

SOLID INFLAMMABILITY BOUNDARY AT LOW SPEED (SIBAL)*

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564-25
02/1/01

Introduction

This research program is concerned with the effect of low speed flow on the spreading and extinction processes of flames over solid fuels. We are particularly interested in the flammability boundary and the near-limit flame behavior in a microgravity environment. Primary attention is given to flame propagation in concurrent flow -- the more hazardous situation from the point of view of fire safety. Both theoretical modeling and experimental research are in progress.

This project passed the Science Concept Review (SCR) in 1996. As a result, the experiment continues on the flight definition path, and is currently scheduled to be performed in the Space Station Fluids and Combustion Facility (FCF).

Flame Spread Model

Modeling efforts on low-speed concurrent-flow flame spread over solids have advanced significantly. First, the model with only surface radiation [1] was extended to include gas radiation from CO_2 and H_2O for forced flow using a discrete-ordinate method assuming gray, participating media [2]. More recently, this model was modified to study purely buoyant upward flame spread in reduced gravity [3]. In this investigation, it is found that

- (1) For thin solids, steady upward flame spread is possible (at least for the low-gravity levels investigated).
- (2) The flame lengths and spread rates are approximately proportional to gravity level.
- (3) A low-gravity flame quenching limit, attributed to radiative loss, is predicted.
- (4) Flame radiative feedback constitutes an important part of the solid surface energy balance.
- (5) The quantitative prediction of the flame spread rate alone does not give a good indication as to whether the theoretical model is complete.

The model in [2] was also extended to flame spread inside a flow tunnel [4]. Because of both the restrictions on the size of the hardware and the rate of supply of fresh gases in a flight experiment in space, a flow tunnel of finite cross-sectional area and limited length has to be used. However, a finite tunnel height can cause substantial influence on the flame through gas dynamic interaction. In addition, the radiative interaction between the flame, the burning solid, and the tunnel wall can alter the energy balance in the system.

The model predictions shown in fig. 1 compare flammability boundaries with and without tunnel walls present. In the tunnel case, the half-height is 5.5 cm, a uniform flow starts 8 cm upstream from the solid burnout point (fixed in space by a feedback system, see fig. 3), and the tunnel wall is assumed to have no radiation reflection. Both of these two flammability boundaries are U-shaped. However, the case with the tunnel is shifted to the left, i.e., extinction occurs at lower inflow velocities.

To understand the reason for this shift of extinction boundary, we computed the flow velocity vectors and the flame shapes as a function of tunnel wall height (fig. 2). When the tunnel height, D_h , is decreased from 10 cm to 2 cm, the flame lengths increase dramatically. This is the result of the flow field change. At large channel height, thermal expansion of hot combustion products can have a velocity component in the vertical direction (perpendicular to solid surface). But at small channel height, this is forbidden. Consequently, the longitudinal velocities are greatly increased as can be seen for $D_h = 2$ cm in fig. 2. These larger velocities parallel to the solid surface increase the rate of flame conductive heat transfer to the solid which produces more fuel vapor and a longer flame. We refer to this as the flow channeling effect.

From $D_h = 2$ cm to 1 cm, fig. 2 shows a decreasing flame length because of two effects. First, the flames are very close to the tunnel wall which is maintained at 300 K in the computation. The conductive loss cools the flame and the combustion products, reduces the thermal expansion effect, and shortens the flame. Second, there is less oxygen available in the narrower channel since the flow area is reduced.

* Work funded under NASA Grant NAG3-1046.

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The effect of thermal radiation reflected from the tunnel wall was also studied in [4]. Increasing wall reflectivity was found to lengthen the flame and increase the spread rate, which is expected due to the lessening of heat loss from the system. The study in [4] demonstrates that the influence of the experimental setup on the flame can be substantial. Furthermore, a detailed modeling study is needed both to identify the experimental design parameters and for meaningful comparison to experimental results.

Flame Radiation Studies

Since thermal radiation is a key factor affecting the flame behavior in low-speed flows, considerable effort has been spent in the last couple of years on improving the computational scheme for flame radiation. Using a one-dimensional stagnation-point solid-fuel diffusion flame as a test case and CO_2 and H_2O as the radiation participating gases, various gray and non-gray models were evaluated for accuracy and computational time [5]. This study shows that

- (1) Low-stretch diffusion flames are in general not optically-thin.
- (2) The use of a Planck-mean absorption coefficient under-predicts absorption and over-predicts emission.
- (3) The three non-gray models (narrow band, wide band, and sum of gray gases) give comparable predictions, but the computational times can be quite different.

