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SMOLDERING, TRANSITION AND FLAMING IN MICROGRAVITY

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INTRODUCTION

A research project is underway to study smolder and the transition to flaming in microgravity. The Microgravity Smoldering Combustion (MSC) flight project is an ongoing research project to provide a better understanding of the controlling mechanisms of smoldering combustion. The Smoldering Transition and Flaming (STAF) project is a recently established research program that will utilize the Fluids and Combustion Facility (FCF) of the ISS [1] to examine the transition from smolder to flaming in microgravity.

In forced flow smolder experiments ambient pressure in the MSC chamber rises, thus motivating the need to understand the effects of pressure on smoldering combustion. Further, the STAF experiment has constraints on experimental scale and testing at elevated pressure may be a mechanism to reduce the sample size by enhancing the smolder reaction. In the work we are reporting here, a series of ground-based tests determine the effects of pressure on smoldering combustion. These tests are compared with data obtained from experiments conducted aboard the Space Shuttle in flights STS-69 and STS-77. Measurements of one-dimensional smolder propagation velocity are made by thermocouple probing and a non-intrusive Ultrasound Imaging System (UIS) [2, 4]. Thermocouples are also used to obtain reaction temperatures and the UIS is used to determine permeabilities of the fuel in real-time.

EXPERIMENTAL HARDWARE AND PROTOCOL

Ground-based and microgravity tests were conducted in the MSC flight hardware on 120mm diameter and 150mm length cylindrical samples of open-cell, unretarded, polyurethane foam [5]. The tests were conducted in 3 configurations: opposed forced flow in normal gravity and microgravity, and natural convection. A range of ambient pressures from 1.0 to 3.5 atm was tested.

In normal gravity forced flow experiments, the oxidizer mass flux was a controlled parameter. Tests were conducted at a specific pressure, which was held constant throughout the test via a pressure relief valve. A constant oxidizer mass flux was delivered by a mass flow controller (MFC). The experimental setup was similar in the forced flow microgravity tests [5]. In both of these forced flow tests, an igniter setting of 90W for 600 seconds was chosen to simulate the mission ignition criteria [5].

In the natural convection tests, the ends of the fuel sample were exposed to the ambient chamber pressure. The igniter power chosen was 70W for 1200 seconds, similar to STS-69 and STS-77 quiescent tests [6], as well as previous natural convection smolder experiments [7].

BACKGROUND

Smolder often occurs under oxygen-limited conditions [8], in which case the rate of heat release from the smolder reaction is directly proportional to the oxidizer mass flux. The smolder propagation velocity is then proportional to the heat release rate minus heat losses to the environment [9]. The effect of pressure on the oxidizer mass flux will be discussed in order to clarify the experimental results. With buoyancy as the driving force the pressure gradient along the length of the cylindrical sample can be written as $dP/dz = -\rho g$. For a flow in a porous medium Darcy's Law is applicable [10] $dP/dz = -(\mu/K)u_D$ and equating these two gives an estimate of the buoyant flow velocity, u_D, through the medium. The resulting oxidizer mass flux is $\dot{m}''_{O_2,Buoyant} = y_{O_2}\rho_{atr}u_D = y_{O_2}(\rho_{atr})^2 gK/\mu$. A calculation of the buoyancy-induced oxidizer mass flux is conducted based on data from the natural convection tests. It has been observed that permeability changes with the passage of the smolder propagation front and the final char permeability increases with increasing oxidizer mass flux [2, 7]. An increased oxidizer mass flux leads to a more vigorous reaction, which consumes more fuel, and leads to a higher permeability of the residual char. In normal gravity tests, increased pressure leads to increased buoyancy-induced oxidizer mass flux, and consequently to an increased permeability.

The pressure effects on diffusive transport of heat and mass are determined by examining the effects of pressure on the binary diffusion coefficient. The diffusive mass flux is given by $\dot{m}''_{O_2,Diffusive} = \rho D\nabla y_{O_2}$. The binary diffusion coefficient is proportional to $T^{1.5}/P$ [11]. Thus it is expected that the diffusive mass flux is relatively independent of the pressure insomuch as the reaction temperatures are not significantly changed over the range of pressures tested.

The forced oxidizer mass flux is given by $\dot{m}''_{O_2,Forced} = y_{O_2}\rho_{atr}u_{forced}$. In the present experiments the mass flux is controlled through the MFC, and therefore is independent of pressure.

The total oxidizer mass flux is the sum of oxidizer mass fluxes from buoyancy-induced flow, diffusive transport, and controlled forced flow. The total oxidizer mass flux is therefore expressed as:

$$\dot{m}''_{O_2,Total} = \frac{y_{O_2}(\rho_{atr})^2 gK}{\mu} + \rho_{atr}D\nabla y_{O_2} + \dot{m}''_{O_2,Forced} \tag{1}$$

Concerning the heat losses to the environment, an analysis of free convection on the outside of the sample cylinder indicates that heat losses, as described by the Nusselt number, are proportional to the Rayleigh number to the power of ¼. Since the Rayleigh number is proportional to the square of the pressure, then the heat losses from the smoldering sample are expected to rise as $P^{1/2}$ [12].

For an oxygen-limited reaction the heat release rate can be estimated by multiplying the oxidizer mass flux by the heat of smolder combustion (per unit mass of oxidizer). The effect of pressure on the heat of smolder combustion is not well known, although since the heat of combustion depends on the products of combustion it should depend on the characteristics of the smolder reaction. The effect of pressure on heterogeneous reaction chemistry is difficult to quantify, but assuming that the reaction rate behaves as an Arrhenius reaction of first order in oxidizer, then the reaction rate should be proportional to pressure [13]. Thus it could be inferred that the rate of heat release would be proportional to pressure, although most likely weakly.

