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Flow-Assisted Flame Propagation Through a Porous Combustible in Microgravity

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ABSTRACT

Experiments were conducted to measure the flame propagation rate of a plug-flow flame through a combustible matrix of randomly oriented cubes of polyurethane foam in microgravity and normal gravity as a function of the forced air flow. The experiments in microgravity were conducted at the Japan Microgravity Center (JAMIC) drop tower, which provides 10s of microgravity. The normal gravity experiments were simulations of the microgravity experiments, and by comparison, were used to determine the effect of gravity on the flame propagation process. The experiment was conducted in a cylindrical geometry. Ignition was accomplished by means of a hot-surface igniter brought into direct contact with the foam at one end of the sample holder. The other end of the sample was sealed to a fan drawing air through the sample, which was adjustable using a variable DC power supply. In this configuration the flame propagation is flow-assisted. The flame propagation rate was determined by means of the temperature histories provided by thermocouples placed along the centerline of the sample. It is found that, both in normal and microgravity, as the air flow rate is increased the flame propagation velocity increases. Comparison between the normal and microgravity experiments shows that the microgravity combustion is greatly influenced by the ignition period. In microgravity the time to initiation of flame propagation is significantly longer than the corresponding time in normal gravity. This is due to the contribution of the buoyant flow that assists the forced flow during the initiation period in normal gravity. A simplified analytical model is presented for correlation of the velocity data.

INTRODUCTION

Porous materials such as polyurethane foam are used extensively in insulation and packing applications. Their extensive use raises concerns of fire safety and flammability associated with these materials. These materials are capable of sustaining smoldering combustion and can transition to gas-phase flaming combustion [1], which is faster and more hazardous.

These materials see extensive use as well in space-based applications. Polyurethane foams are used as insulation, and packing and stowage foam aboard the Space Shuttle. With the construction of the International Space Station (ISS) and long-duration space missions planned, there is greater concern of accidental fire aboard space vehicles. To date there have been minor instances of charred and overheated electrical cables on Space Shuttle flights [2, 3]. In an enclosed environment aboard a spacecraft, containing very sensitive electronic components, even small fires can cause serious damage to these electronic components (through short circuit by deposited soot, or through corrosion by chlorinated products [4]). Thus there is a need to preempt the possibility of, or minimize the damage from, a space-based fire.

The present work focuses on understanding the behavior of the flame in the post-transition-to-flaming regime from smoldering, as it propagates through the porous material. This work is part of the Microgravity Smoldering Combustion (MSC) project, which aims to understand the behavior of smolder combustion in microgravity and, to a limited extent, the phenomenon of transition to flaming. There have been prior microgravity experiments conducted on flame spread over the surface of a slab of porous foam [5]. These experiments study the one-dimensional flow-assisted (forward) flame propagation through the interior of a porous combustible. Microgravity experiments were conducted in the Japan Microgravity Center (JAMIC) 10-second drop tower facility, with complementary ground-based experiments.

EXPERIMENTAL SETUP

The experimental setup consists of a combustion vessel, sample holder and complimentary instrumentation. The sample holder is a transparent polycarbonate cylindrical sheath 70mm in diameter and 150mm in length. Fuel porous matrix consists of randomly oriented cubes of 10mm dimension of polyurethane foam. A schematic of the sample holder is presented in Fig. 1.

Sufficient material was placed in the cylinder to insure a 10% compression of the fuel, thereby preventing preferential oxidizer flow around the fuel. The bottom of the cylinder was notched to accept a ceramic filament hot-surface igniter used to ignite the fuel in physical contact with the igniter. A 12 V, 0.15 A brushless DC fan was mounted in a sheet metal shroud, fitted to the opposite end of the cylinder from the igniter, to provide forward flame propagation through the fuel. A loosely spaced 1mm.wire grid strung above and below the foam cubes fixed the samples in place between the igniter and DC fan.

The air flow velocity induced by the fan was measured by insertion of a hot-wire anemometer along the centerline of the sample at three axial locations: the top of the sample just below the fan; the bottom of the sample below the wire grid used to hold the fuel sample in place; and the center of the sample. In the case of air flow measurements at the center of the sample, the fuel sample below the anemometer was removed so that the fuel sample filled only the upper half of the cylinder. This was done to simulate air flow velocities at a point halfway through the cylinder during flame propagation, in which there is no longer material in the lower half of the cylinder. Air flow measurements during the flame propagation were not possible, and measurements capable of finer spatial resolution of the air flow velocity are beyond the scope of the present work.