In [5] and [6], we further show that if only the heat flux to the solid surface is important and a gray gas model is preferred (e.g., for computational efficiency), it is possible to multiply the Planck-mean absorption coefficient by a correction factor to obtain reasonably accurate results. For one-dimensional and quasi one-dimensional flames, an empirical relation to determine this correction coefficient is suggested in [6]. A review article on radiative extinction of diffusion flames summarizes this and other aspects [7].

Experimental Work

The ground-based experiments done to date consist of two series of drop tower tests using a sample translation carriage, and aircraft tests using a fuel positioning device. In addition, two series of glovebox tests were recently performed on the Space Shuttle and Mir Space Station as a preliminary for the proposed full-scale experiment.

In the drop tower tests [8, 9], the relative flow between the gas and solid fuel was generated by moving the sample through a quiescent atmosphere (This approach is well-suited to studying low-speed flows given the time and space limitations of the drop tower). The effect of varying flow speed, oxygen percentage, and ignition technique was examined. In summary, these tests provided an indication of the general flame appearance and behavior, and agreed qualitatively with model predictions. However, the flames did not quite reach steady state, restricting direct comparison to the model results.

A theoretical expression of the time needed to reach steady state was derived based on pyrolysis length and spread rate. Using the thinnest "practical" fuel¹, we can use the computed results to evaluate the expression: the time needed to reach steady state turns out to be about 16 seconds. Clearly, available drop tower experiment time is inadequate.

Besides this, in the time it takes a flame to reach steady state, it will have spread some distance. This makes sizing the chamber and positioning any viewing windows difficult or impossible. Therefore, to permit the flame to reach steady state in a reasonably sized volume, a fuel positioning device, called the Solid Fuel Delivery System (SFDS), was built. The central idea of this experimental concept is maintaining the flame fixed in space as the solid fuel is consumed by feeding fuel into the flame at the necessary rate (fig. 3).

Reduced gravity aircraft tests with this hardware were performed. The main purpose was to examine the engineering concepts in microgravity, and the results were very encouraging. Ignition was attained reliably using a retractable, hot-wire. The fuel remained flat, and the flame was held stationary during combustion. Fuel fed smoothly into the flame zone, effectively providing an unlimited supply, while allowing long duration burns [11].

The parabolic trajectories provided reduced-gravity durations of up to 25 seconds, which would seem long enough to reach steady state. However, both experimental results and model predictions demonstrated that the residual g-level ($10^{-2} g/g_E$) disturbed the flame to such a degree that the objectives of the project were not achievable using airplanes.

Ultimately, the only way to conduct long-duration experiments in microgravity is by going to space, and in fact, hardware for this project is currently being developed to that end. Since typical flight project development time is several years, we took

¹The flame will quench if the fuel becomes too thin [10].

advantage of an opportunity to conduct a preliminary, small-scale space experiment. This was called the Forced Flow Flame Spreading Test (FFFT), and was able to be developed and flown quickly because it was small and simple. The FFFT utilized the Microgravity Glovebox which provided containment, power, and viewing access.

The FFFT hardware consisted of a low-speed wind tunnel within which fuel samples could be burned. The edge view of the flame was photographed using a 35 mm camera, and the top view was recorded on videotape. Up to six thermocouple displays provided flame and fuel temperature data. Gas sample bottles were used to collect products of combustion from selected tests.

The first series, conducted in the STS-75 (USMP-3) mission in March 1996, consisted of two solid fuel configurations: 1) thin, flat samples of ashless filter paper (cellulose) and 2) cylindrical samples of cast cellulose formed around a cylindrical cartridge heater. In this series, concurrent flow velocities were varied from 1-8 cm/sec [12]. The second series, conducted aboard the Russian Mir Space Station in August 1996 consisted of flat samples of cast cellulose of different thicknesses, and cylinders of polyethylene (conventional wire insulation). In this series, the flow velocity was fixed at 3 cm/sec. Below we will briefly describe and summarize some of the observations for the thin, flat samples.

Flame and Fuel Behavior

In fig. 4, the edge view of a flame in 1 cm/s flow (from left to right) is shown. The flame appears dim blue and diffuse, typical for microgravity. The model prediction of the same case is shown also. We assume that the predicted fuel consumption rate distribution correlates with the visible flame. The flame shape agrees qualitatively with the model prediction, in that the contours follow the flame outline. However, the quantitative comparison depends on which particular fuel consumption contour coincides with the minimum flame luminosity. In earlier work, the fuel consumption rate of 10^{-4} g/cm³/s was found to give a good indication of the visible flame, based on drop tower results [1].

