Sub Topic: Fire

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Concurrent flame growth, spread and extinction over composite fabric samples in low speed purely forced flow in microgravity

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Abstract: As a part of the NASA BASS and BASS-II experimental projects aboard the International Space Station, flame growth, spread and extinction over a composite cotton-fiberglass fabric blend (referred to as the SIBAL fabric) were studied in low-speed concurrent forced flows. The tests were conducted in a small flow duct within the Microgravity Science Glovebox. The fuel samples measured 1.2 and 2.2 cm wide and 10 cm long. Ambient oxygen was varied from 21% down to 16% and flow speed from 40 cm/s down to 1 cm/s. A small flame resulted at low flow, enabling us to observe the entire history of flame development including ignition, flame growth, steady spread (in some cases) and decay at the end of the sample. In addition, by decreasing flow velocity during some of the tests, low-speed flame quenching extinction limits were found as a function of oxygen percentage. The quenching speeds were found to be between 1 and 5 cm/s with higher speed in lower oxygen atmosphere. The shape of the quenching boundary supports the prediction by earlier theoretical models. These long duration microgravity experiments provide a rare opportunity for solid fuel combustion since microgravity time in ground-based facilities is generally not sufficient. This is the first time that a low-speed quenching boundary in concurrent spread is determined in a clean and unambiguous manner.

Keywords: flame spread in forced flow, microgravity combustion, quenching extinction, flammability boundary, concurrent flow

1. Introduction

Flame spread and extinction over condensed fuels in a microgravity environment has been the subject of extensive theoretical and experimental studies due to the importance of fire safety in human space missions [1-4]. Compared with burning in normal gravity, diffusion flames in microgravity are not affected by buoyancy-induced flow, thus providing a chance to study the fundamental mechanism(s) of low speed flame quenching [5]. Transition from solid diffusion flame spreading to quenching extinction is a slow heat loss process characterized by a relative increase in the rates of radiative and conductive heat losses compared to the rate of heat generation [3]. Long duration microgravity time is desired for such studies, which in general cannot be achieved by ground-based facilities.

Recently, NASA's Burning and Suppression of Solids (BASS and BASS-II) project examined the burning and extinction characteristics of a variety of solid fuel samples aboard the International Space Station. Different thermally thin and thermally thick solid fuels were burned in concurrent, opposed or stagnation flow configurations in a small flow duct. Each experimental run took tens of seconds to minutes, depending on the sample type and flow conditions. The challenge with thin solid samples in concurrent flow, compared with other configurations, is that flame spreads much faster, and flames can become quite long. Because of size limitations, the fuel sample is relatively short and so a concurrent spreading flame may not reach fully steady spread within the sample length. The transient ignition and flame growth process, however, provides a flame spread history that can be useful for the development of transient flame models [6]. In BASS-II, a nitrogen dilution scheme is used whereby the oxygen percentage in the Glovebox can be decreased to a preset value so that flame spread can be studied with oxygen percentage as an additional variable parameter [7]. This facilitates the determination of the oxygen-flow velocity flammability boundary of materials.

In this paper, BASS and BASS-II results will be discussed in detail. Flame growth, spread and quenching extinction will be presented for a thin composite cotton-fiberglass fabric burning in various oxygen concentrations and concurrent flow speeds.

2. Experimental

All tests were conducted in a small flow duct (shown in Fig. 1) within the Microgravity Science Glovebox aboard the International Space Station. The sample used is a composite cotton-fiberglass fabric blend (75% cotton, 25% fiberglass). The thickness of the sample is about 0.32 mm with an area density 18.2 mg/cm^2. The fabric is custom-made for a previous project SIBAL [8], hence it is referred to here as the SIBAL fabric. One major advantage of this fuel sample is the retention of sample structure integrity after the combustible (i.e. cotton cellulose) is consumed because of the fiberglass mesh. It does not crack or produce curly ash typically seen in pure cellulose samples such as paper or cloth. In addition to [8], experimental studies using SIBAL fabric can be found in [9, 10].

