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Microgravity Ignition Delay of Solid Fuels in Low-Velocity Flows

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Experiments have been performed in microgravity and normal gravity to determine the effects of low-velocity airflows on the piloted ignition delay of solid fuels. Natural convection prevents material testing at the low oxidizer velocities encountered in space facilities (~ 0.1 m/s); thus, it is necessary to conduct these tests in reduced gravity. Tests have been conducted with two types of fuels, polymethylmethacrylate (PMMA) and a polypropylene/glass fiber composite, aboard the NASA KC-135 aircraft, under air velocities below those induced by natural convection. The short reduced gravity period (~ 25 s) provided by the aircraft limits the testing to high external fluxes (~ 30 kW/m^2) so that the ignition delay times are shorter than the microgravity time. In normal gravity, the ignition delay and critical heat flux for ignition decrease as the forced-flow velocity decreases, until they reach minimum values that are limited by natural convection. The microgravity data indicate that ignition delay is further reduced as the air velocity is lowered. A theoretical model is used to predict the ignition delay for PMMA at low flow velocities in microgravity. The model predicts that the critical heat flux for ignition at the flow conditions expected in space facilities could be as much as half the value measured in normal gravity. The results are important because they imply that, in space facilities, ignition may occur more easily than in normal gravity. If the results are confirmed by long-term microgravity testing, they may have important implications for the fire safety design of space facilities.

Introduction

THE planned long-term missions in the International Space Station, and other space facilities, bring concern about the possibility of an accidental fire in a remote space vehicle.[1,2] Because the space facilities are being designed with a life expectancy of 20 years, and given that there are combustible materials and sources of ignition in these facilities, the probability of a fire in such a long period of time is significant. In fact, there have already been some minor incidents of overheated and charred cables and electrical components reported on space shuttle flights.[3] More recently,[4] a fire caused by a solid fuel oxygen generator on the MIR Space Station, although it caused only minor damage to the hardware, could have had disastrous consequences for the station and the lives of the astronauts. Furthermore, considering the enclosed nature of space facilities, their dependence on electronic components, and the sensitivity of these components to combustion products (small amounts of soot can instantaneously short circuit electronic boards and small amounts of chlorinated products can cause serious corrosion damage[5]), a fire does not have to be large to cause serious damage. Thus, if a fire in a space facility were to reach conditions where the release of toxic pyrolysis and combustion products or the destruction of components (electrical or structural) is significant, the event would have disastrous consequences. Consequently, the characterization of the fire properties of materials used in the space facilities under the ambient conditions expected in the facility is of critical importance, so that appropriate decisions can be made about material usage.

In a space facility, the absence of gravity eliminates natural convection that is the transport mechanism for mass and heat in normal gravity fires. In the absence of any forced flow, microgravity combustion of solid fuels is generally limited by the diffusion of oxygen to the reaction zone. Because diffusion transport is slow in comparison to convection, the resulting combustion is weak when combined with ongoing heat loss. This has given way to the notion that materials do not burn as well in reduced gravity. Although this is often true in a quiescent environment,[6] space facilities have low-velocity air currents (of the order of 0.1 m/s) that are induced by their heating and ventilation systems. Recent experiments of flame spread in microgravity show that at low forced velocities the flame spread is higher and the limiting oxygen concentrations for flame spread (opposed) are lower than in normal gravity.[7–9] The reason is that, at these low velocities, the transport of oxidizer to the reaction zone is sufficient while the convective heat losses from the reaction are reduced. (The air velocities induced by a flame in normal gravity are of the order of 0.8 m/s.) Furthermore, the CO_2 removal and oxygen replenishing system in the facility cause fluctuations in the ambient oxygen concentration, for example, in the space station it is expected that the ambient oxygen concentration may vary from 18 to 24%. Thus, it is important to determine the combustion characteristics of materials under conditions that are expected to be encountered in a

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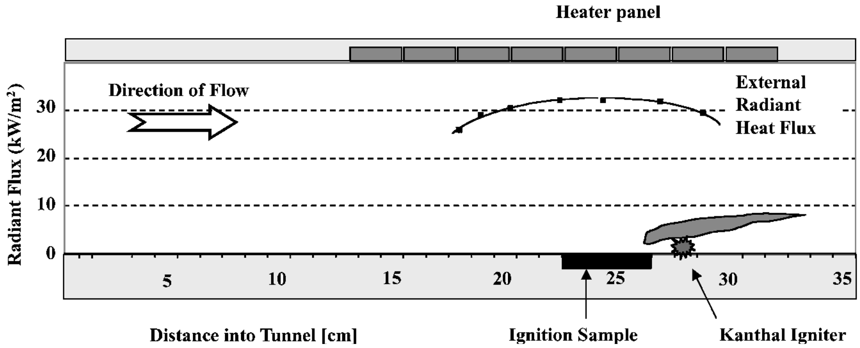

Fig. 1 Schematic of the FIST concept with placement of the fuel samples and typical imposed radiant flux distributions.

space facility, that is, microgravity, low-velocity oxidizer flow with variable oxygen concentration.