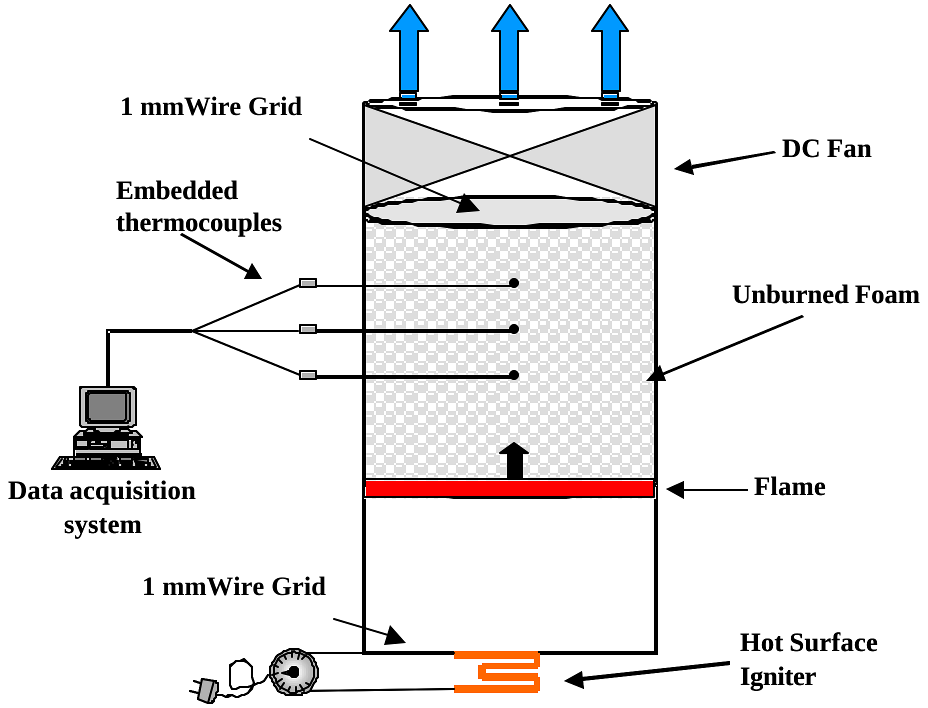

Fig. 1 Schematic of the experimental sample holder

Temperature measurements in the interior of the fuel were made using 0.005 in diameter, type K thermocouple wires were strung at intervals of 20 mm axially along the sample cylinder, with the first thermocouple wire strung at a distance of 10 mm axially from the igniter. A total of 5 thermocouples were used for each sample cylinder in normal gravity testing, and 4 thermocouples were used for each sample cylinder in microgravity testing, in the latter case due to limitations in the data acquisition system. All beads were placed at the centerline of the cylinder. Data acquisition was handled by an onboard computer with an analog-to-digital converter data acquisition system. Thermocouple data was collected at a scan rate of 1000 scans/s, in order to resolve the fast moving flame.

Experiments were conducted in a 21-liters hermetically sealed chamber with optical access. Two sample cylinders were used per test, each at a different fan voltage set point. Two machined circumferential aluminum mounting brackets and arms matted each sample cylinder to the inside surface of the experimental test stand. Separate aluminum mounts supported the igniter assemblies. Bulkhead connections provided feed-through access for the thermocouples and igniter and fan power. A photograph of the experimental apparatus containing two sample cylinders is shown in Fig. 2.

For the microgravity testing, the entire apparatus was mounted to an experiment platform for insertion into the inner capsule of the JAMIC drop package. The platform contained programmable DC power supplies used to independently control the voltage to each fan. Each of the 4 thermocouples for each sample cylinder were amplified using external thermocouple amplifiers mounted to the platform, prior to feeding the thermocouple signal to the data acquisition system. Data acquisition was controlled by a laptop computer mounted to a second tier of the experiment platform. The platform also contained a normally-closed relay trigger system to activate the igniter from the control room of the JAMIC drop tower. The completed experiment platform is shown in Fig. 3.

Fig. 2 Photograph of combustion chamber and two instrumented sample holders

Prior to insertion into the JAMIC drop package, the data acquisition system was initiated and remained scanning throughout the assembly of the drop package and the subsequent 10-second drop. Similarly, the power to the DC fans was initiated before insertion into the drop package and continued to provide power to the fans during assembly of the drop package and throughout the drop. This was done to insure that no transient flow conditions associated with the startup of the fans were encountered during the drop. Although a video camera was installed on the experiment pallet to image the flame propagation through the optical panel, the video data did not provide much information since soot production from the flame blocked optical access shortly after ignition.