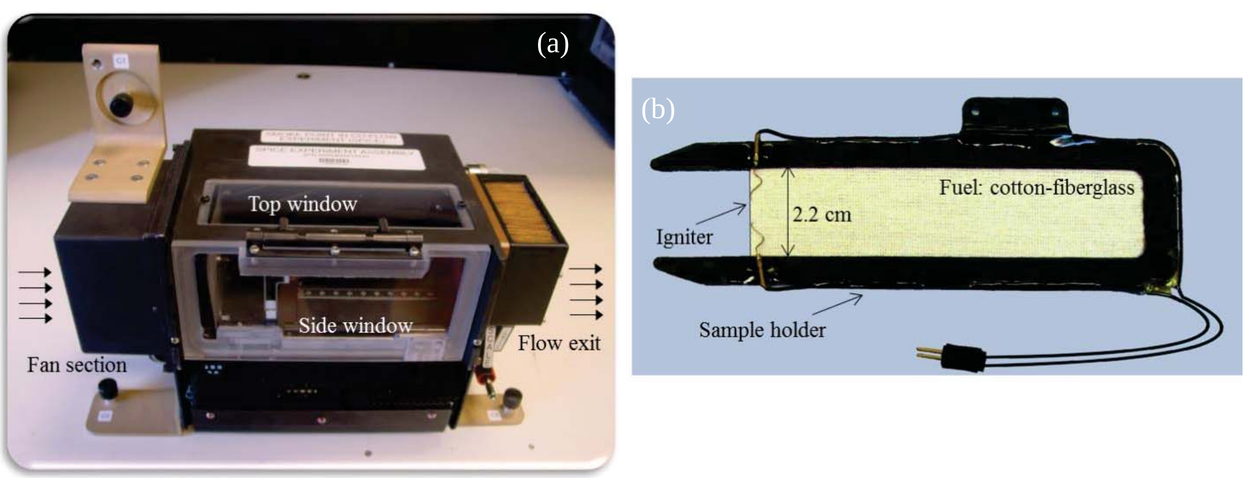

Figure 1: Experimental setup. (a): small flow duct. (b): fuel sample, sample holder and igniter.

In the experiment, SIBAL fuel samples of two different widths, 1.2 cm and 2.2 cm, were used. Both have exposed length of 10 cm. The samples were mounted in stainless steel sample holders.

The fuel sample mounted to the holder was placed in the small flow duct of cross-sectional size of 7.6 cm × 7.6 cm. The flow speed could be varied from 1 to 55 cm/s. The tests were conducted in ambient oxygen molar fraction of 16% to 21%. Ambient pressure was 1 atm. It should be noted that for a given test the oxygen concentration was fixed while the flow speed could be varied.

A Kanthal™,[1] hot wire was used to ignite the fuel sample leading edge so that the flame can spread in a concurrent configuration. The flame growth process was recorded by two cameras. The side-view video camera provided edge-on images of the flat samples at standard video framing rates (29.97 frames per second). The top-view digital camera looked down on the top fuel surface and provided high resolution still images of the flame at a rate of about one image every 1.2 seconds. When flow speed and oxygen concentration were low, the flame became very dim blue and was difficult to see in the side video camera. The top-view camera exposure times were long enough (1/8 s-1/4 s) to easily capture high quality flame images even for dim flames right before quenching. These still images provide a time history of flame quenching that can be used to compare with transient model results.

3. Results and Discussion

A total of 27 tests were carried out for the fabric samples in BASS-II, including 6 quenching tests, 3 non-ignited tests, and 1 blow-off test. These are listed in the table in the Appendix. In addition, four tests from the BASS series were selected as listed at the bottom of the Appendix. These four tests are all 21% O_2 cases at a fixed flow velocity during each test. For those cases with flow velocity variations, the starting and the final velocities are indicated in the velocity column. The rate of velocity change varies from case to case depending on the communication between the astronauts and the ground crews and the manual adjustment time by the crew. Many of these tests were used to determine the low-speed quenching limits as a function of oxygen percentage. In some tests, the flame quenched quickly or was not ignited. These samples were reused in additional tests as indicated in the Appendix. These partially burned samples were ignited with a retractable igniter on one side of the sample at the fuel burnout position. These reused samples in general had a short unburned length and provided less quantitative data, thus will not be discussed in this paper.

