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# IGNITION AND SUBSEQUENT TRANSITION TO FLAME SPREAD IN A MICROGRAVITY ENVIRONMENT

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## Introduction

The fire safety strategy in a spacecraft is (1) to detect any fire as early as possible, (2) to keep any fire as small as possible, and (3) to extinguish any fire as quickly as possible. This suggests that a material which undergoes a momentary, localized ignition might be tolerable but a material which permits a transition to flame spread would significantly increase the fire hazard. Therefore, it is important to understand how the transition from localized ignition to flame spread occurs and what parameters significantly affect the transition. The fundamental processes involved in ignition and flame spread have been extensively studied, but they have been studied separately. Some of the steady state flame models start from ignition to reach a steady state, but since the objective of such a calculation is to obtain the steady state flame spread rate, the calculation through the transition process is made without high accuracy to save computational time.

We have studied the transition from a small localized ignition at the center of a thermally thin paper in a microgravity environment [2]. The configuration for that study was axisymmetric, but more general versions of the numerical scheme have been developed by including the effects of a slow, external flow in both two and three dimensions. By exploiting the non-buoyant nature of the flow, it is possible to achieve resolution of fractions of millimeters for 3D flow domains on the order of 10 centimeters. Because the calculations are time dependent, we can study the evolution of multiple flame fronts originating from a localized ignition source. The interaction of these fronts determines whether or not they will eventually achieve steady state spread. Most flame spread studies in microgravity consider two-dimensional flame spread initiated by ignition at one end of a sample strip with or against a slow external flow [4]. In this configuration there is only one flame front. A more realistic scenario involves separate, oppositely directed fronts in two dimensions, or a continuous, radially directed front in three dimensions.

## Results and discussion

We present here some results of both the two and three dimensional codes. Unless otherwise noted, the ambient oxygen concentration for the simulations is nominally 30%. The gas phase reaction parameters were chosen to roughly match the experiments of Olson; it is not our intention to fine-tune the parameters to agree with the data exactly but rather to assess qualitative trends.

The spatial resolution for both the 2D and 3D codes is the same; grid cells for the finite difference scheme are 1 mm in length in the directions parallel to the surface and about 0.25 mm in the normal direction, expanding to about 1 mm farther away. The increased resolution in the normal direction is intended to capture large gradients at the surface. For this grid resolution, the 2D calculations require less than an hour of CPU time on a typical workstation, while the 3D calculations require several tens of hours. Increasing the resolution in the 2D simulations did not effect the results appreciably, thus the resolution was chosen to match the 3D cases for consistency. Obviously, most of the parameter studies were conducted with the 2D code, reserving the 3D code for examination of special geometric effects.

The effect of a slow external flow on the transition period is considered first. A strip is ignited in the middle in order to generate two flames at the same time. An external wind of 2 cm/s is imposed along the length of the strip. Fig. 1 displays the evolution of the two flames during the transition period. The wind blows from left to right. The upwind flame (left) successfully makes the transition to flame spread and propagates into the wind at about 1.5 cm/s. The downstream flame, however, does not survive the transition, as it lifts off from the surface and a clear flame front does not appear. Not only does the upwind flame survive, but it is about twice as strong as a flame spreading in the absence of wind as measured by the peak gas phase reaction rate. The quiescent flame propagates at about 1.2 cm/s.

The experiments of Olson [5] for this configuration show the flame propagating at about 1.95 cm/s while the quiescent counterpart spreads at about 1.8 cm/s. The downstream flame in these experiments is reportedly much weaker, much sootier, and in the short test time likely to extinguish. The dependence of the upstream flame spread rate on flow velocity has been attributed to oxidizer transport effects [5], or radiative loss effects [1]. Both of these theories is supported by the numerical simulations. The experiments and numerical simulations both show a strengthening of the upstream flame due to increased oxidizer transport in the presence of a slow external wind. Also, reduced radiative loss from the sample surface in front of the flame leads to faster flame spread. It is difficult to judge which is the more important effect due to the uncertainty about the gas phase kinetics, which for this model is described by a one step global reaction of fuel and oxygen.

The weakness and extinction of the downstream flame of the sample strip seems to be due to lack of available oxygen. Clearly in the two flame case, the upwind flame robs the downstream flame of the oxygen needed to survive the transition. To show this, a few single flame simulations are performed using the same sample strip as before, except that no fuel is present upwind of the ignition point. For an imposed wind of 2 cm/s, where no upwind flame is present, the downstream flame is weak, but unlike before it survives the transition period. Fig. 2 displays the computed oxygen mass fraction contours, along with the gas phase reaction zones, of three other single flames under different wind speeds. The case of no wind represents an opposed flow, because in flame fixed coordinates the flame encounters a flow equal to its spread rate. The case of a 5 cm/s wind represents a concurrent flow, because the wind speed is faster than the spread rate. The 1 cm/s case is neither concurrent nor opposed because the wind speed is about the same speed as the flame spread rate (at least before the flame dies out). It is clear from the oxygen contours why the 1 cm/s case extinguishes — the oxygen concentration gradients are the least steep among the three cases and the oxygen is unable to reach the reaction zone in sufficient concentration to maintain combustion. The flame exposed to a 5 cm/s external wind is strengthened by increased convective transport of oxygen due to the wind, and by the preheating of the sample, again due to the wind. As seen by Ferkul and T'ien [3], the overall flame length increases with increasing wind speed.

