N96- 15588

# INTERACTIONS BETWEEN FLAMES ON PARALLEL SOLID SURFACES

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Program Began 1994

## Introduction

The interactions between flames spreading over parallel solid sheets of paper are being studied in normal gravity and in microgravity. This geometry is of practical importance since in most heterogeneous combustion systems, the condensed phase is non-continuous and spatially distributed. This spatial distribution can strongly affect burning and/or spread rate. This is due to radiant and diffusive interactions between the surface and the flames above the surfaces. Tests were conducted over a variety of pressures and separation distances to expose the influence of the parallel sheets on oxidizer transport and on radiative feedback.

Owing largely to their practical importance, flame interactions have been an area of active research, however microgravity research has been largely limited to candles (Ref. 1) and droplets, (Refs. 2 & 3 ). Consideration of parallel solid surfaces has been limited to 1-g studies (Refs. 4 - 9). Of these works, (Refs. 4, 6 and 7) considered flame spread.

Emmons and Shen (Ref 4.) studied horizontal flame spread over an array of vertically oriented paper sheets. The flame spread rate was found to be proportional to the fuel sheet aspect ratio (height/separation) for small and large values of the aspect ratio. However, the proportionality was different in these two cases and, at intermediate values, the correlation broke down. Using a simple model for the energy transport ahead of the flame and a value for the burning zone width estimated from the data, acceptable agreement was obtained with the experimental data.
Kim, De Ris and Kroesser (Ref. 5) performed a theoretical and experimental analysis of the downward burning rate between two parallel fuel surfaces. Assumptions similar to those in the work of De Ris (Ref. 10) were made (unity Lewis number, infinite gas phase reaction rate and insignificant radiative transport). Burning rate was found to be controlled by the product of the Grashof number and the channel aspect ratio (b/l (channel half width/length) ). Good agreement was found between the theoretical formulation and the burning rate for methanol-soaked slabs. The selection of methanol as the test fuel increased the suitability of the assumption that radiation could be neglected since methanol flames produce little soot and consequently the radiative transport from the flames can be expected to be small. Three burning regimes were found depending upon the ratio $l/b^4$. For small values of $l/b^4$, the burning rate was independent of b; for larger values, the burning rate is independent of l but proportional to the $b^3$. At intermediate values a simple parameter dependence was not observed.

Ohlemiller and Villa (Ref. 11) and Ohlemiller (Ref. 12) suggest the importance of considering the radiant interaction between two surfaces in NASA's flammability assessment of materials. The current flammability standard for materials to be used on spacecraft (Ref. 13) is an upward burning test with a single sheet of material. As Ohlemiller (Ref. 12) suggests, this is a geometry that is not necessarily the worst case it is intended to be. Without radiant preheating of the unburned material, the flammability hazard is lower than with modest radiative feedback. The radiant interaction between surfaces is also very important in terrestrial fire safety; the classic example is wood, which is nonflammable as a single large sheet but very flammable if multiple pieces are arranged to allow radiant interaction.

## Experiment Description

The tests were conducted for downward flame spread over parallel sheets of paper. The fuel was stored in a desiccator and the chamber filling process exposed the fuel to vacuum or dry air for at least two hours. The low gravity tests were conducted in the NASA LeRC 2.2 second drop tower in a 45 liter quiescent chamber. The normal gravity tests were either conducted in the 45 liter chamber or a new 27 liter chamber. The fuel was Kimwipe™ laboratory wipes, selected because of their uniform thickness and low mass/area (1.9 mg/cm$^2$) The sample frame opening was 5 cm wide and the flame spread rate and flame structure were observed using a color video camera on the edge view. The oxidant was either mixed in the chamber using partial pressures or supplied directly from a gas bottle, in either case the mixture error was less than 0.5 mole %. The bulk of the low gravity tests were conducted at 30% oxygen because a value within the quiescent microgravity flammability range for Kimwipe™ was desired, while the normal gravity tests were conducted at 21% oxygen. The diluent was either helium or nitrogen. Test pressures ranged from 100 to 1000 Torr, with the majority conducted at 760 Torr, and separation distances varied from 6.4 to 50 mm. Unlike single sheet tests, it was learned that the ignition process must be carefully controlled to prevent the ignition products from filling the gap between the fuels, thereby preventing development of internal flame(s).