It is clear that no single test can be used to quantify the potential of a material to sustain a fire under all possible conditions. In most cases, to extrapolate to real fire scenarios, combinations of tests must be performed, and case-specific interpretations of the results must be made. For example, according to NASA specifications, all materials to be used in space vehicles must pass two tests, one being the upward flame propagation test (UFPT) and the other the heat and visible smoke release rates test (HVRT).[10] Together, these are expected to evaluate properly the flammability of a material in microgravity conditions. The basic principle behind the NASA methodology is to provide a worst-case scenario (UFPT) and a measure of the fuel-heat release (HVRT) and, in this manner, the damage potential of a fire. A detailed description of these test methods is provided in Ref. 10, and an extensive list of materials that have been tested is provided in Ref. 11.

At present, no standard testing methodology exists that specifically addresses the flammability performance of materials subjected to the conditions expected in space installations. A general overview of fire safety practices for space applications is provided in Refs. 12–14, but to the best knowledge of the authors, the only existing work that addresses the actual relevance of normal gravity-based tests to material flammability for microgravity applications is that of Ohlemiller and Villa[15] and Ohlemiller.[16] The latter works present results of a series of tests following the protocol of the UFPT, modifying it to include preheating by external radiation, and comparing the results with tests conducted with the cone calorimeter[17] and the lateral ignition and flame-spread test (LIFT).[18] The result of the tests emphasize the influence of natural convection on the data obtained by all methods in normal gravity and how results obtained with these test methods may not be an accurate representation of phenomena in microgravity conditions.

By the elaboration of these findings, the present authors developed and formalized the methodology for a new test, forced ignition and spread test (FIST),[19,20] to study the flammability characteristics of solid combustible materials in environment expected in space-based facilities, that is, low-velocity, variable concentration oxidizer flows. The FIST methodology is based on the principles underlying American Society for Testing and Materials E-1321-93, LIFT,[18,21,22] although buoyancy is replaced with a forced flow as the transport mechanism. Both the LIFT and FIST consist of a series of piloted ignition delay and lateral flame spread tests, performed by irradiating a sample of a solid combustible material with a radiant flux of known intensity and distribution. The data obtained with the apparatus are used to construct the flammability diagrams of the material[19–22] that are of curves of piloted ignition delay and flame spread rate as a function of an externally applied radiant flux. The flammability diagrams provide key properties related to the ignition and flame spread of the material, specifically, the thermal inertia of the material (product of the thermal conductivity, density, and specific heat), the critical heat flux for ignition (heat flux below which ignition does not occur), and a flame spread constant that encompasses the heat flux from the flame to the unburned fuel and the length of heated region of the material. These properties can then be used for fire protection design purposes, or to rank materials according to their fire risk. The LIFT apparatus, however, relies on gravity to bring the air to the combustion zone and the fuel vapor to the pilot flame and, thus, cannot describe the conditions expected in space facilities. The FIST on the other hand, by relying on a forced flow as the dominant transport process, can be used in tests conducted in reduced gravity to simulate conditions expected in space facilities.

In the FIST methodology, schematically shown in Fig. 1, a slab of fuel is exposed impulsively to an external heat flux of known intensity and distribution. Simultaneously with the beginning of the heating process, a forced flow of prescribed velocity is imposed parallel to the irradiated fuel surface. Two types of measurements are performed: piloted ignition delay and flame spread rate as a function of the external heat flux and oxidizer flow velocity. The data are used to produce the flammability diagrams of the fuel for the prescribed environmental conditions.[19,20] The work presented here concentrates on the ignition portion of the FIST test. It examines the piloted ignition delay of combustible materials in environments that are expected in space facilities, that is, microgravity, low-velocity oxidizing flows. The experiments are conducted in a KC-135 aircraft following a parabolic trajectory. Comparison is made with data taken in normal gravity and convective flows equal to or greater than those generated by normal gravity.