Even for the thinnest fuel, the time it takes for the flame to consume the sample is around 15 seconds. In fig. 5, two temperature traces are shown for such a sample burning in an airflow of 3 cm/s. Looking at the thermocouple initially mounted in the solid fuel, we can see that it is first heated to approximately 400 C, at which point the temperature levels off due to pyrolysis. Then as the fuel is burned out, the flame moves past the thermocouple yielding a temperature peak. The gas-phase thermocouple, located about 1 cm above the fuel, indicates a maximum temperature of around 1100 C. The temperature traces observed agree qualitatively with the steady model predictions, but because the sample size is limited, the flames have not yet reached steady state.

Despite the limitations of this small and simple experiment, there are several findings which are helpful to the development of the full-scale space experiment. The most valuable is the behavior of the ashless filter paper in concurrent-flow flame spreading that we had not seen in our earlier ground-based testing. In the longer tests, fuel under the lengthier flames fractured (cracked) in the pyrolysis zone, propagating the flame in a highly three-dimensional manner. The cracks also permitted fuel curling, further complicating the flow field. Since making these observations we have begun a program to screen various types of thin solid fuel candidates using low-pressure upward flame spread tests. In addition, the development of the glovebox experiment provided an opportunity to design an ultra-low-speed flow tunnel that is needed in the proposed space experiment. The control and measurement of flow magnitude and uniformity in this regime is a real challenge since conventional and advanced flow measurement techniques fail at low velocities or interfere in some way with the weak flames there.

Summary

This project will attempt to validate the theoretical prediction of the flammability boundary for a thin combustible solid in low-speed, forced-concurrent flow. So far, we have utilized the available ground-based facilities (drop towers and aircraft) as much as possible, and have gone as far as we can here. The extensive experiments we conducted show that the time required to determine the solid flammability limit and for the flame to reach steady state is not sufficient in ground-based facilities. Further, the g-jitter in an airplane flying a parabolic trajectory was shown to introduce too high a flow disturbance or too short a test time during free float. The small-scale glovebox experiment yielded useful but incomplete information. The only way we can obtain complete and meaningful experimental results to validate the theory adequately is by performing an extended microgravity experiment using advanced diagnostic techniques.

In light of the volume and stowage limitations of spacecraft, we have developed a novel flammability test device which facilitates the proposed experiment. The proto-type version of this device was tested successfully in low-gravity aircraft trials. This concept will permit a systematic investigation of the model-predicted flammability boundary and critical low-oxygen limit. The existence of this limit for materials is not only of scientific interest, but has significant implications for spacecraft fire safety.

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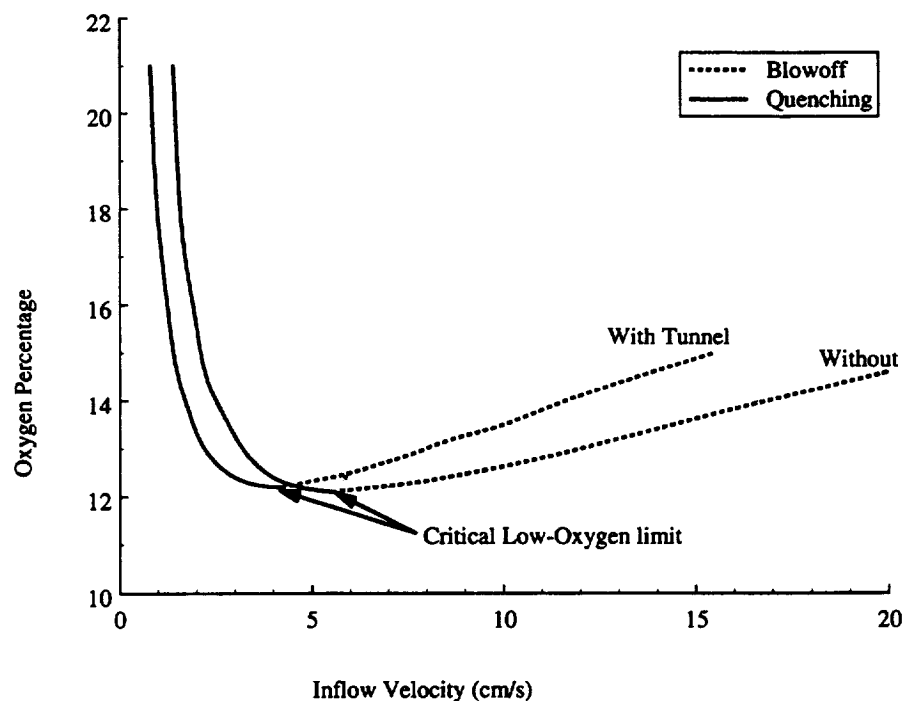


Figure 1. Flammability Boundary.

