

INTERACTIONS BETWEEN FLAMES ON PARALLEL SOLID SURFACES

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Introduction

The interactions between flames spreading over parallel solid sheets of paper are being studied in normal gravity and in microgravity. This geometry provides interesting opportunities to study the interaction of radiative and diffusive transport mechanisms on the spread process. Radiative losses from flames are recognized as an important component of flame spread [1, 2]. These loss mechanisms are changed when the flame interacts with other flames. Most practical heterogeneous combustion processes involve interacting discrete burning fuel elements, consequently, the study of these interactions is of practical significance. Owing largely to this practical importance, flame interactions have been an area of active research, however microgravity research has been largely limited to droplets, [3, 4]. Consideration of parallel solid surfaces has been limited to 1-g studies [5, 6, 7, 8, 9, 10]. Of these works, [5, 7, 8] considered flame spread.

Emmons and Shen [5] 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 [6] performed a theoretical and experimental analysis of the burning rate between two parallel fuel surfaces. Assumptions similar to those in the work of De Ris [11] 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 [12] and Ohlemiller [13] 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 [14] is an upward burning test with a single sheet of material. As Ohlemiller [13] 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. This issue is also being addressed in another program [15] where the influence of radiant preheating on ignitability and spread is addressed. The radiant interaction between surfaces is also very important in terrestrial fire safety; the classic example is wood, which is nearly nonflammable as a single large sheet but very flammable if multiple pieces are arranged to allow radiant interaction.

The parallel spread geometry offers several distinct differences from single sheet spread, the appearance of the internal flame, instabilities of the internal flame, pressure dependence of spread rate and spread rate variation with separation distance. These issues are being studied as part of this program and are discussed below.

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. The majority of the tests were conducted in a 27 liter chamber although some of the early tests were in a 45 liter chamber. The fuel was Kimwipe laboratory wipes, selected because of their uniform thickness and low mass/area (1.1 mg/cm^2). The sample frame opening was 5 or 7.5 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 0.13 to 2 atmospheres, and separation distances between the fuel sheets varied from 6.4 to 76 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 could not be tracked; for these cases the spread was determined from only the sheet aligned with the camera. The overall spread rate measurement accuracy was greater than the repeatability which was of the order of 0.15 cm/s.

A limited number of tests were conducted in flowing air on the NASA DC-9 aircraft using the Spacecraft Fire Safety Facility. This facility provides a flow through a chamber that is similar to the one used in the drop tower tests. Experimental timing and video recording were similar to the drop tower tests. The details of the experimental facility are described elsewhere [16].

Interferometer Development

To study the conductive transport in these flames, an interferometer system is under development for use in the drop tower. The system takes advantage of a single beam interferometer: Point Diffraction Interferometry (PDI) [17] which uses a portion of the light through the test section to provide the reference beam. This provides considerable resistance to vibration effects seen with traditional interferometers. Like other interferometric and Schlieren systems, it is fundamentally a line of sight measurement and is subject to the usual edge and concentration effects. The advantage over Schlieren and shearing interferometry systems is that the fringes are lines of constant index of refraction rather than of the gradient so the images are more readily interpreted. The disadvantage is that it is less adjustable to accommodate a range of temperature gradients. The implementation of the system took advantage of an imaging soot volume fraction system which was already configured for use in the 2.2 second drop tower. Results from a breadboard system are shown in figure 1 which contains the interferogram of a vertical flat plate at 300 C and figure 2 which contains a comparison of temperature profiles from the vertical flat plate obtained with a thermocouple and the interferometer. Figure 3 is an interferogram of flames spreading over parallel sheets in normal gravity. The system offers significant promise as a diagnostic for visualizing the interactions between these flames in drop tower applications.

Results and Discussion

It was found that although the flame interactions in microgravity display trends similar to those seen in normal gravity, the microgravity flames exhibit greater interaction for a given separation distance, the difference being attributed to the absence of the buoyant flow. The interaction displays four phases as separation distance is increased (Fig. 4): 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, and 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 [7] 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 (Fig. 5) where separate flames are observed at 10 mm separation while the low-g flames were still connected at 40 mm separation.

