Sub Topic: Fire

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The Saffire Experiment: Large-Scale Combustion aboard Spacecraft

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Abstract: As part of the Saffire project, solid materials were burned aboard orbiting spacecraft in two sets of experiments. The materials, mounted within a large air flow duct, were substantially larger than fuel samples in all previous microgravity tests. Large-than-typical samples could be accommodated because the tests were remotely conducted in unmanned ISS supply vehicles just days before their controlled re-entry and burn-up in the atmosphere. In the first experiment, a large cotton-fiberglass fabric measuring 40.6 x 94 cm was burned in two separate tests (concurrent and opposed). In the second experiment, nine samples measuring 5 x 30 cm in area were burned in succession. Of these nine, two were sheets of cotton-fiberglass fabric, identical to the material burned in the first experiment, and were burned in the concurrent-flow configuration. Two digital video cameras were used to record flame behavior and spread rate. Other diagnostics included radiometers, thermocouples, oxygen, and carbon dioxide sensors. Results demonstrate the unique features of purely forced flow in microgravity on flame spread, the dependence of flame behavior on the scale of the experiment, and the importance of full-scale testing for spacecraft fire safety.
Keywords: Microgravity Combustion, Flammability

1. Introduction

Understanding the ignition and flame growth of burning materials is central to developing fire safety protocols for space. Currently, NASA relies on a test performed on Earth to rate materials for space use [NASA-STD-6001B]. If a material passes the test then it is assumed that it will be safe in the microgravity environment of space. However, there is a growing body of reduced-gravity experimental and theoretical evidence that some materials which do not burn on Earth will burn in space in similar conditions, as first suggested in [1].

An upward-spreading (concurrent-flow) flame on Earth is nearly always more hazardous than a downward-spreading (opposed-flow) flame. However, it is unclear which configuration is more hazardous in reduced gravity. Research shows that the answer may depend on the speed of the oxygen stream [2], so extrapolating Earth-based test results to space is even further complicated. In spacecraft, forced air circulation conveys oxygen to potential fires while on Earth, natural convection is the predominant means by which oxygen is transported to a flame.

Although large-scale fire tests on Earth are common, they had never been attempted in a space experiment for obvious reasons of practicality and safety. This is despite the fact that fire is a catastrophic hazard for spaceflight where the crew has very limited or no escape options. The spread and growth of a fire, combined with its interactions with the vehicle cannot be expected to scale linearly based on small-scale test data, and so there remains a substantial gap in our understanding of fire behavior in spacecraft.

2. Methods / Experimental

The Saffire experiments investigate intentionally-set, large-scale fires inside a spacecraft. For safety, they were conducted in unoccupied resupply vehicles for the International Space Station (ISS) [3]. The vehicles launched to the ISS with Saffire stowed onboard. Saffire stayed in the resupply vehicle and remained dormant while the vehicle was berthed with the ISS and its supplies were unloaded. After all supplies had been transferred, the crew carefully stowed ISS trash in the resupply vehicle, leaving adequate room for air circulation. Once the vehicle departed ISS, the Saffire tests were completed and all data was relayed to Earth. Finally, the vehicle was guided for destructive re-entry into the Earth's atmosphere.