The experiment imaging was recorded in S-VHS video format. After the tests, the video frames were digitized using a frame grabber and the flame spread rate was determined using object tracking software which stepped through the video images and determined the position of the leading edge of the flame. The spread rates were very stable throughout the tests with correlation coefficients greater than 0.99. Where there was a flame between the sheets of paper (internal flame), the reported spread rates are the average of the spread rates of the internal and external flames on at least one of the sheets. The camera was centered on the edge of one of the sheets to provide optimum imaging of one pair of flames. At large separation distances the flames on the second sheet were sufficiently distorted that they were not trackable; for these cases the spread was determined from only the sheet aligned with the camera.

In process of these tests, numerous deficiencies were observed in the 20 year old generic combustion drop package that was being used. The most important of these was inflexibility concerning sample size and separation distances. In addition, it was found to be unsuitable for normal gravity testing due to the support hardware needed to support the samples impeding buoyant air flow. A new drop package was designed and fabricated. It was used for limited normal gravity testing and is now ready for use in the drop tower. This apparatus allows more systematic sample configuration variation and also improves the quality of the recorded images.

## Results and Discussion

It was found that flame interactions occur in a manner similar to that reported for normal gravity downward spread. The microgravity flames, however, exhibit greater interaction for a given separation distance, the difference being attributed to the influence of the buoyant flow. Similar to the normal gravity case, the interaction displays four phases as separation distance is increased(Fig. 1): 1. no flame between the sheets of paper (internal flame), 2. an unstable internal flame, 3. a single internal flame which becomes more deeply notched with separation distance, 4. individual internal flames on each surface which in the limit of large separation become independent of each other. These results are similar to those reported for normal gravity flames by Kurosaki, Ito and Chiba (Ref. 6) who reported, as separation distance was reduced, a progression from independent flames through increasing flame interaction to ultimate extinguishment of the internal flame. The range of separation distances over which the interaction was apparent was much greater than that seen in normal gravity tests where separate flames are observed at 10 mm separation while the low-g flames were still connected at 40 mm separation. (Fig 2.)

Figure 3 contains the low-gravity spread rates for parallel sheets at various separation distances with helium and nitrogen diluents. As expected, the spread rate is higher for helium for all cases; this is consistent with the thin fuel spread model of De Ris (Ref. 10) which shows linear dependence on gas phase thermal conductivity. The greater dependence on separation distance for the helium case is also consistent with helium's larger thermal diffusivity, which was also evident in the fact that the helium flames were much larger than the corresponding nitrogen flames, and interacted over greater separation distances. The tendency of the internal flame to extinguish at larger separations for helium is most likely due to increased conductive losses to the paper. The limited change in the spread rate with nitrogen diluent is surprising given the evident interaction in the video record.

Kurosaki, Ito and Chiba (Ref. 6), in similar normal gravity tests, reported that as separation was increased, after passing through a maximum value, the spread rate decreased asymptotically to the single sheet value. In this work, for nitrogen, the spread rate for multiple sheets was very close to that of the single sheet; for the case of helium diluent, test chamber limitations prevented increasing the separation distance enough to see the low-gravity spread rate return to the single sheet values. The flames were largely blue and therefore the radiant contribution is likely to be low, however at this point it is not possible to determine whether the increased spread rate was due to the increased radiant transport due to the higher flame temperature or due to the increased thermal conductivity of the helium diluent. In their work Kurosaki, Ito and Chiba (Ref. 6) found (by analysis) that radiation from the ember section of the opposing sheet was of the same order as conduction; their fuel was computer cards which can be expected to produce a more significant ember section than the thin paper used in these tests. Their results showed that the interaction increased with sample width (consistent with radiation view factors). Due to access limitations, the sample width could not be significantly varied in the old drop rig, however the new drop rig will accommodate a variety of sample sizes and this parameter will be varied in future tests.