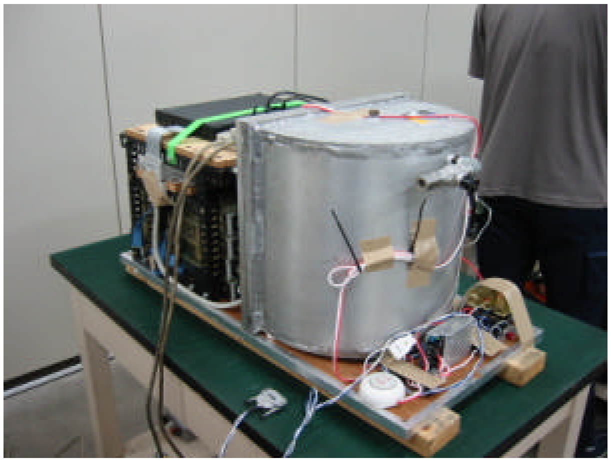

Fig. 3 Assembled experiment platform

Once completed, the drop package provided all power and data feeds through the JAMIC control center. Power to the igniters was triggered at 12 seconds before the drop. Normal gravity data indicated that the time for the hot-surface igniter to reach an ignition temperature for the foam was approximately 13 seconds. This insured that the actual ignition took place during the 10-second microgravity period. Normal gravity testing was conducted in the same combustion chamber, with all power control and data acquisition handled by similar ground-based systems.

RESULTS

Results obtained were the flame propagation velocity in normal and microgravity. The thermocouple histories were used to obtain the time of arrival of the flame front at the axial location of the thermocouple. This was done by projecting a tangent line to the thermocouple history at the first rise in temperature, and intersecting this tangent by a criterion temperature. This method was used for both normal gravity testing and microgravity testing, with the exception of one microgravity test. In this test the first thermocouple failed immediately after the arrival of the flame front at that thermocouple's position. In this instance, the velocity was obtained by looking at the change in the second derivative of the temperature with respect to time, for both this thermocouple and the successive thermocouple. With this criterion applied, a velocity was obtained between these two thermocouples. Sample thermocouple histories in microgravity and normal gravity are shown in Fig. 4.

The thermocouple data is used to determine the time to initiation of propagation, defined as the time from triggering of the igniter to a criterion temperature of 400°C as measured by the first thermocouple. Since the thermocouple histories are not used to measure a