Figure 6 contains the spread rates for parallel sheets at various separation distances with helium and nitrogen diluents. A separation distance of infinity was used to represent the single sheet case. As is evident on the plot, the spread rate reduction at close separation extended to greater separation distances for helium than for nitrogen. For nitrogen diluent, once the inner flame was completely established, the spread rate approximated the single sheet value. For helium, an actual maximum is present, similar to the 1-g results of Kurosaki et al. [7]. The greater dependence on separation distance for the helium case is 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 can be attributed to increased conductive losses to the paper. Assuming the inner flame to be an oxygen limited process a simple dimensional comparison of the heat loss to the fuel surface suggests that as the separation distance is reduced, the heat loss to the surface becomes greater than the energy available from reaction. The limited change in the spread rate with separation for the nitrogen diluent is less extensive than that reported for 1-g interactions [7] particularly given the evident interaction in the video record.

The change in the non-dimensional spread rate as a function of pressure is presented in figure 7. The rates are non-dimensionalized using the thin fuel spread model of De Ris [11]. Using this relation the non-dimensional spread rate is:

$$\bar{V}_f = V_f / \left(\frac{\sqrt{2}\lambda}{\rho_w c_{pw} \tau} \frac{(T_f - T_v)}{(T_v - T_\infty)} \right)$$

Where the flame temperature is calculated using the adiabatic flame temperature [18] and the vaporization temperature was taken to be 618 K. The product of the solid thickness and density is 0.0011 gm/cm² for the half-thickness and the specific heat is 1.26 kJ/kg/K. The mixture thermal conductivity was calculated using the Sandia Transport Package [19]. The De Ris model predicts that spread for a thin sheet is independent of pressure. However for sets of parallel sheets in microgravity, there is a clear pressure dependence, whereas the 1-g data show very limited dependence once the inner flame is established at approximately 0.15 Atm. This pressure dependence, in microgravity is consistent with the results of Bhattacharjee et al. [2] who observed similar pressure dependence for the Solid Surface Combustion Experiment (single sheets). Their modeling suggests that the difference between the measured spread rate and the De Ris [11] prediction is due to radiative losses from the flame while the spread rate increase with pressure is also due to radiation, in this case, radiative heating of the preheat zone. Figure 8 is a logarithmic plot of the same data with associated linear fits which show the spread rate dependence on pressure is well predicted by a power between 0.75 and 1.

Conclusions

The current work has shown the importance of detailed understanding of the transport processes that contribute to the flame spread. The planned implementation of an interferometer in the drop rig combined with radiometric measurements of flame radiation will help determine the extent to which radiation from the flame to the surface participates in the spread. The flame spread as a function of separation distance shows stronger interaction effects for helium than for the nitrogen case. This is attributed to the difference in the thermal diffusivity.

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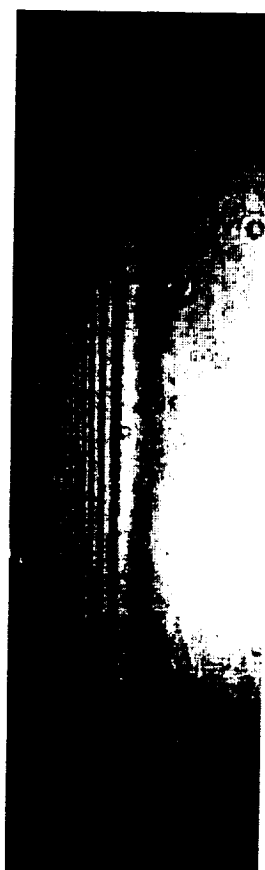


Figure 1. Interferogram of the edge view of a vertical heated flat plate at 300 C. The surface of the heated plate is on the left of the image