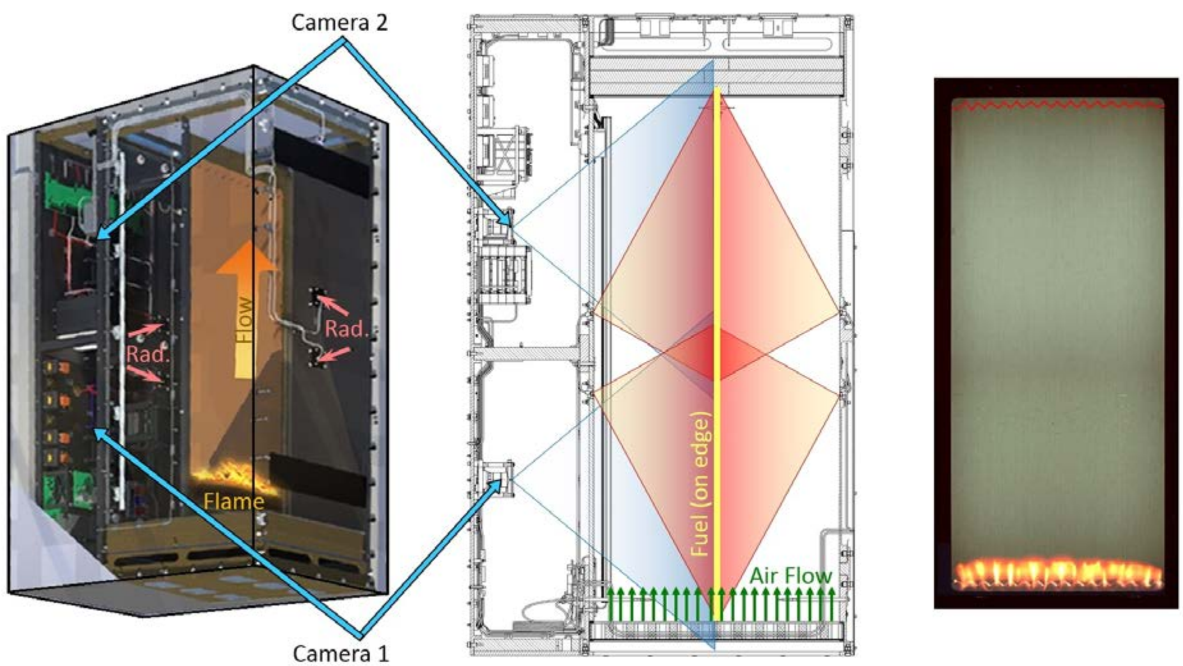

Figure 1: The Saffire flow duct (with the large sample) is shown on the left. Two cameras and four radiometers are indicated. In the center drawing, the camera and radiometer fields of view are shown by the cones, shaded blue and red, respectively. The right panel shows the flame shortly after ignition.

The hardware was a rectangular flow duct measuring 46 x 51 cm in cross section. Air flowed through the duct uniformly during the tests. Fig. 1 depicts the first experiment with the thin fuel sample, a fabric comprising 52 g of cotton and 17 g of fiberglass and measuring 94 cm long by

40.6 cm wide, mounted on a metal frame in the center of the flow duct. This sample was an order of magnitude larger than anything studied to date, and was of sufficient scale that it consumed 1.5% of the available oxygen in the atmosphere of the vehicle. The non-combustible matrix of fiberglass remained after the flame spread to prevent the fabric from cracking and curling which would destroy the symmetry of the flame and complicate the modeling of the system. Ignition was caused by a resistively-heated hot wire (29-gage Kanthal®, 0.286 mm, 3.85 A) which was woven across the sample in a saw-tooth pattern.

Two cameras imaged one side of the burning sample, with each spanning just over half of the sample. The flow duct was darkened in order to facilitate flame imaging, but the fuel sample was illuminated periodically so that the char front could be seen as the fuel burned. Four radiometers measured front and back-side radiation coming from the flame and fuel surface. Each radiometer spanned just over half of the sample, with two on each side to provide an indication of symmetry between the front and back halves of the flame. Thermocouples were arrayed to provide temperature measurements at key location on and near the fuel and throughout the flow duct. Oxygen concentration, carbon dioxide, and pressure were also recorded just upstream of the fuel in the flow duct.

The first Saffire experiment consisted of two consecutive tests at 20 cm/s air flow: concurrent-flow flame spread and opposed-flow flame spread. The original intention was to conduct only the first test, and the second test was a contingency in case the igniter failed, the air flow shut off, or some other anomaly extinguished the flame prematurely. Everything performed nominally for the first test which was allotted 420 s before the air flow turned off. After 210 s, the flow was re-established and the contingency test was initiated. Since telemetry was unavailable during operations, the software was written to perform both tests dutifully without regard for whether or not there actually was a flame. As it turned out, the flame in the first test was slower than anticipated, burning only about 90% of the fuel and leaving 10% unburned (based on the uncharred area). Therefore, the second test serendipitously yielded meaningful data, although it was relatively brief since only a fraction of the fuel remained.

Using an entirely separate piece of hardware in a later ISS re-supply vehicle, the second Saffire experiment burned nine smaller samples (5 cm x 30 cm), of which two were cotton/fiberglass samples. Only these two samples are considered in this paper. Both were burned in concurrent-flow but at different flow speeds, 20 cm/s and 25 cm/s.

3. Results and Discussion

For the concurrent-flow tests, the flame was ignited across the bottom of the fuel (for example, as shown in Fig. 1). At ignition, the flame was mostly bright yellow and relatively vigorous but it soon developed a blue base and a pattern of orange radiation coming from incandescent soot. After the flame had passed, exothermic surface smolder spots burning some of the leftover fuel were visible.

As mentioned above, there was a small but sufficient amount of fuel remaining after the concurrent-flow test of the first experiment to permit a second burn, this time in the opposed-flow geometry. Only about 10% of the fuel remained after the concurrent test, but that was enough to make conclusions about the opposed-flow flame spread and development. In this case, ignition was achieved at the top of the sample and the flame spread downward into the flow. The igniter is depicted by the red saw-tooth line in the right panel of Fig. 1.