Olson reports an experiment in 30% oxygen (Ref. [5]) in which a wind is directed in the same direction as the flame spread, and the wind speed is slightly slower than the flame speed (characteristic relative velocity is 0.1 cm/s). She notes that the flame is very sooty, and propagates more slowly than the opposed flow counterparts. The numerical simulation in which the flame is neither concurrent nor opposed shows this flame dying out, but again this is due to the choice of the gas phase reaction parameters.

It has been pointed out by Bhattacharjee *et al.* [1] that for low speed flame spread heat loss in front of the flame has a significant impact on the steady state spread rate. This effect is also seen in the transition period between ignition and flame spread. If the distribution of the radiative ignition source is spread out, it takes longer for ignition to occur, and the accumulation of fuel vapors then generates a larger flame and increases the heat feedback rate during the transition. In effect there is greater preheating of the sample in front of the developing flame front. Fig. 3 shows the effect of varying the initial flux profile, while fixing the total energy delivered to the sample. Ignition is triggered most rapidly by a sharp radiative flux distribution with a high peak flux (20 $W/cm^2$). However, for a wider distribution with lower peak flux (5 $W/cm^2$), the preheating of the sample in front of the flame causes it to propagate at a higher rate of speed during the transition period. Also, its overall width is wider than that of the flame ignited with a sharp radiant flux profile (or a pilot wire). Bhattacharjee *et al.* note that more preheating of the sample surface in front of the flame causes an increase in flame speed and a widening of the overall flame.

Next, we examine some calculations of the transition to flame spread in three dimensions. Fig. 4 shows the evolution of a flame ignited at the center with an axially symmetric radiative flux in the presence of a 2 cm/s wind. The umbrella-shaped flame appears initially due to the expansion of hot gases. Then it changes to a horseshoe-shaped flame propagating upwind. The downwind part is extinguished, as was seen in the 2D simulations. This simulation clearly shows the effects of a slow wind on the transition.

Fig. 5 shows a 3D simulation of a quasi-2D experiment, that of the ignition of a 5 cm wide strip with a 2 cm/s wind blowing along the length (which has been discussed above). For the short duration of the simulation (3 seconds) the centerline flame profile was similar to the 2D counterpart. However, the downstream flame at the edge of the strip is stronger than the upstream flame and propagates more rapidly due to the increased supply of oxygen there. Fig. 6 displays the flow vectors for this simulation near the sample surface. Note the higher velocities near the edge. The three dimensional nature of the flow field cannot be ignored. Indeed, it has been observed when comparing the 2D and the 3D simulations of the strip ignition that the downstream flame in the 2D simulation dies out before the 3D counterpart (measured at the strip centerline). This difference is mainly due to the lateral transport of oxygen, both convective and diffusive, which occurs over a few seconds.

## Conclusion

It has been seen in the experiments that a slow external wind strengthens the upstream, while weakening the downstream flame. The numerical simulations agree qualitatively, and a close examination of gas phase fuel and oxygen concentrations near the flame fronts offer explanations as to the cause of the strengthening/weakening. It has been observed in the two simultaneous flame configuration that the downstream flame which are viable on their own cannot survive the transition when an upstream flame is present to rob the oxygen.

For low speed flame spread, heat losses from the sample have a great effect on the flame spread. This has also been seen in the transition process when radiative sources of various widths have been used to heat the samples. Wider sources generate more preheating in front of the flame, and the flame spreads more rapidly during the transition. Ultimately, the flame spread rate is independent of how ignition is achieved.

We are presently conducting studies of the transition to flame spread in three dimensional configurations. In addition to providing us with a useful tool to consider problems that were considered intractable before, the 3D runs also point out the limitations of 2D simulations of experiments which use relatively narrow sample strips. Experiments are presently underway in a 10 second drop tower at the Japan Microgravity Center and some of the experimental results will be presented and compared with the calculated results at the meeting.