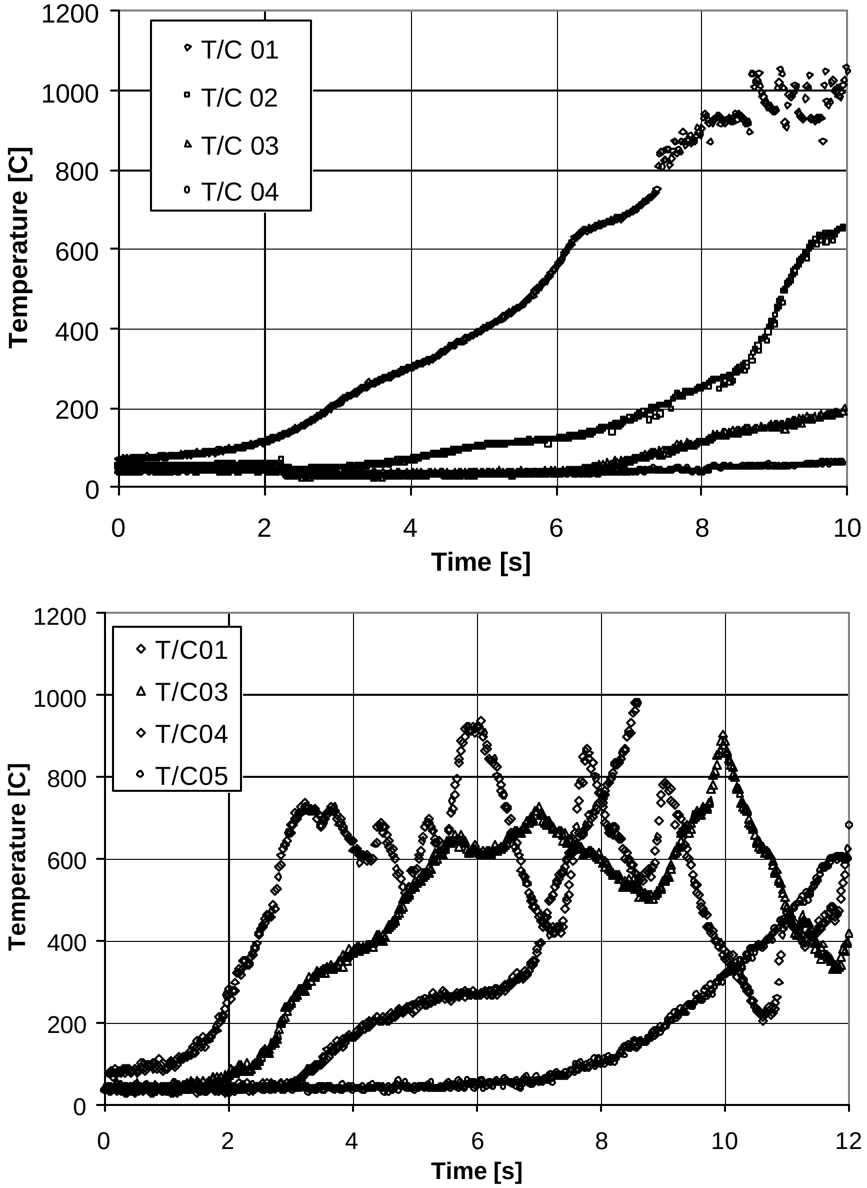

Fig. 4 Sample thermocouple histories; (top) in microgravity, (bottom) in normal gravity

unique flame temperature, the criterion temperature is selected only to compare normal and microgravity data self-consistently.

The results of time to initiation of propagation are presented in Fig. 5. As can be seen, the time to initiation of propagation is always greater in microgravity than in normal gravity. This is likely due to the absence of a buoyant flow near the igniter during the ignition period

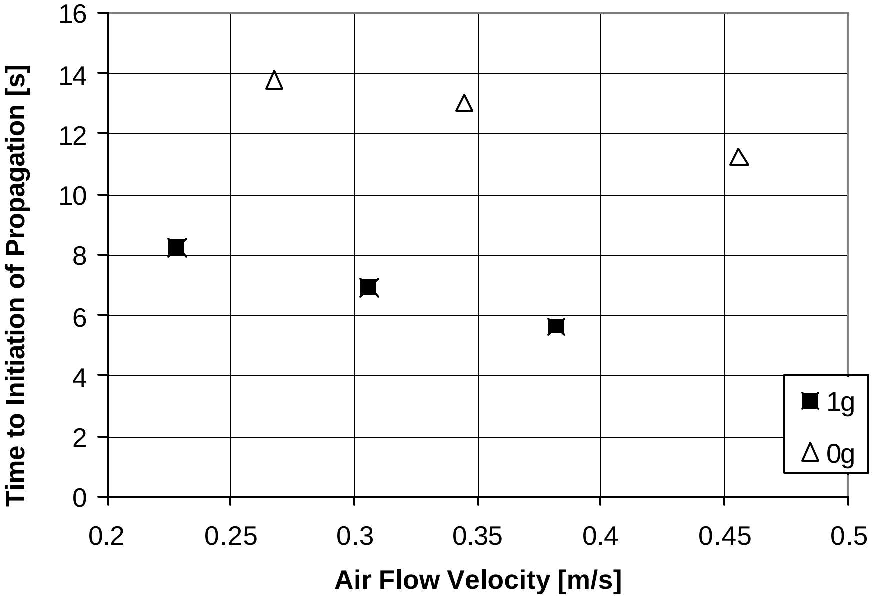

Fig. 5. Time to initiation of flame propagation vs. air flow velocity in normal and microgravity

The results of flame propagation velocity as a function of the air flow velocity are for normal and microgravity tests are presented in Fig. 6. In both normal and microgravity, the flame propagation velocity increases with increasing air flow velocity.