Figure 2 shows flame development stages of a 2.2 cm sample in 10 cm/s flow, 21% O_2. Figure 2(a) shows side-view flame tracking of flame tip, flame base, and flame length. Figure 2(b) shows flame edge view video still images at different stages. Note in the figure, flow is from right to left. After the igniter was turned on, a strong flame was initiated on both sides of the solid fuel. The flame was stabilized and started to grow and move downstream. At about 19s, the flame reached a limiting constant length and a steady spread rate relative to the laboratory [11]. This steady spread state lasted for around 9s. The flame images look almost identical during this stage, as can be seen at 20.17s and 24.83s in Fig. 2(b). Then the flame tip (or more precisely the flame preheating front) moved close to the end of the fuel sample, and the flame decayed in size until complete burnout. The whole combustion process took about 40s.

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[1] Mention of trade names or commercial products is for descriptive purposes only and does not constitute endorsement or recommendation for use by the U.S. Government.

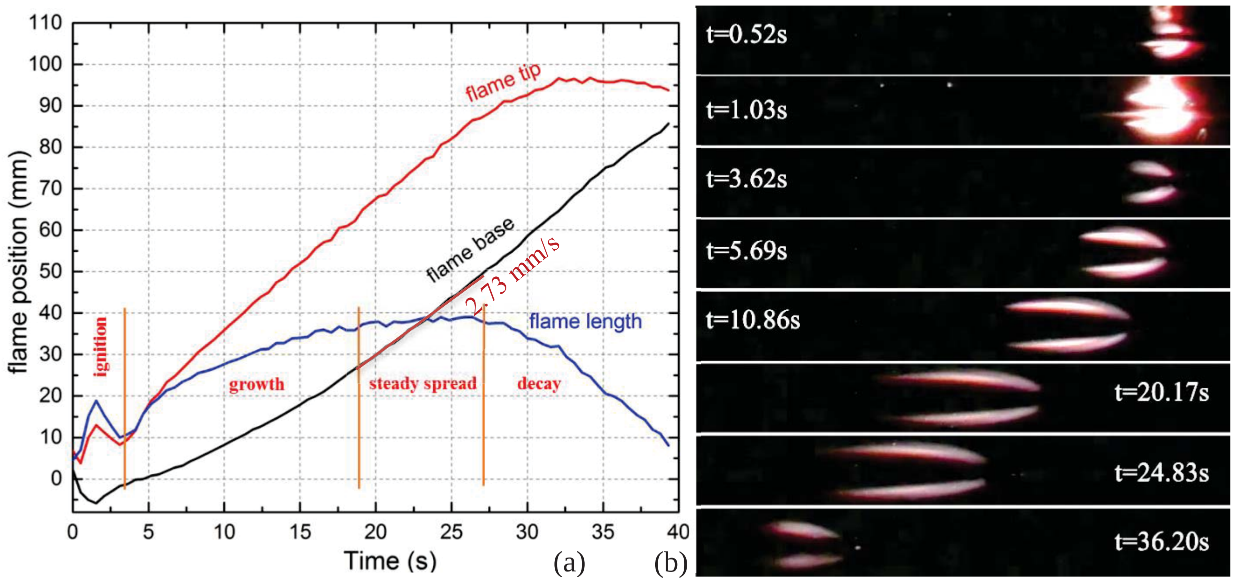

Figure 2: Flame development on a 2.2 cm sample in 10 cm/s concurrent flow, 21% O_2. (a): Side-view flame tracking. (b): Side-view image sequence. Flow is from right to left.

