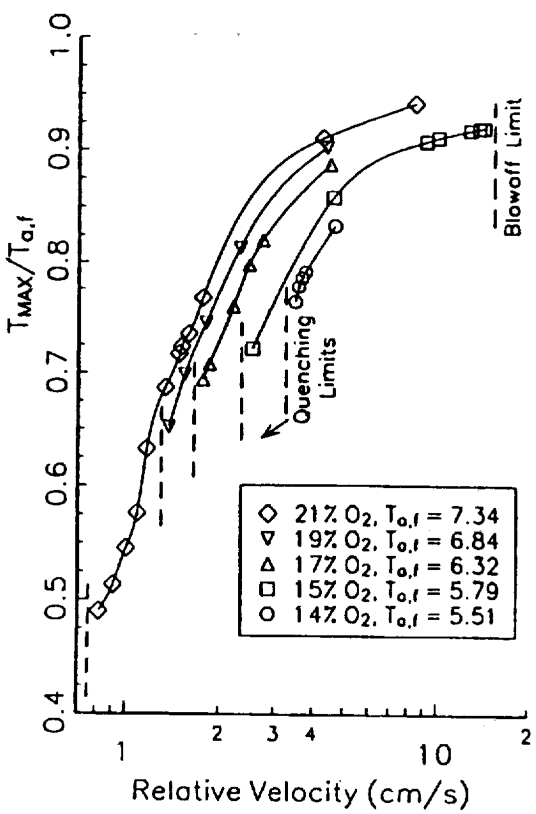

Fig. 2 Maximum Flame Temperature

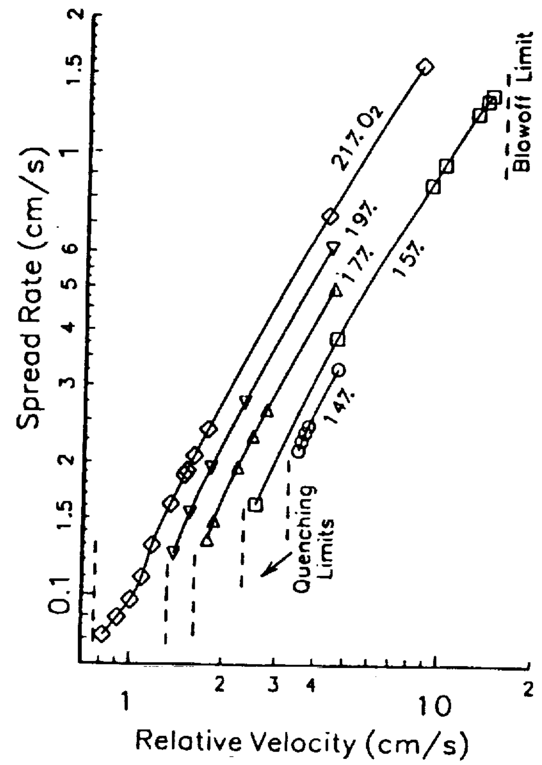

Fig. 3 Flame Spread Rate

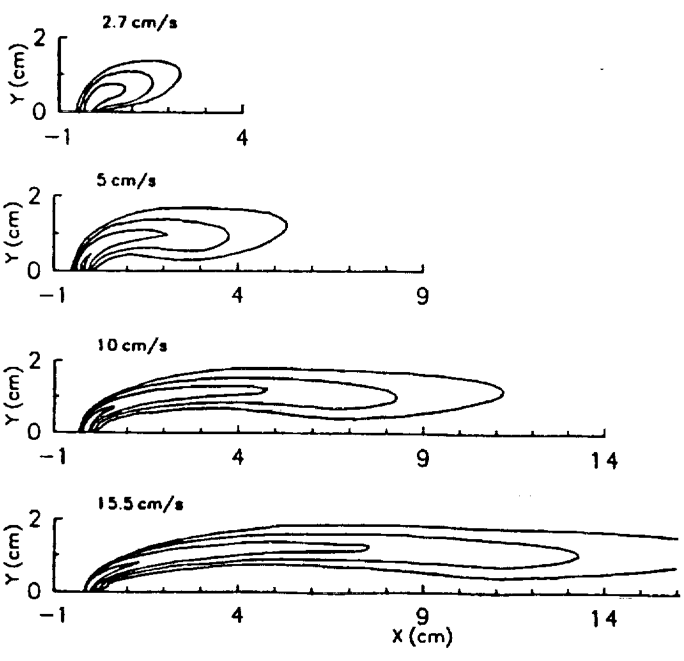

Fig. 4 Reactivity Contours at 15% Oxygen from Quenching to Blowoff (Outermost contour is 10^{-6} g/cm^3/s; a factor of 10 separates contours)

