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# Diffusion Flame Tip Instabilities of a Wide Sample in Microgravity

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## Introduction

This work is a study of diffusion flame tip instabilities of a wide thermally thin sample in a microgravity environment. The purpose of this work is to determine the thermodiffusive and hydrodynamic instability mechanisms which cause a spreading diffusion flame to become corrugated and later fragment into smaller separate flames that we call flamelets. These thermodiffusive and hydrodynamic mechanisms are prominent forces in the near limit because buoyancy is quashed in the microgravity environment. A fundamental knowledge of the underlying mechanisms controlling the extinction limit of a diffusion flame can be applied to any real world device involving a spreading diffusion flame as well as fire safey applications on earth and in space.

Our work, which combines microgravity experiments, theoretical models, and numerical computation, is a joint effort between NASA and Michigan State University. Experiments in the 2.2 second drop tower at NASA Lewis Research Center in the Microgravity Combustion Branch have been a preliminary step in locating a region where these instabilities are prevalent. These positive results will be discussed as well as the second phase of our project and future plans and recommendations.

## Experiment

### Combustion Wind Tunnel Rig

Experiments were conducted by dropping the Microgravity Combustion Tunnel Rig in the 2.2 second drop tower at NASA. The Combustion Tunnel Rig is a droppable wind tunnel that provided opposed flow velocities of 1-5 cm/s at atmospheric pressure. A rig gas resevoir filled prior to dropping supplied a chamber that contained the sample with premixed air. The flow was preset by a pressure regulator at the bottom of the rig and was controlled by a critical flow nozzle. Before entering the chamber, the air was straightened by parallel plates and then proceeded through a porous plate. A T-vent at the top of the chamber exhausted the flowing gas.

Two video cameras showed a front and side view of the burning sample by recording through portholes on the chamber walls. These videos will be quantitatively analyzed by digitizing the frames using the Tracker 3 Object Tracking and Image Processing Software.

### Sample

The fuel used was Kimberly Clark brand kimwipes 10.5 cm in width which was ignited using a Kanthall hotwire. A thin strip of nitrocellulose was glued across the top of the sample and the samples were glued to a Micarta board sample holder. An alumina ceramic bar that held the wire in place and the Micarta board insulator holder provided a relatively uniform one-dimensional flame front. For the first half of testing, an aluminum foil backing which acted as a heat sink was placed a finite distance away from the sample which quenched the flame on the back side. Later, a steel backing .001 inch thick was employed because a more one-dimensional flame could be established. The aluminum foil wrinkled ahead of the flame due to heat conduction. Care was taken to prevent the sample and backing from touching. It was necessary to avoid changes in heat conduction which could alter the fundamental processes of the burning sample even though it is considered a thermally thin fuel. The purpose of the steel was to obtain the near extinction limit in air at higher flow velocities rather than at lower $O_2$ concentrations and velocities. Also, a larger range of conditions in the near limit region was obtained.

At the top of the drop tower the sample was ignited in 1-g and flushed with the gas concentration for a proper period of time before dropping. After a one-dimensional flame front was established, the sample was dropped.

**Experimental Results**

The tests which were performed without the steel backing and at $O_2$ concentrations of 17-20% $O_2$ concentrations did not show a region of instabilities. Therefore a heat sink was placed behind the sample to move the extinction limit to a higher $O_2$ concentration and flow velocity. This was predicted by the Diffusion Near Limit Flame Spread Map of S. Olson [4]. This was desirable because higher $O_2$ concentrations would give a more robust flame established in 1-g and higher opposed flow velocities would wash away buoyant effects in the transition period from 0 to 1-g more quickly.

The first heat sink backing employed was aluminum foil. Results from this test are shown in Table 1.

| Velocity (cm/s) | Number of tests | Tests with flamelets | Tests that extinguished |
|---|---|---|---|
| 2 | 2 | 1 | 1 |
| 3 | 3 | 1 | 1 |
| 4 | 6 | 4 | 0 |
| 5 | 3 | 0 | 0 |

**Table 1. Experimental results for sample with aluminum foil backing**

For all tests using this backing, air was the opposed flowing gas, and an aluminum sample holder was used instead of the insulating Micarta Board. Four of the six tests at 4 cm/s opposed air velocity produced flamelets. After dropping, a transition period which depends on the opposed air velocity occured in which the flame front turned from yellow to blue with the exception of char pieces. For all tests with the aluminum holder, the blue flame front retreated inward from the sides of the holder to form flamelets. No more than two flamelets would form with the aluminum holder which was probably caused by a loss of heat at the sides near the holder. Prior to flamelet formation, the smooth flame front would become corrugated and would eventually break apart. For two tests at 4cm/s in which flamelets occurred, the beginnings of oscillations were observed. The spherical flamelet area would become larger, then smaller. Flamelet observations at 2 and 3cm/s showed unstable behavior because no increase in surface area occurred. Only a rapid decrease in size was seen. One of the two tests at 2cm/s opposed flow showed the flame to extinguish before hitting the ground. One of the three tests at 3cm/s did likewise.

The side views of these flames showed very large standoff distances from the leading edge of the flame which was retreating rapidly from the flow.