Figure 3 shows flame development stages of a 2.2 cm sample in 5 cm/s flow, 21% O_2. Unlike the flame in 10 cm/s flow in Fig. 2, the flame from the side-view video is very dim in this case. Figure 3 thus shows the top-view images and tracking from those images. Because the flow speed is lower, it took more than 60s to burn the whole sample. Steady spread time lasts for about 21s, much longer than the 10 cm/s flow case. Virtually identical images at 35.59s and 45.59s are shown in Fig. 3(b). In the top-view images, we can find bright spots behind the flame base when the flame passes. The spots come from the smoldering of a small amount of fuel that is not complete consumed by the flaming combustion. Compared with the 10 cm/s case, the 5 cm/s case has a shorter flame and spreads more slowly.

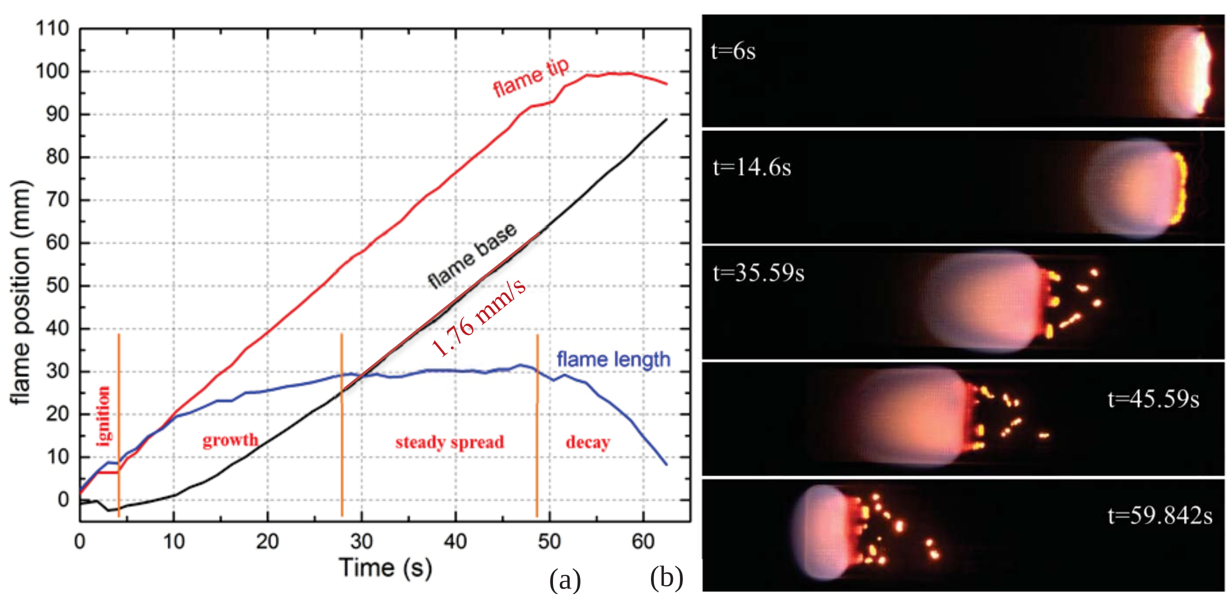

Figure 3: Flame development on 2.2 cm sample in 5 cm/s flow, 21% O_2 (a): Top-view flame tracking. (b): Top-view image sequence. Flow is from right to left.

Steady flame spread rates in different flow speeds and oxygen percentages are plotted in Fig. 4 for both 2.2-cm and 1.2-cm samples. Note in some cases flow speed was varied during the test. Steady flame spread here means the flame reached a constant spread rate for more than 20s. Flames spread more slowly across the narrower samples, at lower flow velocities and at lower oxygen percentages.