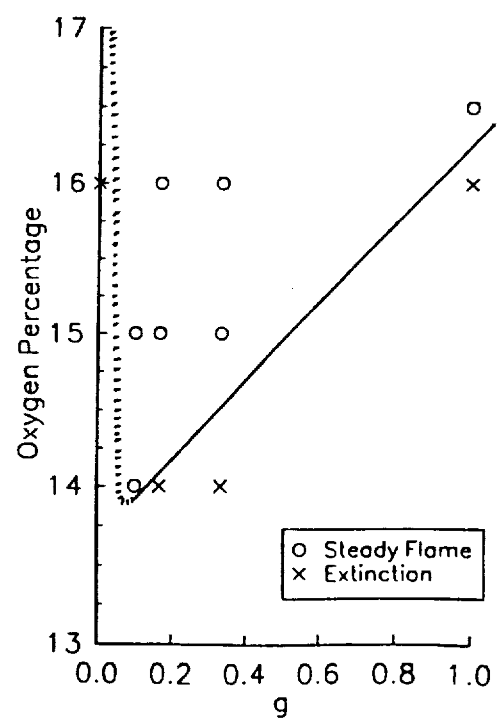

Fig. 5 Extinction Boundary for Kimwipe in Buoyant Opposed Flows (earth: g = 1)