Acknowledgments

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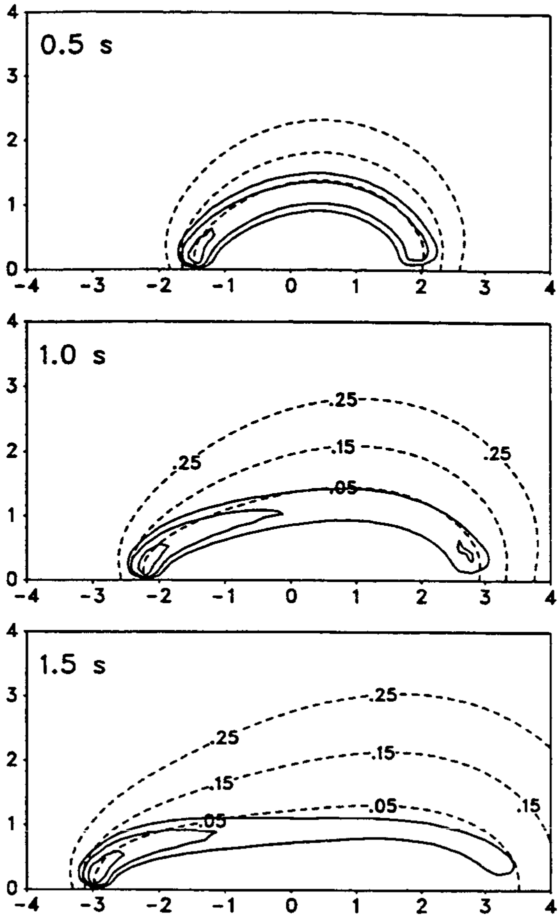


**Figure 1: Transition period for a flame in the presence of a 2 cm/s wind blowing from left to right. Dashed lines indicate oxygen concentration, solid lines indicate the gas phase reaction rate.**

