FORCED FORWARD SMOLDERING EXPERIMENTS ABOARD THE SPACE SHUTTLE

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INTRODUCTION

Smoldering is a basic combustion problem that presents a fire risk because it is initiated at low temperatures and because the reaction can propagate slowly in the material interior and go undetected for long periods of time [1]. It yields a higher conversion of fuel to toxic compounds than does flaming, and may undergo a transition to flaming. To date there have been a few minor incidents of overheated and charred cables and electrical components reported on Space Shuttle flights [2,3]. With the establishment of the International Space Station, and the planning of a potential manned mission to Mars, there has been an increased interest in the study of smoldering in microgravity.

The Microgravity Smoldering Combustion (MSC) experiment is part of a study of the smolder characteristics of porous combustible materials in a spacecraft environment. The aim of the experiment is to provide a better fundamental understanding of the controlling mechanisms of smoldering combustion under normal- and microgravity conditions. This in turn will aid in the prevention and control of smolder originated fires, both on earth and in spacecrafts. The microgravity smoldering experiments have to be conducted in a space-based facility because smoldering is a very slow process and consequently its study in a microgravity environment requires extended periods of time. The microgravity experiments reported here were conducted aboard the Space Shuttle. The most recent tests were conducted during the STS-105 and STS-108 missions. The results of the forward smolder experiments from these flights are reported here. In forward smolder, the reaction front propagates in the same direction as the oxidizer flow. The heat released by the heterogeneous oxidation reaction is transferred ahead of the reaction heating the unreacted fuel. The resulting increase of the virgin fuel temperature leads to the onset of the smolder reaction, and propagates through the fuel. The MSC data are compared with normal gravity data to determine the effect of gravity on smolder.

EXPERIMENTAL HARDWARE AND PROTOCOL

MSC tests were performed in a 21.7 liter combustion chamber. The fuel sample consists of a polyurethane foam cylinder, 120 mm diameter by 140 mm long. The disc igniter consists of an electrically heated wire between ceramic discs. The oxidizer supply system provides a constant oxidizer mass flow through the foam sample. The fuel sample is instrumented with 10 thermocouples which provide a temperature history of the smolder propagation. In addition to the thermocouples, an ultrasound imaging system (UIS) consisting of 5 ultrasonic transducer pairs fixed along the sample is used to obtain average permeability measurements [4]. The UIS is able to image the location and velocity of the smolder front. The oxidizer used is air. The ignition is achieved by supplying a constant heat flux at the igniter end for 400 s. The overall assembly integrates into a Get Away Special Canister or GAS-CAN, which is flown in the Shuttle cargo bay.

The experiments reported here investigate the dependence of the forward smolder propagation velocity along the foam sample on the air flow. Polyurethane foam was selected as fuel because it is representative of materials commonly used on both earth and space based facilities, its material properties are well known, and it maintains its structural integrity upon smoldering. The forward flow smolder experiments of the STS-105 and STS-108 missions were conducted with a forced oxidizer flow velocity of 3 mm/s and 5 mm/s respectively.

Results

The thermocouples placed along the foam sample are used to calculate propagation velocity of the smolder reaction, as well as to provide information about the intensity of the smolder reaction. The UIS provide permeability data as well as a second method to measure the smolder propagation velocity. This work presents the first ultrasonic data obtained from a microgravity forward smoldering combustion experiment.

For both normal- and microgravity experiments, temperature profiles along the foam centerline are presented in Fig. 1. and permeability histories are presented in Fig. 2.