The flame speed and size were measured from the video. The flame position traces for the two tests of the first experiment are shown in Fig. 2a. The flame position curves show that spread rate is steady for most of the tests. For the concurrent flame, after an ignition transient that drives an overshoot in the flame length, the length reaches a plateau value of around 40 mm, while the opposed-flow flame is a bit shorter at 24 mm. The average concurrent-flow flame spread rate is 1.8 mm/s which corresponds to a theoretical heat release rate of 1.5 kW (assuming perfect fuel conversion). The opposed-flow flame average spread rate 1.3 mm/s (1.1 kW).

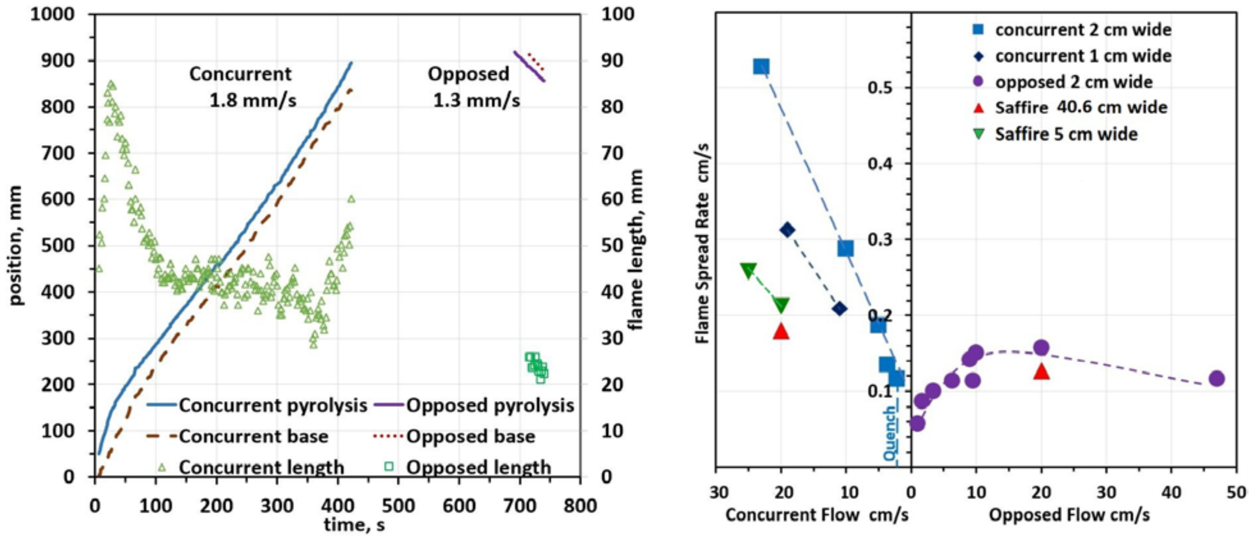

Figure 2: a) Flame base and pyrolysis position for concurrent and opposed-flow test in the first Saffire experiment. Air flow speed was 20 cm/s. b) Spread rate summary for cotton/fiberglass fabric burning in microgravity. Concurrent flames are shown to the left of the origin, and opposed to the right.

In Fig. 2b, the concurrent and opposed flame spread rates for the large samples along with the spread rates of the two smaller samples are plotted on the same graph with earlier results obtained in microgravity [4]. The majority of points were obtained in earlier tests with significantly smaller sample sizes measuring either 2 x 10 cm or 1 x 10 cm. Flow speed is indicated on the x-axis, with points plotted to the left of the origin representing concurrent-flow tests and points plotted to the right, opposed-flow. For concurrent-flow flames, the spread rate increases linearly with flow speed while for opposed-flow flames the spread rate peaks at a moderate flow speed (20 cm/s) before dropping off as flow is increased.

Comparing the two large-scale burns in this work, the concurrent-flow spread rate is markedly faster than the opposed-flow. However, there is some experimental and theoretical evidence which predicts that the faster mode is determined by flow speed [2, 5, and 6]. At low speeds, the opposed-flow spread is faster while at higher speeds the concurrent spread is faster. There is a crossover point where the two rates are equal. It appears that the 20 cm/s flow for the Saffire experiment places us above the crossover point where concurrent spread is faster compared to opposed-flow.

The flame spread rate for the 5-cm-wide sample is slightly faster compared to the spread rate for the 40.6-cm-wide sample for the same flow speed of 20 cm/s. This may be due to the slightly higher starting oxygen percentage (22.1% vs. 21.7%). However, the narrower sample might have enabled faster spread because of larger side entrainment effects compared to the wide sample.