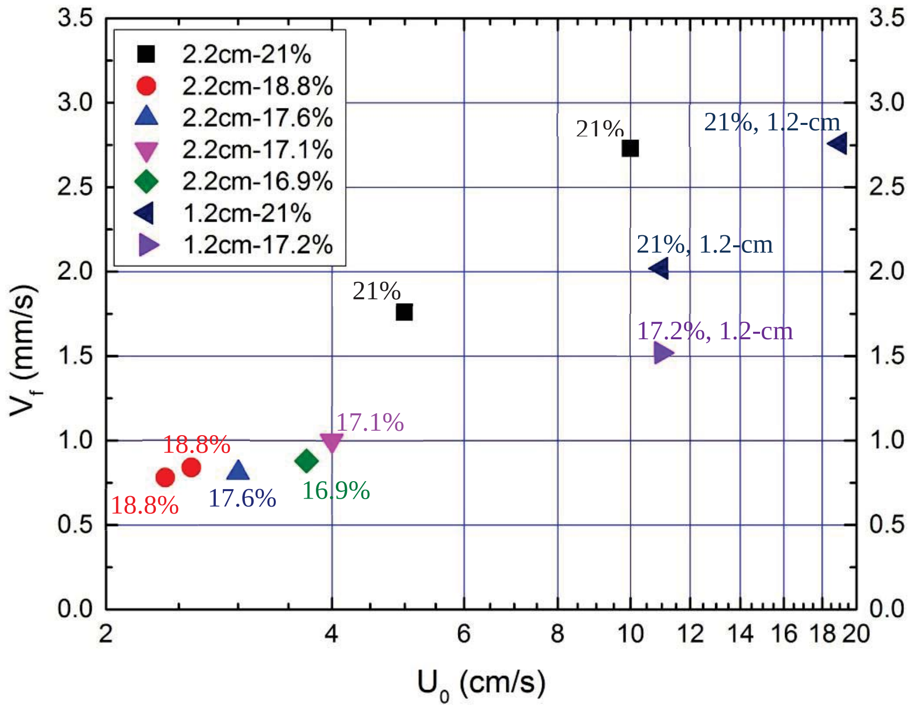

Figure 4: Steady flame spread rate for both 2.2-cm and 1.2-cm wide samples.

Figure 5 shows a typical flame quenching sequence in the BASS-II experiment. A 2.2 cm wide sample in 18.7% O_2 was first ignited at 10 cm/s flow. Flow speed was decreased to 2.2 cm/s incrementally after ignition. Figure 6 shows flame tracking and flow speed vs. time. After ignition, the flame started to grow. As the flow speed was reduced both flame length and flame width dropped accordingly with flow. After 25s, flow velocity was reduced to 2.2 cm/s and held there for the remainder of the test. As shown in Fig. 5, both the flame length and flame width continued to decrease approaching a circular-shaped blue flame seen from the top. The size of the flame continues to shrink until extinction is reached. This is typical in a quenching extinction sequence. As the quenching limit is approached (in this case by turning down the flow velocity), the fuel pyrolysis rate and combustion Heat Release Rate (HRR) are reduced, and radiation loss becomes a significant fraction of the HRR from the shrinking the flame. When the flame becomes small enough, conduction becomes the additional heat loss. The post-burn photo of the sample in Fig. 5 shows the narrowing of the burnt region as the flame shrinks toward extinction with a substantial part of the fuel left unburnt along the two sides of the sample holder. Although this is a concurrently spreading flame, the quenching sequence shows similar characteristics in opposed flow [2]; the flame is becomes circular, indicating the importance of three-dimensional heat and mass transfer near the limit.