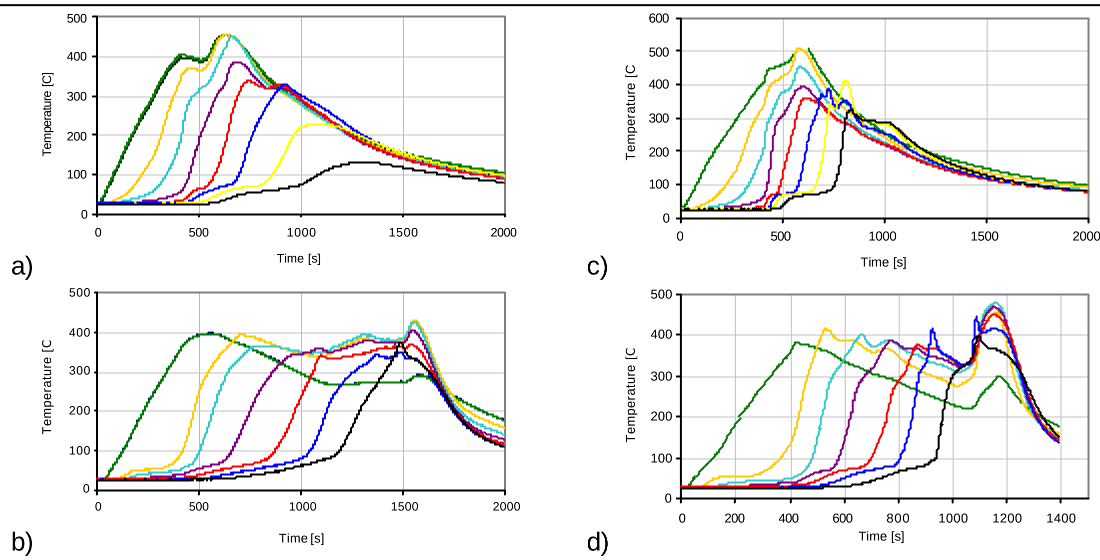

Figure 1. Thermocouple histories for forced air velocity of (a) 3 mm/s for microgravity, (b) 3 mm/s for normal gravity, (c) 5 mm/s for microgravity and (d) 5 mm/s for normal gravity.

In the 3 mm/s microgravity case, as the foam heats up the thermocouples near the igniter (TC 1 and 2) reach a steady temperature of about 400°C, which is characteristic of foam oxidation. Thermocouple 2 follows the same pattern but does not reach as high of a temperature. This is indicative of upstream consumption of oxygen. This is further evidenced with thermocouple 3 that stabilizes at about 320°C (which is a characteristic temperature for endothermic pyrolysis). As the igniter is turned off a slight decrease in temperature can be perceived at the surface of the foam. But it is followed past 500 s by a sudden generation of heat. Temperatures corresponding to the first 35 mm of the sample (TC 0-3) reach about 450°C, which is typical of char oxidation. A weak re-kindling of the reaction is observed on the temperature traces corresponding to thermocouples 5 and 6 (75 and 95 mm). The temperature traces show a reaction first driven by the igniter and then controlled by energy supply from the char oxidation in the first 35 mm of the foam. Char oxidation consumes the oxygen available and the foam oxidation fades favoring pyrolysis. Once the char close to the igniter is consumed and the temperature in this region decreases, oxygen flows again and heat generation can be observed once more between 75 and 95 mm. The reaction is not strong enough to progress through the pyrolyzed fuel and eventually extinguishes more than 35 mm away from the sample end. Figure 2(a) shows a dramatic increase in permeability that coincides in location with the regions where the temperature reached the highest value.

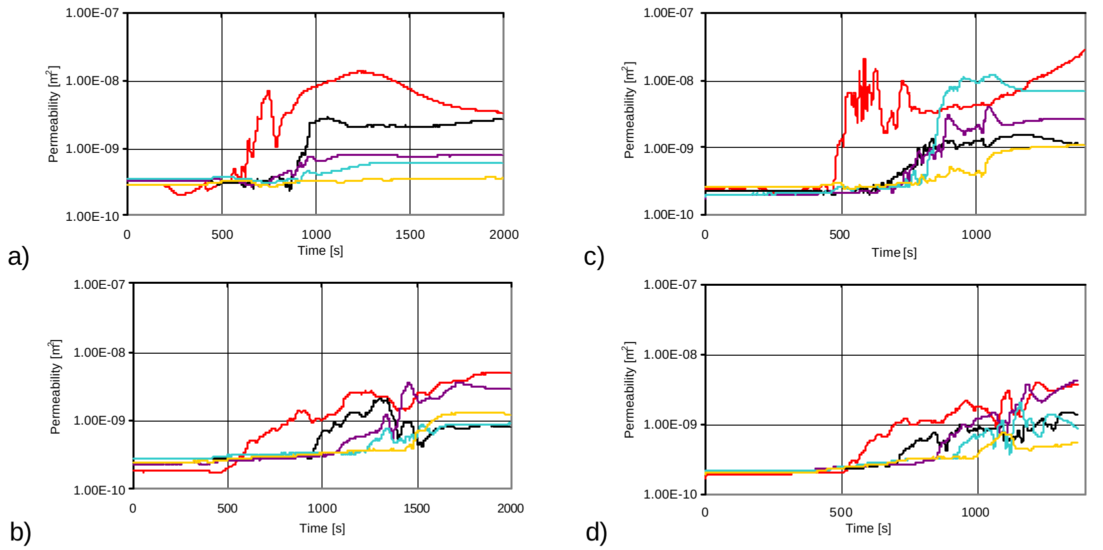

Figure 2. UIS permeability histories for forced air velocity of (a) 3 mm/s for microgravity, (b) 3 mm/s for normal gravity, (c) 5 mm/s for microgravity and (d) 5 mm/s for normal gravity.