RESULTS & DISCUSSION

Figure 1 presents the effect of pressure on the smolder velocity for three smolder test configurations – opposed forced flow smolder in normal- and microgravity, and natural convection downward smolder. It is observed that under similar ignition conditions and for the present sample size, there exists a minimum ambient pressure at which a self-sustaining smolder reaction is observed. In the microgravity tests, this minimum pressure is 1.0 atm, although it is difficult to quantify, because initially smolder occurs under the influence of the igniter. In the forced flow normal gravity tests this minimum pressure is 1.2 atm, and in the natural convection tests it is 2.0 atm.

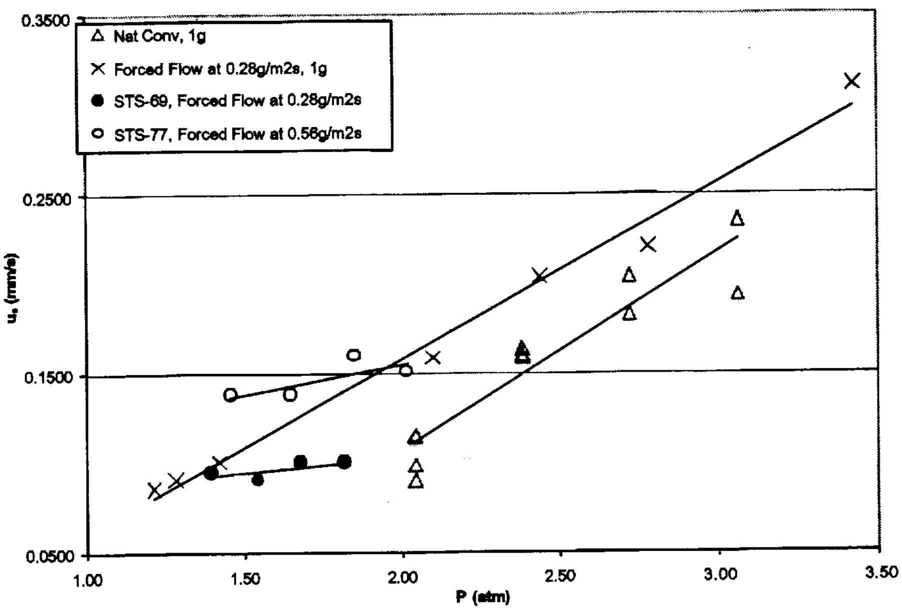

Figure 1 Effect of pressure on the smolder velocity for opposed forced flow smolder in normal- and microgravity, and natural convection downward smolder.

From Eq. 1 it is calculated that in the normal gravity forced flow testing, at 1.2 atm, the oxidizer mass flux is $0.50 g/m^2s$. Also using Eq. 1, in the natural convection tests at 2.0 atm the calculated oxidizer mass flux is $0.53 g/m^2s$, which is consistent with the previous result. These calculations seem to indicate that for the present experimental conditions and sample size, a critical oxidizer mass flux of roughly $0.5 g/m^2s$ is needed to achieve a self-sustaining smolder reaction in normal gravity.

In the microgravity forced flow tests where there is no augmentation of oxidizer mass flux due to buoyancy, the smolder propagation velocity is observed to increase slightly with pressure. Since the mass flux of oxidizer is constant, this indicates that there may be little or no dependence on pressure of the rate of heat release, although it may be difficult to separate the effects of pressure on the rate of heat release from the effects of pressure on heat losses. For the STS-69 tests in which the oxidizer mass flux was $0.28 g/m^2s$, the smolder velocity is basically the same as that of the forced flow test in normal gravity at 1.4 atm. At this pressure, the forced oxidizer mass flux is calculated as $0.53 g/m^2s$, which shows that the lack of convective heat losses in microgravity enhance the smolder reaction to the point that nearly half the oxidizer mass flux is needed to sustain the smolder reaction in microgravity.

Figure 1 also shows that the smolder velocity in microgravity at an oxidizer mass flux of $0.56 g/m^2s$ (STS-77) is the same as that of a normal-gravity forced flow with an oxidizer mass flux of $0.81 g/m^2s$ (Eq. 1), corroborating the above finding that a significantly lower oxidizer mass flux is needed to attain a self-propagating smolder reaction in microgravity than in normal gravity.

It should be noted that the pressure dependence of the buoyancy-induced heat losses is less than that of the buoyancy-induced mass flux, which explains why the difference in the critical mass flux between normal- and microgravity for self-propagating smolder decreases as the pressure increases. Furthermore these results appear to indicate that the effect of pressure on transport is dominant over its effect on chemical kinetics. In microgravity, where there is no buoyancy, the effect of pressure on the smolder velocity is weak ($\sim P^{1/3}$), and the smolder velocity is proportional to the oxidizer mass flux. Also, in normal gravity for the same pressure and consequently the same buoyant heat losses, the smolder velocity is proportional to the oxidizer-mass flux in natural and forced flow smolder.

CONCLUDING REMARKS

A comparison of the tests conducted in normal- and microgravity indicates that there is a critical oxidizer mass flux to attain a self-propagating smolder reaction, and that this critical mass flux is significantly smaller in microgravity than in normal gravity. This finding has important implications from the point of view of fire safety in a space-based environment, since smolder can be initiated at lower oxygen concentrations or mass flows than in normal gravity. Since buoyant heat losses are the primary reason for these results, the quantitative differences are a function of the sample size, decreasing as the sample size increases.

A comparison of only smolder propagation velocities ignores differences in reaction temperatures, in the extent of reaction and/or char conversion, conductive and/or forced convection heat losses. Examination of these effects is ongoing.

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