KC-135 FIST Microgravity Facility

The KC-135 microgravity experimental facility consists of two primary components: the Spacecraft Fire Safety Facility (SFSF)[23] and the FIST component. A photograph of the facility is shown in Fig. 2. The SFSF, which serves as the main support structure for the apparatus, houses a cylindrical environmental chamber and flow control, video imaging, power distribution, and data acquisition systems. The FIST component, which resides within the SFSF environmental chamber, contains the sample positioning system, radiant panel arrays, and supporting instrumentation. The combined facility allows for regulation of experimental parameters and performance of ignition tests in an isolated environment, preventing exposure of potentially harmful combustion products to the operator.

FIST Component

The FIST component is shown in Fig. 3. It is a smaller version of a FIST apparatus developed to conduct tests in normal gravity.[19,20] It consists of a cylindrical aluminum frame that encases a sample positioning system, a radiant heater panel, and supporting instrumentation. The radiant heater is composed of three pairs of electrical strip heaters, with their surface temperature monitored with three type K thermocouples, one for each heater pair. The heaters are controlled through their temperature by Labtech NotebookPro™ software via an Iotech Tempbook66™ digital I/O board and solid-state relays. To maintain a desired temperature, the software employs an on/off algorithm to control the power supplied to the heaters. Heater thermocouple outputs are compared to user input values and the solid state relays, which act as heater power switches and are enabled or disabled accordingly. The heat flux output of the heater panel is a radiometer-calibrated function of the steady-state heater temperature. An evaluation of the equilibrium thermal output of the radiant panel, performed with a water-cooled Schmidt–Boelter heat flux meter, has shown it to vary $\pm 10^{\circ}$C, or approximately 0.2 kW/m^2. These slight oscillations in the heat flux have been found to have a

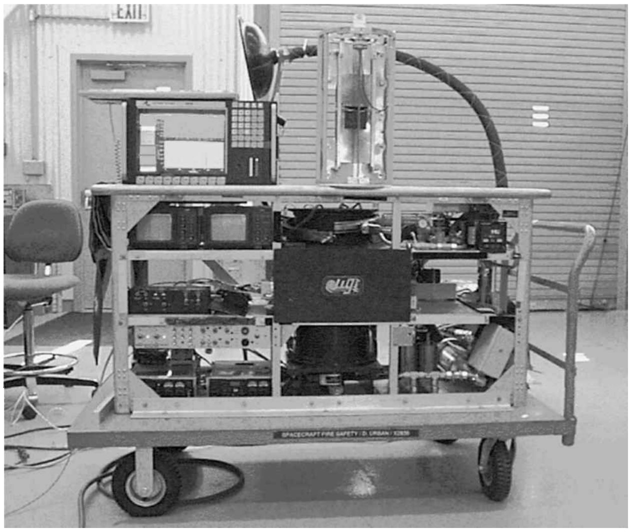

Fig. 2 NASA Spacecraft Fire Safety Facility (SFSF).

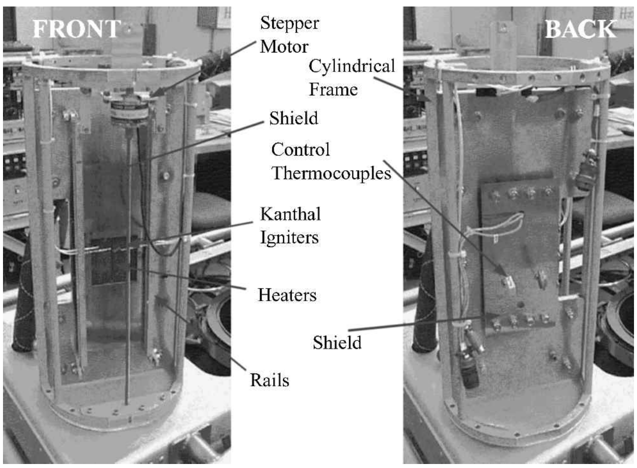

Fig. 3 KC-135 FIST assembly (sample cards not shown).

negligible effect on experimental results. The range of radiant heat flux magnitudes reported here is 25–35 kW/m^2 at the testing location. The reported radiant flux corresponds to that measured in natural convection for a given heater temperature. The radiant flux at the fuel surface for the forced-flow cases, however, may be somewhat affected by the airflow velocity. Radiant flux measurements at air velocities larger than that induced by buoyancy ($\sim$0.7 m/s) indicate that there is a decrease in the surface heat flux measured of approximately 5% per 1 m/s increase in air velocity, depending on the radiant flux and air velocity levels. Because the radiant panel temperature is maintained constant, this effect appears to be due primarily to convective cooling of the test section walls. Although it has not been possible to verify this effect in microgravity, it can be inferred, however, that at the low flow velocities tested in microgravity the actual radiant flux could be up to 5% larger than that reported. Theoretical calculations of the implications of this potential effect show that it does not affect significantly the results or conclusions reported here.