The 3 mm/s normal gravity case in Fig. 1(b) shows a completely different scenario. The temperature increases due to the igniter and the first thermocouples reach the same plateau at approximately 400°C. It is important to note that the temperature increase is slowed down indicating larger losses than in the microgravity case. Once the plateau is reached the temperature immediately begins to decrease. Peak temperatures remain within ranges typical of smoldering. Char oxidation has no significant impact on the temperature traces. After 1000 s the reaction is about 35 mm away from the end of the sample and a gradual increase in the reaction rate throughout the entire foam follows. This effect is related to the decrease in pressure drop through the foam that allows an increase in the total contribution of buoyancy to the supply of oxidizer. An opposed smolder reaction through the char follows (at time greater than 1300 s). A consistent increase in permeability is observed and at each stage of the propagation the change in permeability is smaller. Past 1000 s the increase in permeability continues showing peaks at the locations of the secondary opposed smolder reaction.

Similar to the 3 mm/s microgravity case, the 5 mm/s microgravity case shows a reaction first controlled by the igniter but leading quickly to a strong secondary char oxidation. This secondary char oxidation consumes the oxygen supply, but not completely allowing for a much larger region of secondary char oxidation. Once this secondary char oxidation has consumed the available fuel, the oxygen supply is able to reach further downstream positions. However, the reaction does not extinguish like in the 3 mm/s case, since the supply of oxygen is greater in this case, and stimulates a strong rekindling of the smolder reaction which is able to propagate through to the end of the sample.

Despite the reduced number of experiments, some quantitative data can be obtained. Results for the smolder propagation velocity and smolder reaction temperature from both the normal gravity and microgravity tests are presented in Table 1. The results are divided into regions I, II, and III corresponding to the region influenced by the igniter, the middle region of the sample, and the region dominated by end effects, respectively.

Forced Air Velocity [mm/s]	Smolder Velocity [mm/s]						Smolder Temperature [°C]					
	Region I		Region II		Region III		Region I		Region II		Region III	
	0g	1g	0g	1g	0g	1g	0g	1g	0g	1g	0g	1g
3	0.25	0.19	0.15	0.10	-	0.12	399	396	406	355	-	361
5	0.40	0.24	0.23	0.16	0.25	0.22	398	398	428	387	375	406

Table 1. Smolder propagation velocities and smolder temperatures from normal and microgravity experiments.

A comparison between the temperature profiles in microgravity and in the normal-gravity case shows that the char temperature histories are significantly different between the two cases. In microgravity, the reduced heat losses leads to a hotter char, capable of sustaining a secondary char oxidation reaction but suppressing the smolder reaction through the consumption of the oxygen supply. In the low flow rate microgravity test, the subsequent smolder reaction is extinguished before propagating through the sample, whereas in the high flow rate microgravity test the increased oxygen supply is sufficient to sustain a smolder propagation through the entire sample. The normal-gravity tests display a markedly different behavior. The increased heat losses in normal-gravity force cooling of the char, which allows the forced air flow to pass through the char without significant consumption of the oxygen. This permits the smolder reaction to be sustained and propagate through the sample length at both low and high forced air flow rates.

Concluding Remarks

The present experiments, although limited, are unique in that they provide the only available information about forward smolder combustion in microgravity in sample sizes large enough to allow the self-propagation of the smolder reaction. The experimental results provide further verification about the smolder controlling mechanisms, and data for model verification. Currently the data are being used to verify a numerical model of smolder propagation. Finally, it should be emphasized that since the present conclusions are based on only two microgravity tests, it cannot be generalized until further tests are conducted.

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References

1. Ohlemiller, T.J., Prog. Eng. & Comb. Sci., 11:277 (1986).
2. Ross, H.D., Natl. Fire Protection Assoc. Meeting, May (1996).
3. Friedman, R., NASA TM-106403 (1994).
4. Tse, S.D, Anthenien, R.A., Fernandez-Pello, A.C., Miyasaka, K., Comb. & Flame 116:120 (1999).