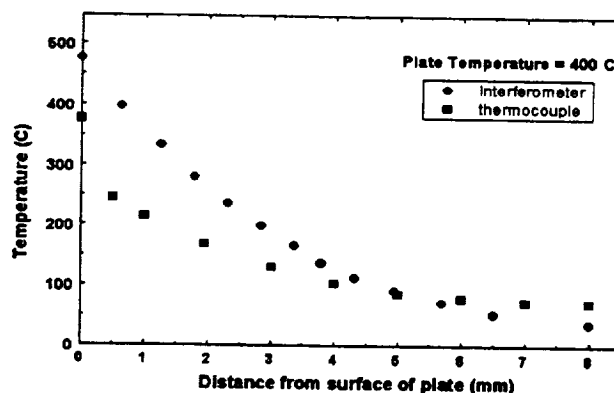


Figure 2. Temperature versus distance from a 400 C vertical flat-plate determined using the Point Diffraction Interferometer versus thermocouple measurements.

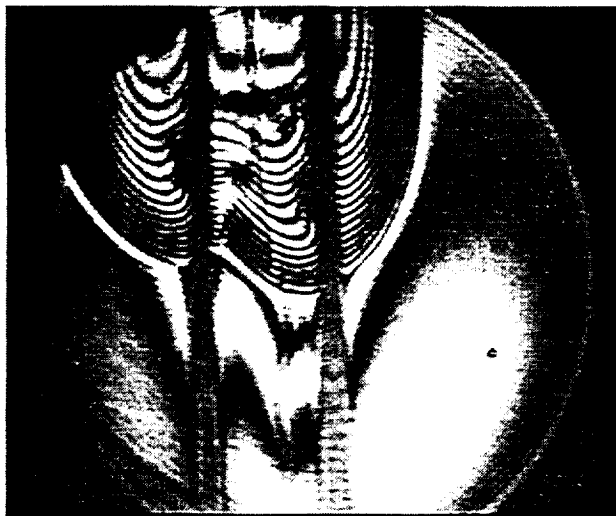


Figure 3 Interferogram of edge view of flames spreading downward (1-g) over parallel sheets in ambient air. The separation distance is 6.5 mm. The line visible between the fuel sheets is the ignitor wire.



Figure 4. Edge view of flames propagating in microgravity over parallel sheets of Kimwipe at different separation distances in 30% oxygen, balance nitrogen, at 1 Atm. Separation distances in order (top to bottom, left to right) are 6.4, 10, 20, 30, 40 and 50 mm. Glowing material at top of each flame is the ignitor wire.

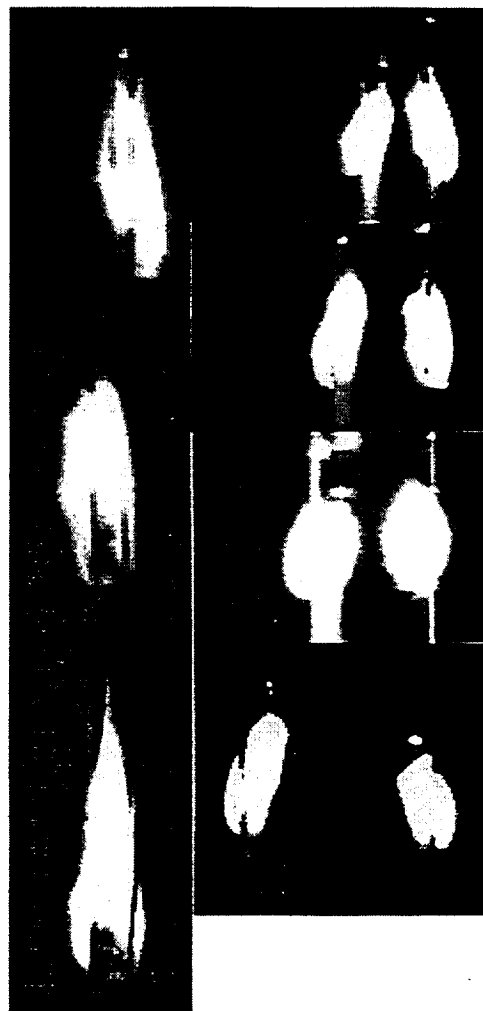


Figure 5. Edge view of flames propagating in normal gravity over parallel sheets of Kimwipe at different separation distances in dry air at 1 Atm. Separation distances in order (top to bottom, left to right) are 3 mm, 4.7, 6.4, 10, 15, 20, and 30 mm.