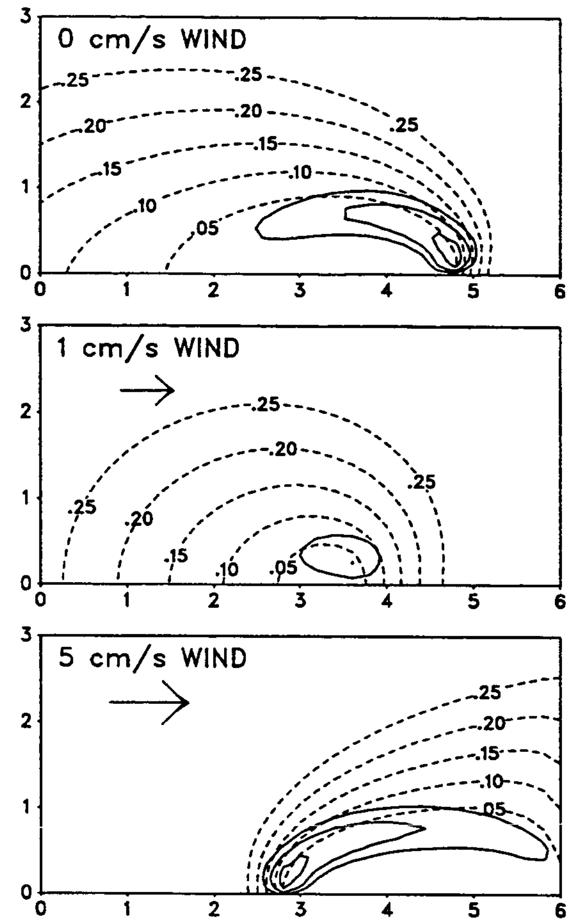


**Figure 2: Three single flames with three different wind speeds 3 s from ignition.**

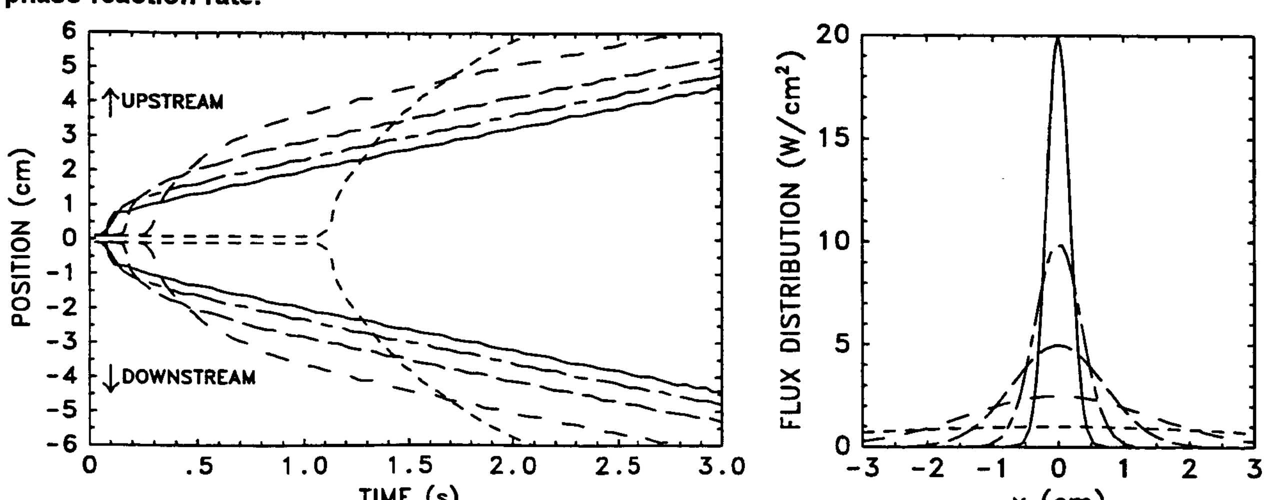


**Figure 3: Flame front trajectories (left) for various radiative source distributions (right), all of which have the same integrated heat flux. The oxygen concentration is 30%; there is no external wind.**

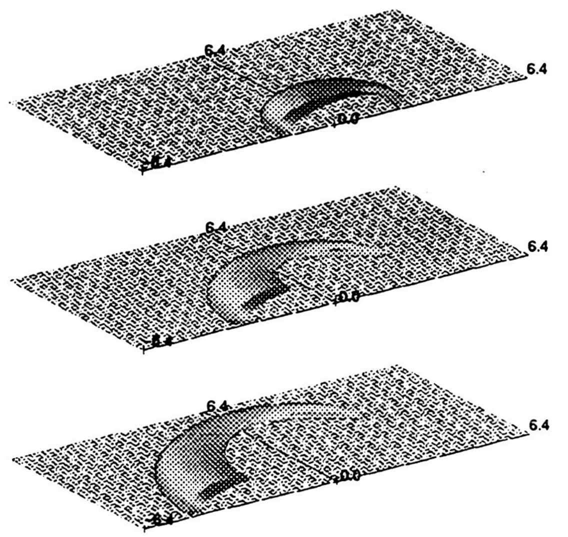

Figure 4: Flame spread with an imposed 2 cm/s wind (left to right) over a sheet, half of which is shown. Shown are flames 1, 2 and 3 s past ignition.

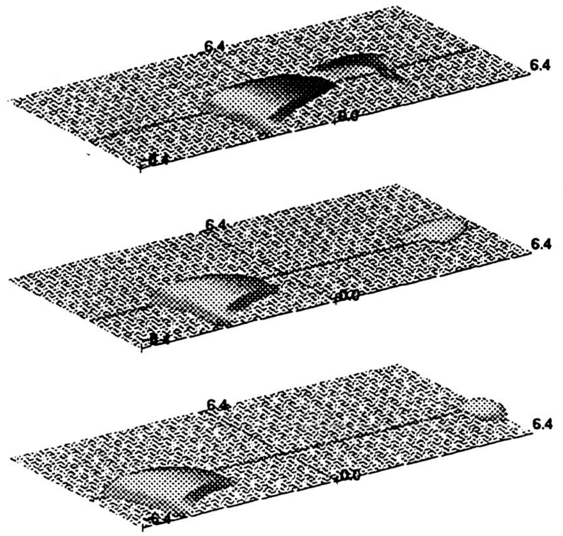

Figure 5: Flame spread with an imposed 2 cm/s wind (left to right) over a 5 cm wide strip, half of which is shown. Shown are flames 1, 2 and 3 s past ignition.

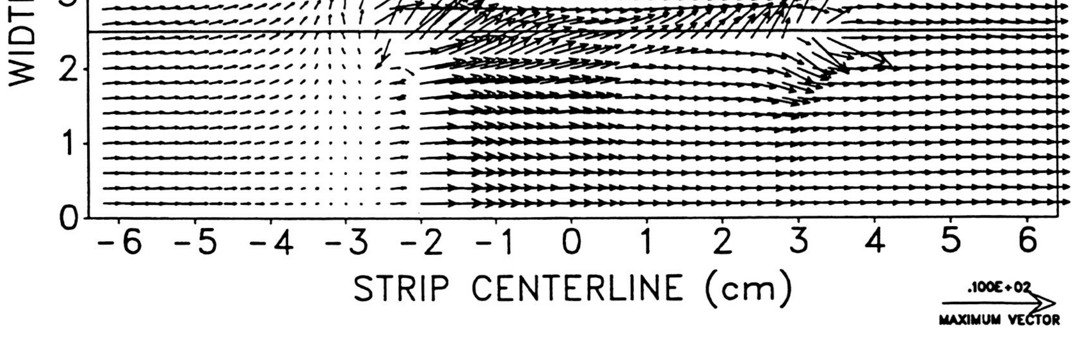


Figure 6: Flow vectors near the surface for flame spread over a 5 cm wide strip 1.0 s after ignition. Half of the strip is shown here. It is assumed that the flow on each side of the strip centerline is symmetric.