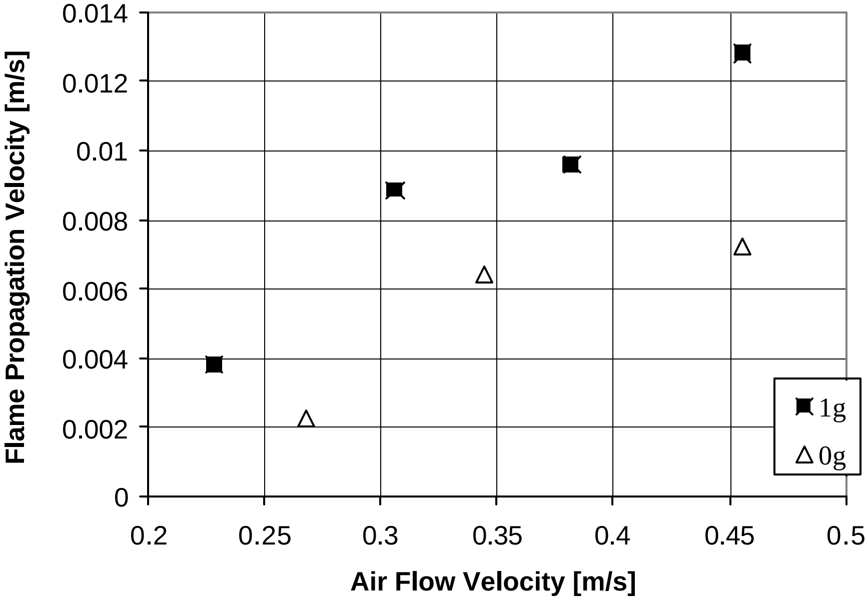

Fig. 6 Flame propagation velocity vs. air flow velocity in normal and microgravity

DATA CORRELATION

A simplified energy model has been used to derive an explicit expression for the flame propagation velocity and to correlate the flame propagation velocity data presented. Although analytical work has been conducted on flame propagation in porous material in the opposed configuration [6], the present experiments were in the forward configuration and analytical work was not available.

In the model, the reaction is considered to be one dimensional and steady with the frame of reference anchored to the reaction zone. In this reference frame, fuel and oxidizer enter the reaction zone from opposite directions (diffusion-like reaction). The gas and the solid are assumed to be in local thermal equilibrium. It is assumed that the process is fuel limited and therefore the heat release is given by the fuel mass flux. The heat of combustion is constant and known and heat losses to the surroundings are neglected. The energy equation under these assumptions is:

$$\dot{m}''_F c_{pF} \frac{dT}{dx} + \dot{m}''_A c_{pA} \frac{dT}{dx} = k \frac{d^2T}{dx^2} + Q \frac{d\dot{m}''_F}{dx} \qquad (1)$$

Where c_{pF} and c_{pA} are the specific heats at constant pressure of the fuel and the air respectively, $\dot{m}''_F$ and $\dot{m}''_A$ are the mass fluxes to the reaction zone of fuel and air respectively, Q is the heat of combustion per unit mass of fuel and x is the axial vertical direction.
Mass fluxes are given by:

$$\dot{m}''_F = (1-f)\, r_F u \qquad (2)$$

$$\dot{m}''_A = f r_A (u_F + u_B) \qquad (3)$$

$$u_B = \Delta r g h \frac{K}{m} \qquad (4)$$

Where u, u_F are the flame propagation velocity and the forced flow velocity respectively, u_B is the buoyancy induced air velocity through a porous media, r_F and r_A are the densities of the fuel and the air respectively, and f is the fuel porosity, Δr is the difference of densities of the air as passes through the reaction, h is the characteristic vertical distance for buoyancy, K and m are the permeability of the foam and the dynamic viscosity of the air respectively.

The boundary conditions applied to the model are:

$$\left.\begin{array}{l} T = T_f \\ \dot{m}''_F = 0 \\ \dfrac{dT}{dx} = 0 \end{array}\right\} \text{at the reaction zone,} \quad \left.\begin{array}{l} T = T_i \\ \dfrac{dT}{dx} = 0 \end{array}\right\} \text{at the virgin fuel ahead of the reaction} \qquad (5)$$

Upon integration of the energy equation with respect to x from the reaction zone to the virgin fuel ahead of the reaction, the following expression is obtained for the flame propagation velocities in normal gravity (buoyancy flow) and microgravity (no buoyancy flow):

$$u_g = \frac{c_{pA}\left(T_f - T_i\right)}{\left[Q - c_{pF}\left(T_f - T_i\right)\right]} \frac{f r_A}{(1-f) r_F} \left(u_F + u_B\right) \qquad (6)$$

$$u_{mg} = \frac{c_{pA}\left(T_f - T_i\right)}{\left[Q - c_{pF}\left(T_f - T_i\right)\right]} \frac{f r_A}{(1-f) r_F} \left(u_F\right) \qquad (7)$$