The change in spread rate as a function of pressure is presented in figure 4. At pressures greater than atmospheric, the limited change in spread rate with pressure is consistent with thin fuel flame spread theory. However, below atmospheric pressure (600 to 700 Torr), there is a dramatic change in the pressure dependence. In these cases, the internal flame does not extinguish until well below the transition point. However, in some cases below the transition point, oscillation was seen in the internal flame. Similar tests were conducted for 1-g flames (Fig. 5). In this case there was also a pressure below which spread rates dropped off, however the change in slope was less abrupt. In 1-g the internal flame was the last to extinguish. This effect was attributed to the chimney effect of the sheets of paper providing enhanced air flow.

In this work, an unstable region was observed in low-g flames for 30% oxygen in helium at 760 Torr for 15 mm separation. The flame between the sheets pulsated six times during the drop, alternating between small pulsations and very large pulsations that filled the entire region between the sheets behind the flame leading edge. The frequency was 2.5 to 3 Hz and the duration of the pulsations was 0.1 to 0.2 s. All of the pulsations involved a flame propagating back from the leading edge toward the ignitor. In another case, with nitrogen diluent (30% oxygen at 645 Torr, 10 mm separation), an unstable internal flame was also observed, however in this case it was a flame bubble that oscillated in both directions as it trailed behind the leading edge of the external flames. In addition to the instability causing the flame oscillation down the channel, it also appeared that the instabilities were alternately starting at the near and far (with respect to the camera) edges of the flame. With a single camera view, it is impossible to confirm this; further study of this phenomenon will require 2 orthogonal camera views. Instability was found in normal gravity near the low pressure extinction limit, however in this case the internal flame would pulsate forward (opposite to the low-g pulsations). The frequency was again approximately 3 Hz but the duration was approximately 0.03 seconds, much briefer than the low-g pulsations. Kurosaki, Ito and Chiba (Ref. 6), reported an intermittent internal flame in their tests in 1-g but little detail was provided.

Instabilities (cellular flames) for flames spreading over single sheets of paper have been reported for low Lewis numbers (Ref. 14), however these instabilities were small scale flamelets meandering across the burning edge of the fuel. In their helium dilution case (Lewis number of 1.4) instabilities were not observed. A pulsating mode has been suggested for high Lewis number cases by Joulin and Clavin (Ref. 15), with the critical Lewis number for pulsations decreasing with increasing heat loss. The difference between this work and the work of Zhang, Ronney et al. (Ref. 14) may be the increased heat loss due to the opposing sheets of paper. More work is needed to confirm this effect and to determine whether the pulsations reported here are a Lewis number effect or an artifact of the sample geometry.

## Conclusions

Interactions between flames spreading over parallel surfaces have been demonstrated in low-gravity. There is an expanded spatial scale over which the flames interact compared to the normal gravity case. These interactions change the response of the flame spread to pressure variation and cause instabilities that have not been observed for normal gravity flames. Further work is needed with a variety of sample geometries and sizes to clarify these results.

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Figure 1. Edge view of flames propagating in microgravity over parallel sheets of Kimwipe at different separation distances in 30% oxygen, balance nitrogen, at 760 Torr. Separation distances in order (top to bottom, left to right) are 6.4, 10, 20, 30, 40 and 50 mm. At 40 mm separation, the flames are nearly separate with slight interaction. At 30 mm the flames have merged, producing a notched blue flame compared to the more luminous external flame. The internal flame is nearly flat at 20 mm and in the 10 mm case the flatness is slightly skewed by slightly delayed ignition for the left sheet. By 6.4 mm the internal flame has extinguished and the fuel burns only on the outer surfaces.