The steel backing provided a much larger region of conditions where flamelets were observed. This was in part due to the conductivity of steel being anywhere from 4 to 10 times smaller than aluminum. Also, the steel was placed at a larger distance from the sample compared to the foil backing, so less heat was taken from the sample. The results are shown in Table 2.

| Velocity (cm/s) | Number of tests | Tests with flamelets | Tests extinguished |
|---|---|---|---|
| 1 | 3 | 2 | 1 |
| 1.5 | 2 | 2 | 0 |
| 2 | 4 | 3 | 0 |
| 3 | 3 | 3 | 0 |
| 4 | 3 | 2 | 0 |
| 5 | 1 | 0 | 0 |

**Table 2. Experimental results of for sample with steel backing**

In two of the three tests that exhibited flamelets for both the 2 cm/s and 3 cm/s conditions, *three* evenly spaced flamelets formed across the sample. The relative sizes of each flamelet were similar, and one or two oscillations were observed in which the surface areas increased and then decreased. The flamelets at these conditions appeared to be relatively stable in the sense that they were not decreasing at a dramatic rate similar to the flamelets that extinguished with the aluminum foil backing. The flamelets at the 2 cm/s and 3 cm/s conditions were not spherical but oval with the major axis along the horizontal axis. The leading edge and sides of the flamelets were bright blue tracing out the shape of a bowl. However, the middle and back portions were more diffuse and darker. This resembled a very round and small flame front, which indicated the stable nature of the flamelets at these conditions. For the conditions at 1.5 cm/s and 1 cm/s where flamelets were unstable and shrinking quickly, the flamelet shape was spherical.

Interactions between flamelets were also observed. In one test at 4cm/s which showed flamelets, the oval flamelets combined to form the original flame front. As the flame front retreated rapidly from the left, a small flamelet broke off from the flame front.

## Data Analysis and Future Experiments

The work completed in the 2.2 second drop tower indicated an observable region where flame instabilities exist and can be studied in greater depth. Since oscillatory behavior was on the order of the spread rates of these flames, no more than 2 oscillations were observed in the 2.2 second drop tower. The oscillatory nature of the flamelets is shown for two separate tests in Figures 1 and 2.

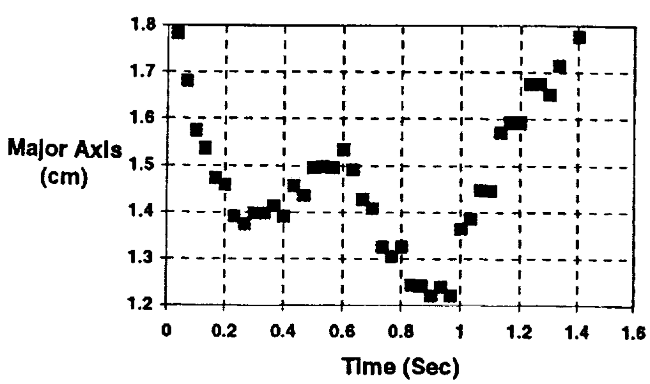


**Figure 1: Major Axis Oscillation Middle Flamelet 2 cm/s Opposed Flow**

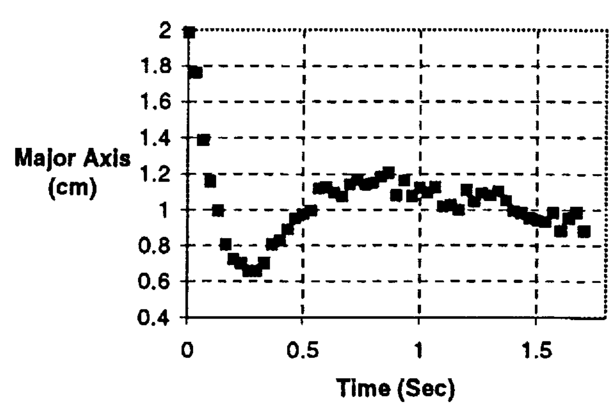


**Figure 2: Major Axis Oscillation Left Flamelet 2 cm/s Opposed Flow**

The unstable behavior is indicated by the oscillatory change in size of the major axis of the flamelet. The major axis of the flamelet was chosen because the most prominent size change was along this axis, however, the minor axis exhibited oscillations also. Time zero is the instant that the flamelet forms from the flamefront within the 2.2 seconds. The oscillations indicated the near limit extinction activity which has also been seen in other microgravity diffusion flames such as the candle flame in microgravity [5] and [1], and the buoyant low-stretch tests of S. Olson [3]. Therefore, these instabilities are fuel independent and can be applied to fundamental knowledge of the near limit region. The goal of this research is to explain flame survival mechanisms that must either optimize or minimize some physical quantity in order to exist. It is expected that the Lewis number of the species that are most important in promoting the reactions are generally less than unity, although the precise implications of this fact are not completely clear. A numerical analysis of the problem will be developed with Lewis number less than one by referring to the linear stability analysis of Kim, et al. [2] as a foundation.

Due to the high maintenance of the 5 second drop tower, the 2.2 second drop tower was used to pinpoint the instability region of interest. Therefore, the second phase of testing in the 5 second drop tower will begin in October of 1998. Weaker flames are observed in the 5 second tower than in the 2.2 second tower, so we will begin testing in air from 3-7cm/s where 7 cm/s will be the maximum velocity tested because higher velocities mask the diffusion characteristics of the flames. The resulting images will be digitized using the Tracker 3 at NASA. The flamelet diameter and the intensities in the blue region will also be tracked over time. If possible, flame temperature will be recorded, so heat flux can be determined, and flamelet interaction will be studied. Experimental results will be compared to the numerical model so fundamental processes can be explained.

## Acknowledgements

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