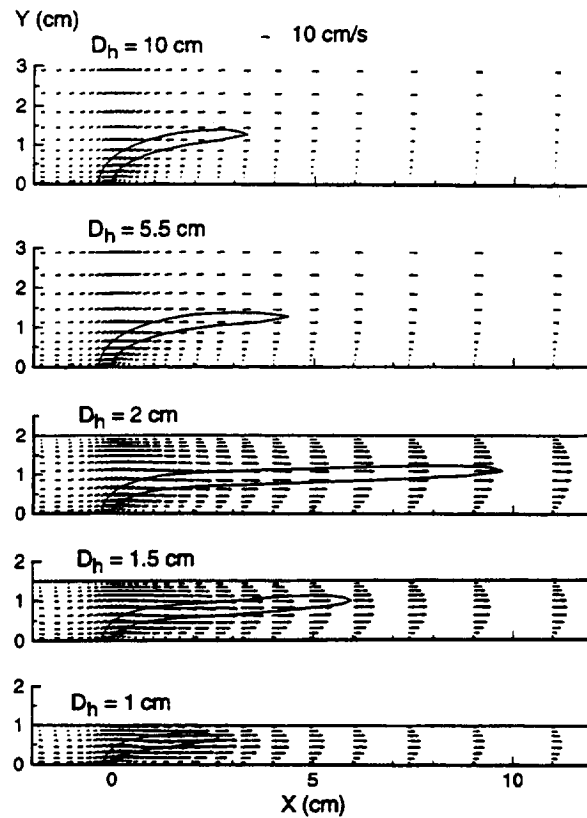


Figure 2. Flame Shape and Flow Structure (Velocity Vectors) for Different Tunnel Heights.

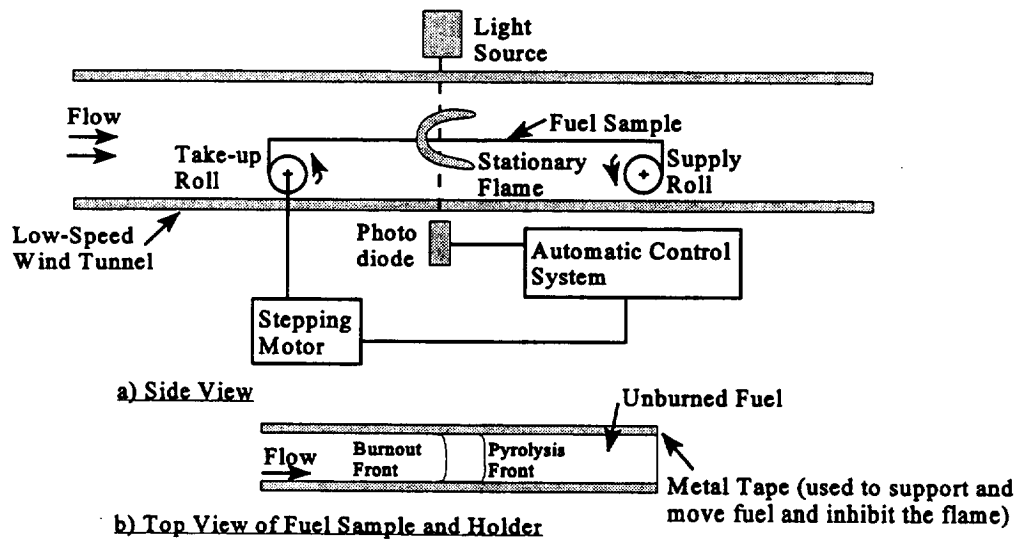


Figure 3. Schematic of Solid Fuel Delivery System.