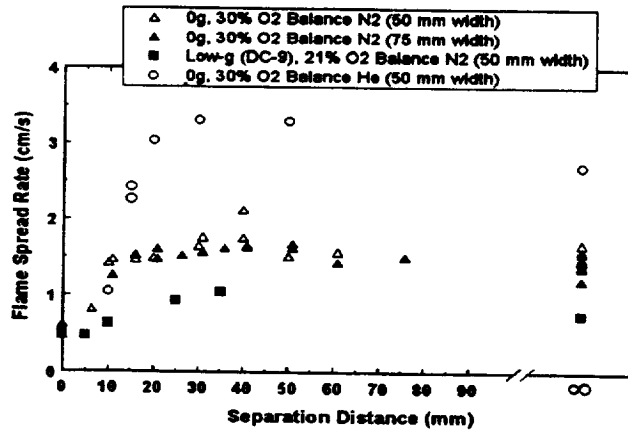


Figure 6. Spread rate versus separation distance for parallel sheets in microgravity at 1 atmosphere. The DC-9 tests were in air with a forced flow velocity of 10 cm/s. The other tests were in quiescent mixtures of 30% oxygen with nitrogen or helium.

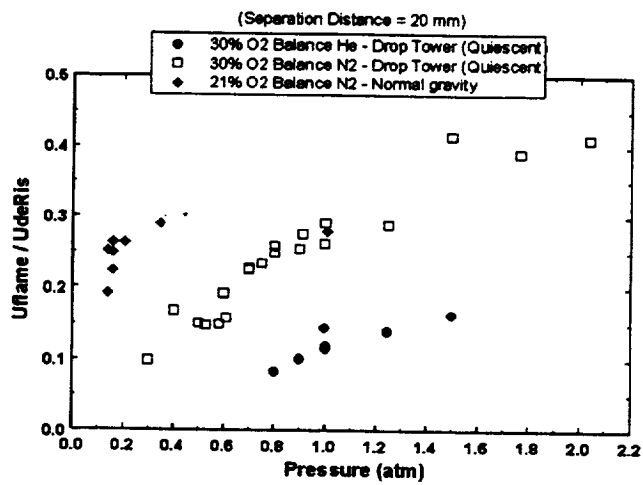


Figure 7 Non-dimensional spread rate versus pressure in 1-g and in low-g.

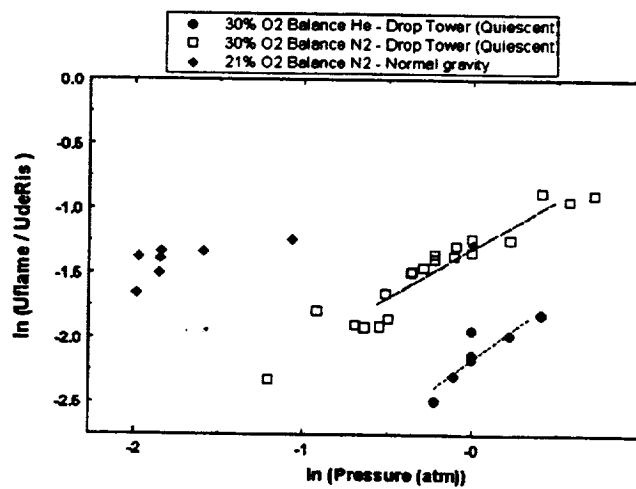


Figure 8 Non-dimensional spread versus pressure. The slope of the nitrogen diluent case is 0.76 and the helium diluent case is 0.98.