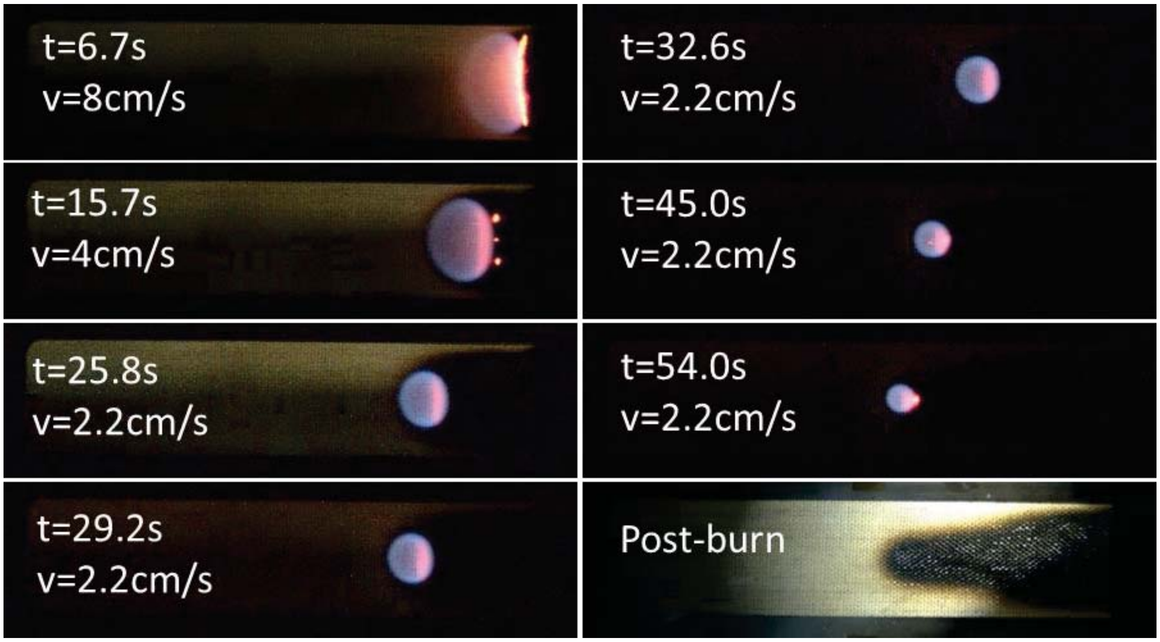

Figure 5: Top-view of a flame quenching sequence. 2.2 cm wide sample in 18.7% O_2. Ignited at 10 cm/s flow, reduced to 2.2 cm/s. Flow is from right to left.

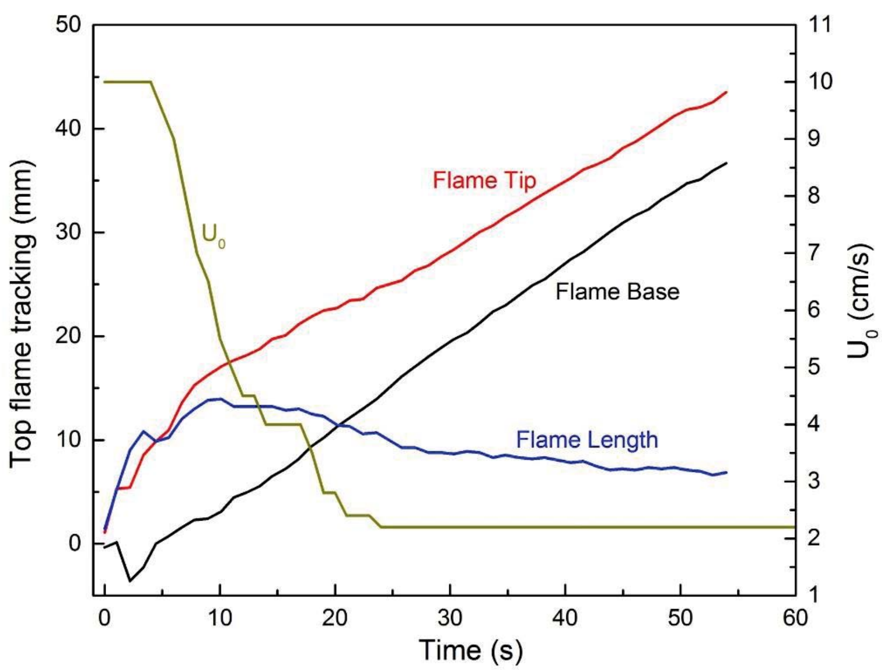

Figure 6: Flame tracking and flow speed vs. time. 2.2 cm wide sample in 18.7% O_2. Ignited at 10 cm/s flow, reduced to 2.2 cm/s.