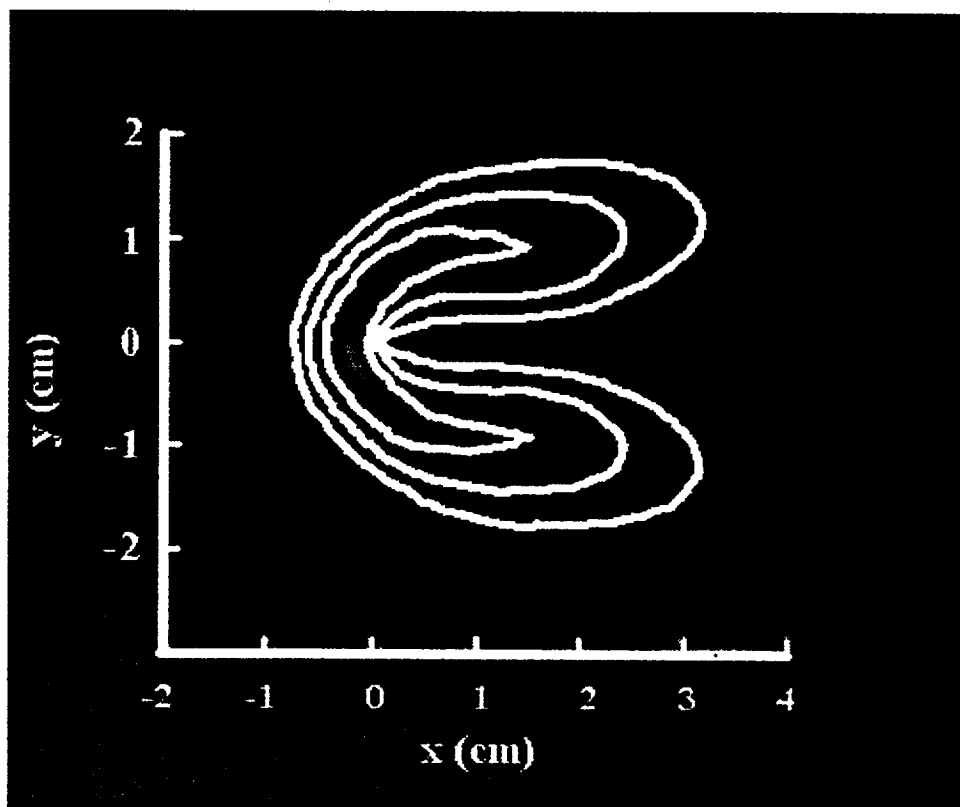


Figure 4. Comparison of Visible Flame and Computed Fuel Consumption Rate Contours. The dim flame essentially fills the innermost contour, $10^{-4} \text{ g/cm}^3/\text{s}$. A factor of ten separates contours.

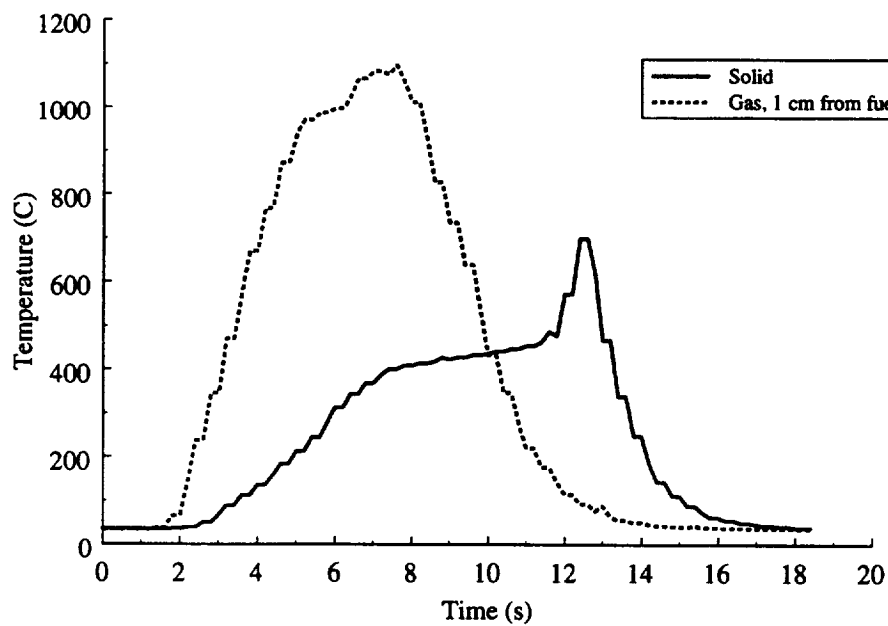


Figure 5. Temperature Traces for Thinnest Fuel in 3 cm/s Airflow, from FFFT Glovebox Experiment.