This expression is used to define the nondimensional flame propagation velocities in normal gravity and microgravity for the experimental data:

$$\hat{U}_g = \frac{u}{u_g} \text{ and } \hat{U}_{mg} = \frac{u}{u_{mg}} \qquad (8)$$

The experimentally measured average temperature of the reaction, 600°C, is used in the non-dimensional flame propagation velocities. The heat of combustion is set to the approximate value of 323 MJ/kg-fuel. The permeability of the foam was measured to be $9{\cdot}10^{-9}$ m^2. The physical parameters of the foam are those corresponding to flexible polyurethane foam [7] and the physical parameters of air correspond to an average temperature of 200°C. The non-dimensional flame propagation velocities of Eq. 8 are used to correlate the experimental data as shown in Fig. 7. The buoyancy induced air velocity u_B, as calculated, is found to be small compared to the forced flow velocity u_F.

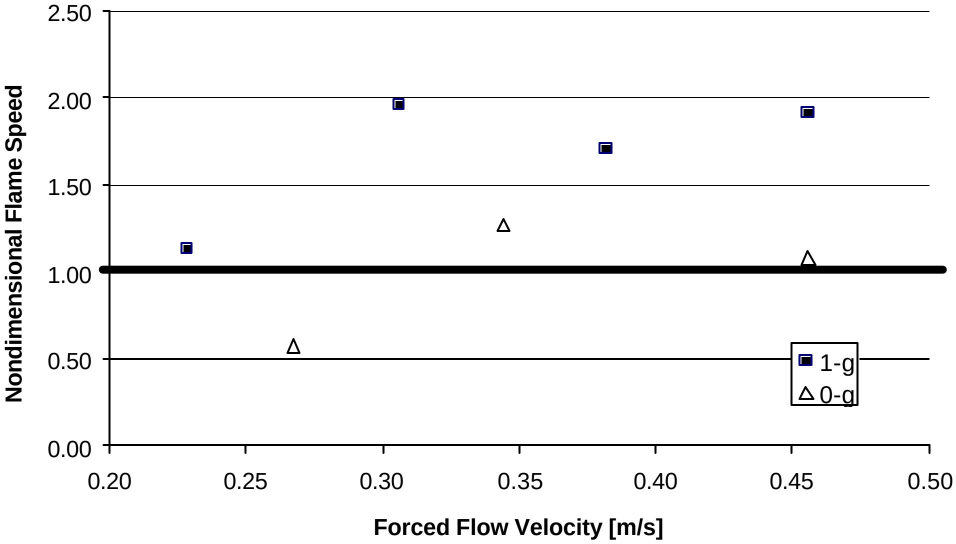

Fig. 7. Non-dimensional flame propagation velocity versus forced flow velocity

The correlation is better for microgravity tests than for normal gravity tests. Possible reasons for this discrepancy are the temperature and heat of combustion values used in the expression and the approximation used to estimate the buoyancy flow.

Analytical work to model the time to initiation of propagation would require a more detailed hydrodynamic analysis of the buoyant flow near the igniter during the ignition period. This analysis is beyond the scope of the present work, and thus no modeling is attempted for the time to initiation of propagation.

CONCLUSIONS

Results from testing in normal and microgravity show that as the forced air flow rate is increased the flame propagation velocity increases. Comparison between the normal and microgravity experiments shows that the microgravity combustion is greatly influenced by the ignition period, within the 10 seconds of microgravity available in the JAMIC drop tower. In microgravity the time to initiation of propagation is significantly longer than the corresponding ignition period in normal gravity. This is likely due to the contribution of the buoyant flow that assists the forced flow during initiation of flame propagation in normal gravity. It is concluded that buoyancy has a significant influence in 1-D flow assisted ignition and flame propagation through porous materials

A simplified model is presented for correlation of the velocity data. The simplified presents a significantly better correlation for microgravity data than for normal gravity data. The poor correlation in normal gravity may be the result of the estimated buoyancy flow. In addition, for both microgravity and normal gravity the heat losses to the surroundings are neglected, leading to an over prediction of the propagation velocity. Another source of discrepancy might be the average reaction temperature and heat of combustion values used in the model.

Although limited, these tests present the only available microgravity data on flame propagation through the interior of a porous fuel matrix. The results can be incorporated into a more detailed model of the smolder, transition to flaming, and flaming combustion of porous materials in microgravity.

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