The FIST methodology calls for stepwise exposure of the fuel sample to a specified external heat flux. This is accomplished with a shield that blocks the radiation to samples while the heaters are brought to the appropriate temperature and between consecutive tests. A thin aluminum plate, which is placed 10 mm away from the radiant heater surface, serves as radiation shield. The plate is supported by two vertical slide rails located parallel to the radiant heater panel and is covered on one side with a layer of Fiberfrax® insulating paper to increase the characteristic heating time and reduce reradiation effects. The plate has a 50 × 50 mm aperture in the center to allow the radiant flux to pass at the sample test location.

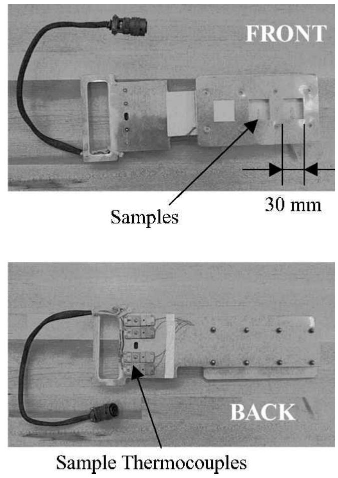

Fig. 4 KC-135 FIST sample cards.

The fuel sample is moved in and out of the test position (the shield aperture) by the sample holder positioning system, which includes a sample holder, holder slide, and a stepper motor operating on a lead screw. The fuel samples are placed in the sample holder, or card, which is capable of holding three fuel samples (Fig. 4). The sample holder consists of two 12.7-mm Marinite® boards sandwiched between a rigid back aluminum plate and a thin front aluminum plate. One of the Marinite boards is milled out to accept three 40 × 40 mm samples (one of them a positioning blank), whereas the other serves as an insulating backing material. The flush-mounted front plate is machined to expose a 30-mm side square of the surface of each fuel sample. Four type K thermocouples are used to provide solid fuel surface, rear surface, and ambient temperature. The movement of the sample card/motor assembly is controlled with Labtech software via a chopper drive that delivers high-frequency voltage pulses to the stepper motor. The bidirectional stepper motor is capable of positioning the sample within 1 mm of the designated location. The card can be moved to a holding, loading, or three testing positions by varying the number of pulses sent to the stepper motor. Each pulse accounts for a set angle of rotation and, thus, a corresponding vertical displacement. The positioning operation is entirely automated once the sample card is inserted because the SFSF environmental chamber remains sealed during the test. Multiple sample cards are used during the flight to allow for quick removal of spent samples and loading of fresh ones.

Above the fuel sample test position, a Kanthal wire coil is placed and used as the igniter. The protocol based on normal gravity infrared camera measurements produces a sufficiently hot igniter (igniter temperature is maintained at 1000°C or above for all flow velocities tested) such that the gas-phase induction time can be neglected. To determine the current necessary to achieve consistent ignition delay times, a series of preliminary tests were conducted, and a minimum current was identified. For the given coil resistance, length, and flow conditions, a current of 4.5 A is generated when a 28-V dc voltage is applied across the igniter. A more detailed description of the FIST component is provided in Ref. 24.

SFSF Combustion Chamber

The SFSF combustion chamber has an internal volume of 36 liters and domed ends to provide a smooth flow of the oxidizer. The oxidizer flow rate into the chamber is regulated by computer-controlled solenoid valves. The oxidizer is forced into the chamber through a sintered bronze plate that provides a uniform velocity in the chamber of up to 0.40 m/s. The chamber gases are exhausted to an overboard vent in the KC-135 through a proportional-integral-derivative (PID)-controlled solenoid valve, which maintains a constant specified pressure throughout the chamber. Flow velocity and chamber pressure levels are monitored and varied by Labtech software installed on the SFSF computer. The SFSF is also instrumented with a single-axis accelerometer and a video imaging system and handles the power distribution to the combined facility. The imaging system, which includes dual Super-VHS recorders and a digital video camera, captures images of the ignition tests through a quartz window in the environmental chamber. A detailed description of the SFSF facility is provided in Ref. 23.

Test Protocol

The integration of the FIST with the SFSF facilities allows the user to choose the heat flux intensity, the flow rate, and the material type and to record test data on computer and video. The tests can be performed on the ground, under normal gravity, with mixed (free and forced) convection flow, and in microgravity with pure forced flow.