The Saffire concurrent-flow flame spread more slowly compared to the prior microgravity tests burning smaller samples of the same fuel in similar conditions [4]. These earlier tests were conducted in a much smaller flow tunnel where the thermal expansion of the hot combustion gases caused the free stream to accelerate in the confined duct, forcing the flame closer to the fuel sample and leading to a higher spread rate. An important consideration for spacecraft fires is revealed, namely that a flame burning in a larger, more open volume will be quite different compared to a flame burning in a more confined volume even if fuel and flow parameters are otherwise comparable. Thus a flame located behind a panel or between components in microgravity may be more hazardous than if it was in a bigger volume [7]. This has crucial implications for developing a criterion to rate the flammability of materials especially if it depends on normal gravity tests, such as the NASA Standard 6001 Test 1.

For all tests, the flame length reached a nearly steady value. Even for non-thin samples, a theoretical model predicts a limiting length in microgravity [8]. After growing to the limiting length, the flame becomes stationary until the flame base moves (i.e. sample burnout). This has recently been verified in a space experiment which burned thick plastic rods of fuel in low-speed concurrent flow [9]. Gas phase diffusion flames burning over a porous metal plate in microgravity at a constant fuel flow rate also exhibited a limiting flame length due to quenching at the flame trailing edge, attributed to soot radiation [10]. On the other hand in earlier experiments, 1-g upward spread over a tall, thick, sample yielded a continuously growing flame. The investigators reasoned that this behavior was enabled by increasing soot radiation of the larger flame [11], highlighting here the ambiguous role that soot may play depending on the convective environment.

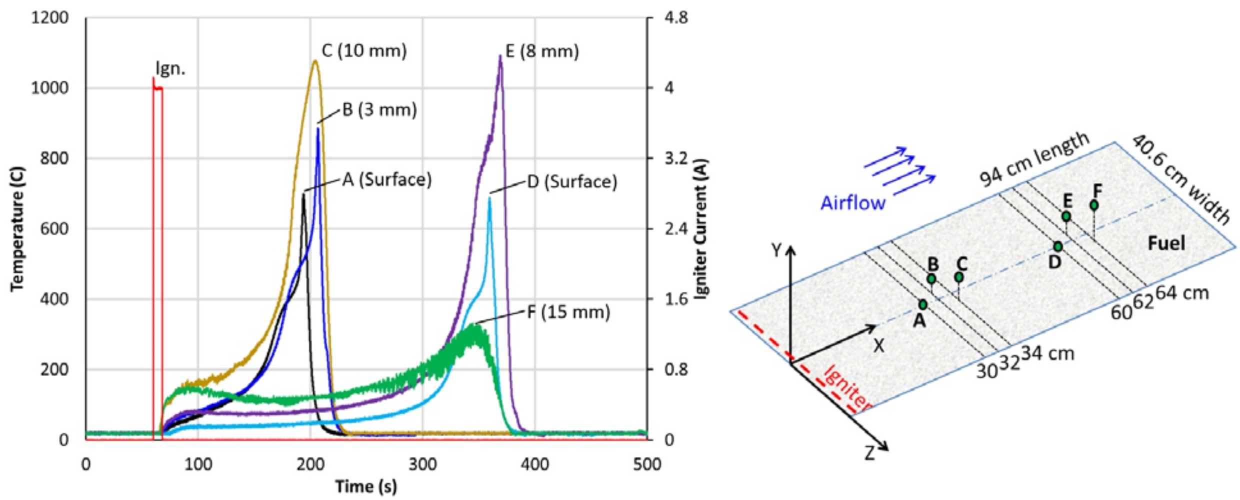

Figure 3: Plots of igniter current and thermocouple temperatures. X-distance along the sample for each thermocouple is shown on the diagram. Heights above the surface are indicated on the plot.

The samples were instrumented with six thermocouples: two surface-mounted and four in the gas-phase. Fig. 3 shows temperatures for the concurrent-flow test in the first experiment. The similarity of the surface temperature traces (A and D), are another verification that the flame had indeed reached a steady condition. When plotted on top of each other they are virtually indistinguishable.

4. Conclusions

For the first time, a large-scale fire was intentionally set inside a spacecraft while in orbit. A large fuel sample consisting of a cotton-based fabric sheet was burned in two separate tests. In addition, two smaller samples of the same material were burned in a subsequent spaceflight. Unlike 1-g, the results revealed that a steady flame could be achieved even for a wide sample burning in concurrent-flow. The flames spread more slowly than prior tests in smaller ducts. This behavior of the flame demonstrated the importance of confined spaces for potential spacecraft fires. Current fire safety practices for spacecraft rely on rating materials based on 1-g tests and the results obtained suggest that underlying assumptions need to be modified to account for the observed burning behaviors.

There are plans for the Saffire project to continue with additional experiments examining the effects of enhanced oxygen at reduced pressure. The results of this series of large-scale spacecraft fire safety tests will increase our knowledge of how a fire spreads in a large enclosure, and what effects the fire has on the spacecraft. This understanding will influence vehicle design and materials screening, ultimately increasing the safety of the crew.

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