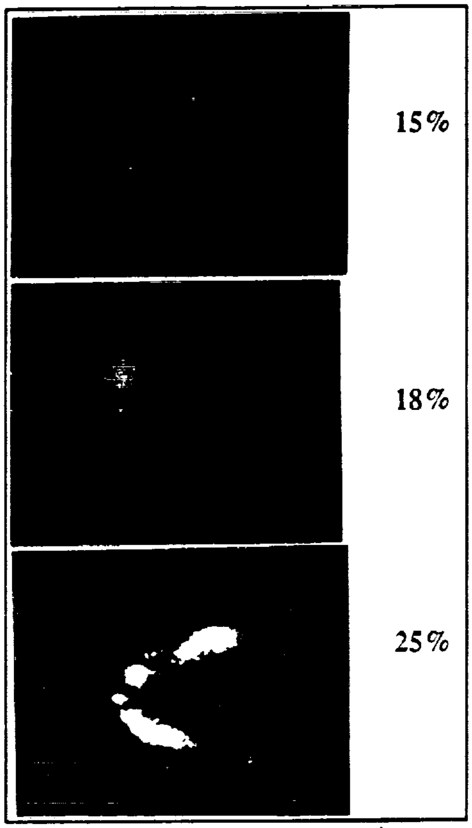

Fig. 6 Flame Shapes at 5cm/sec Relative Concurrent Flow

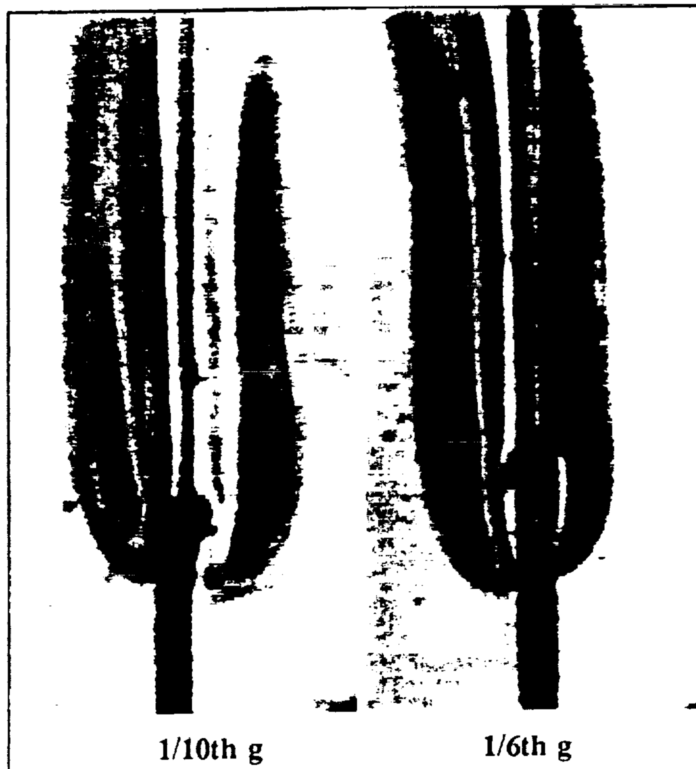

Fig. 7 Downward Spreading in 15% Oxygen, 1 Atm

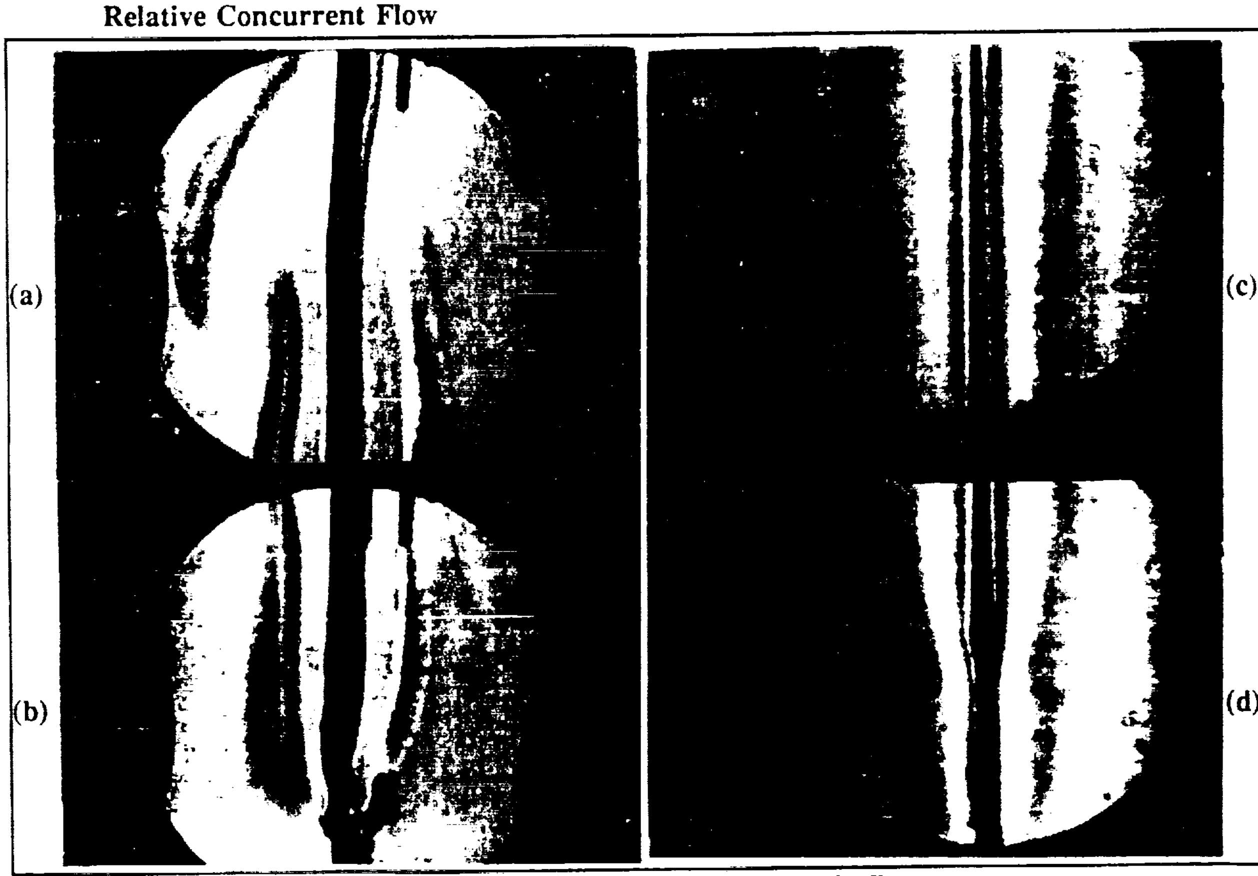

Fig. 8 Upward Spreading in 15% Oxygen, 1 atm (a,b), 0.5 atm (c,d)

See Color Plate F-3