For this thin fabric fuel in concurrent flow, flame spread rate is relatively large and the sample is not long enough to fine tune the flow speed during the one to two minutes of experimental run time. It is difficult to get to the desired near-quenching-limit state every time. Six quenching cases were achieved during BASS-II for the SIBAL sample, four of them were for the 2.2-cm width samples. Along with the near-limit stable flame data, we were able to draw part of the quenching branch of the flammability boundary as shown in Fig. 7 for 2.2cm wide SIBAL fabric. Quenching flow velocities were found to be between 1 and 5 cm/s with higher velocity at lower oxygen percentage. This trend of the quenching boundary supports the prediction by earlier theoretical models [1, 8]. The bottom part of the flammability boundary that supports combustion in the lowest oxygen environment is expected to be flat in this figure and cannot be determined accurately by this velocity-varying procedure. Very near the boundary, ignition of the sample is sporadic. A procedure with gradually decreasing oxygen is needed. In addition, because of the limited number of tests, the quenching limit for the 1.2-cm wide sample was not resolved. But it can be seen that the narrow sample has a smaller flammable domain, as expected.

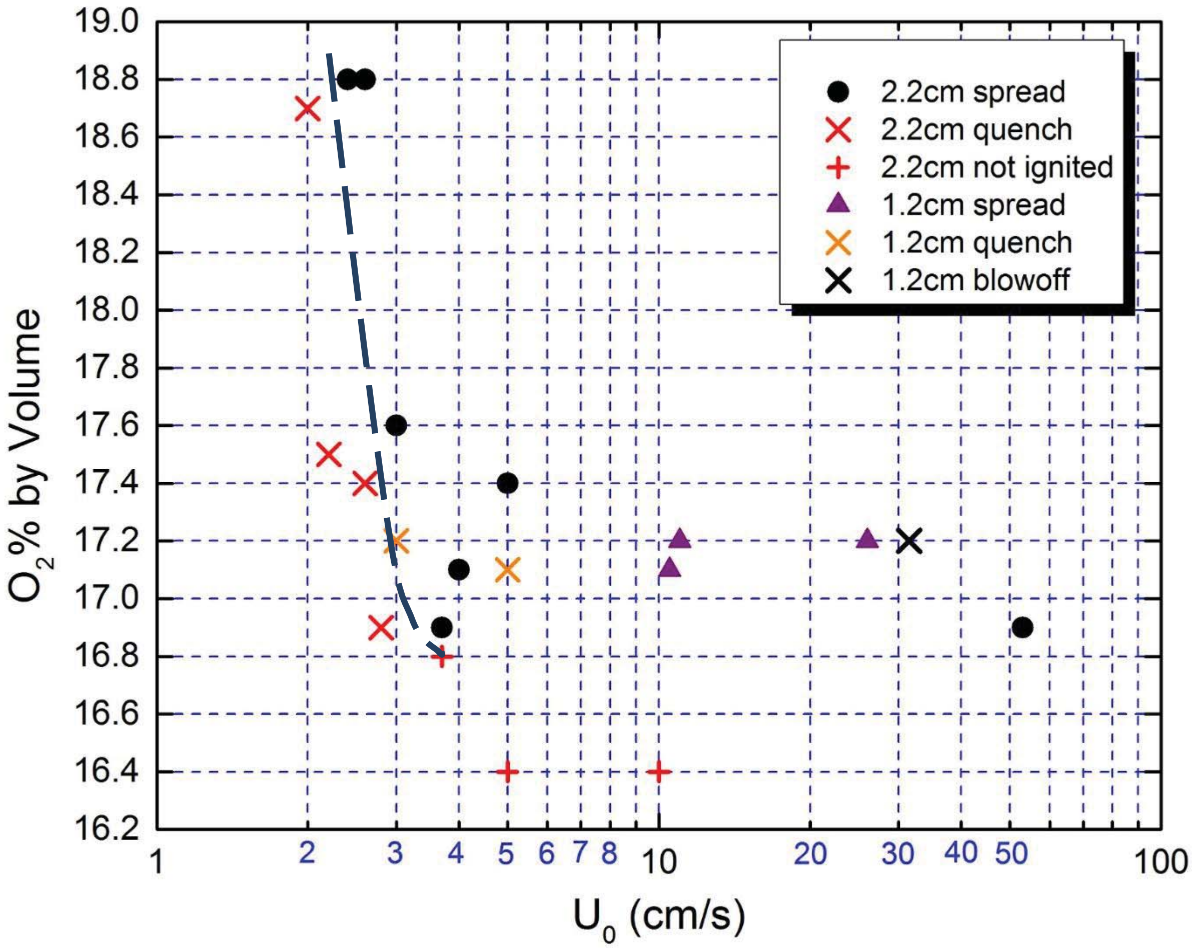

Figure 7: Flammability map for SIBAL fabric in concurrent flow in microgravity. The dotted line marks the experimental quenching boundary for the 2.2cm wide sample.