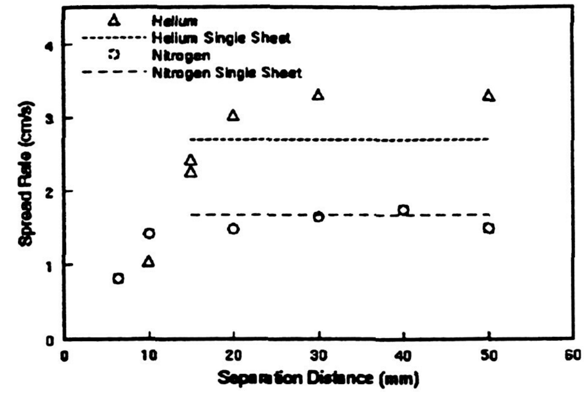


Figure 3. Flame spread rate versus separation distance for two parallel sheets in microgravity in 30% oxygen, balance helium or nitrogen at 760 Torr. Single sheet values are shown as dashed lines. The sharp slope change below 20 mm separation for helium and 10 mm for nitrogen, is a result of the extinction of the internal flame.

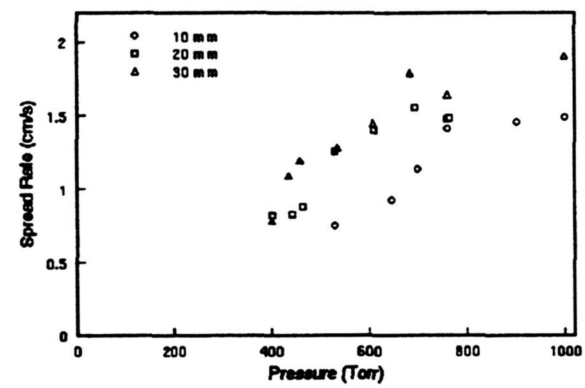


Figure 4. Flame spread rate versus pressure for two parallel sheets at 10, 20 and 30 mm separation distances in 30% oxygen, balance nitrogen, in microgravity.

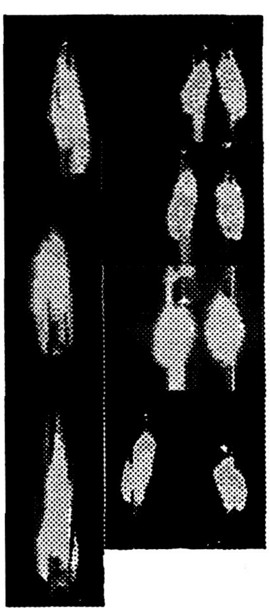

Figure 2. Edge view of flames propagating in normal gravity over parallel sheets of Kimwipe at different separation distances in dry air at 760 Torr. Separation distances in order (top to bottom, left to right) are 3 mm, 4.7, 6.4, 10,

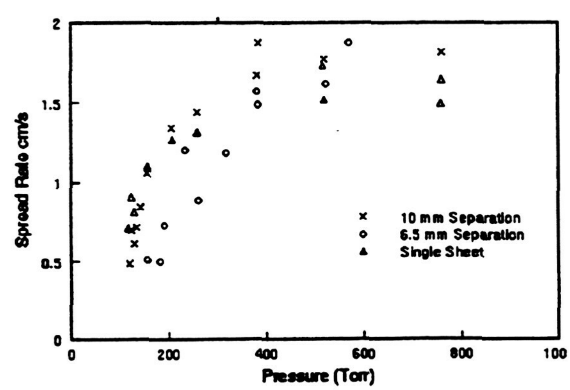


Figure 5. Flame spread rate versus pressure for single sheets and parallel sheets 6.5 and 10 mm separation distances in dry air in normal gravity. Flames were propagating downward.