4. Conclusions

Concurrent flame growth and extinction over a thin flat cotton-fiberglass composite fabric sample was studied as part of the BASS and BASS-II space experiments aboard the International Space Station. These long duration microgravity experiments provided rare opportunities for solid fuel combustion studies. By reducing the flow velocity during the tests, quenching extinction limits were obtained accurately. The quenching velocities are small (between 1 and 5 cm/s), and an accurate determination is necessary to resolve the slope of the quenching boundary. The experimental data obtained supports earlier theoretical predictions (at least qualitatively) of solid flammability limits at low flow velocities due to radiative and conductive losses. The flame image sequence at quenching shows the flame shrinks both in length and width and the flame goes out in a three-dimensional manner.

In addition to obtaining quenching limits, the sequence of sample ignition, flame growth, and steady spread to final decay across the entire sample in low-speed purely forced flows were experimentally recorded. These are precious data to help us to understand the entire process of flame development in microgravity. They also provide the basis to check the theoretical model development. Recently, a three-dimensional transient numerical model has been published [6] that is suitable to simulate the present experiment. The model contains many material properties including kinetic rate constants. Currently, we are measuring and deducing the pyrolysis rate constants for SIBAL fabric in order to perform quantitative comparisons between the model and experiment.

5. Acknowledgements

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6. References

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Appendix: Test summary of flat SIBAL fabrics in concurrent flow in BASS and BASS II

Test No.	Sample width (cm)	Flow (cm/s)	O2 % by Vol.	Comments
GMT45-T1	2.2	10	18.5*	
GMT45-T2	2.2	10→5	18.5*	
GMT45-T4	2.2	10→2.2	18.7	Quenched
GMT45-T15	2.2	10→29	18.7	No Blow-off
GMT100-T5	2.2	10→2.4	18.8	
GMT100-T6	2.2	4.5→2.6	18.8	
GMT100-T13	2.2	4→2.2	17.5	Quenched
GMT100-T16	2.2	4→3	17.6	
GMT175-T9	2.2	10	16.4	No ignition
GMT175-T10	2.2	5	16.4	No ignition
GMT175-T18	2.2	5→2.6	17.4	Quenched
GMT178-T11	2.2	4	17.1	
GMT178-T12	2.2	5	16.8	No ignition
GMT178-T14	2.2	4→2.8	16.9	Quenched
GMT178-T17	2.2	6→53	16.9	No Blow-off
GMT190-T19	1.2	11	17.2	
GMT190-T20	1.2	11→3	17.2	Quenched
GMT190-T21	1.2	11→47	17.2	Blow-off
GMT190-T22	1.2	10.5→5	17.1	Quenched
GMT190-T23	2.2	10	17.2	Reused, did not ignite
GMT190-T24	2.2	10	18.2	Reused, one sided flame
GMT216-T25	2.2	5→2.5	20.8	Reused, ignited
GMT216-T26	2.2	5→2.5	20.8	Reused, ignited
GMT216-T27	1.2	5→2	20.7	Reused, ignited
GMT216-T28a	1.2	5	20.7	Reused, did not ignite
GMT216-T28b	1.2	5	20.7	Reused, did not ignite
GMT216-T29	1.2	5→2	20.7	Reused, ignited
GMT96-T8	2.2	5	21	BASS
GMT96-T7	2.2	10	21	BASS
GMT131-T10	1.2	11	21	BASS
GMT222-T11	1.2	19	21	BASS

*O_2 reading in these two tests might be inaccurate.