In microgravity, the ignition tests are conducted in the KC-135 aircraft, following a predetermined protocol. The KC-135 flies a parabolic trajectory to produce periods of low gravity lasting about 25 s, with typical accelerations of approximately ± 0.2 m/s^2. Each parabolic trajectory is initiated and terminated with a pullup and pullout of 1.8–2.0 g. These trajectories are flown consecutively, typically in groups of 10, with a total of 30–40 parabolas per flight. Before entering the first parabolic trajectory, the heaters are brought to the desired temperature set point. During the trajectory pullup (gravity above normal), the oxidizer flow is set, and the sample is moved into position. The igniter is manually activated at the beginning of the low-gravity period and shut down when high-gravity levels resume (pullout) to ensure that no ignition occurs during the elevated gravity periods. Once ignition is observed, the burning samples are extinguished by shutting off the oxidizer flow, and venting the chamber gases overboard. In those cases that the reduced gravity period is shorter than the ignition delay, the fuel samples are subjected to the external radiant flux during the pullup period. This results in increased surface cooling due to the induced elevated gravity buoyant flows. For this reason the testing is limited to high heat fluxes with 25–35 kW/m^2 to minimize the time period that the samples are irradiated during elevated gravity levels. Quantification of the surface cooling is difficult due to the large variation in gravitational acceleration. However, the gravitational changes occur primarily in the initial inert heating of the sample where surface temperatures and consequently the convective cooling is small. Residual buoyant flows may also slightly affect these results, but simple scaling indicates that the impact on the ignition delay due to surface cooling by residual flows is negligible. The microgravity tests are reproduced in normal gravity following similar protocol for comparison purposes.

Tested Materials

Polymethylmethacrylate (PMMA) was selected as the base material in these tests because of its homogeneous structure, well-defined thermal properties, consistent behavior, and abundant experimental data on its burning characteristics. Thorough examination of the effects of all pertinent parameters such as flow velocity, heat flux magnitude, and oxidizer concentration on the behavior of PMMA has allowed for the establishment of a baseline against which other materials can be compared. The consequences of the elimination of gravity effects can also be studied in reference to the baseline data. The samples tested are made of type G, PMMA, 40 × 40 mm and 12.7 mm thick. The sample size is much smaller than the characteristic length of the combustion chamber (30 cm in width); thus, the confinement effects are minimum.

Because composite materials are commonly used in the aerospace industry, a composite material consisting of a blend polypropylene/glass (PP/GL) was also selected for the present experiments. The PP/GL blend is a composite commercially made by mixing together PP and loose glass fiber and subsequent molding the mixture and is used in the transportation industry, normally for paneling. The uniform distribution of glass fibers within the PP matrix results in globally isotropic properties that simplify the analysis of the experimental results. The samples tested are made of 70% PP/30% GL by mass, 40 × 40 mm and 3.2 mm thick. The properties relevant to the thermal heating of these materials are shown in Table 1 (see Refs. 25–27).

Results

Video records of the fuel sample ignition process, together with the sample surface temperature histories, are used to determine the

Table 1 Tested material properties

Property	Unit	PMMA (Ref.)	PP/GL (Ref.)
Composite type	——	Homogeneous	Isotropic
% by mass			70/30
ρ	kg/m^3	1170 (25 and 26)	1130 (27)
K	W/mK	0.185 (25 and 26)	0.218 (27)
C_P	J/kgK	1220 (25 and 26)	1626 (27)

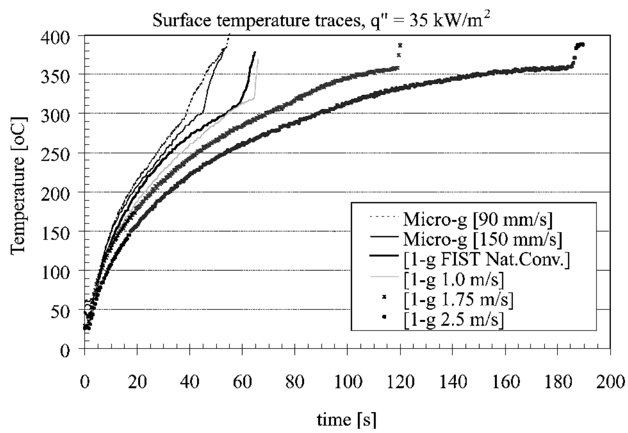

Fig. 5 PMMA surface temperature histories at several airflow velocities.

ignition delay time for each setting of the radiant heat flux and airflow rate. In the former case, the ignition delay is obtained by timing the period between the initial exposure of the sample to the radiant flux, and the visual observation of sustained burning. In the latter case, ignition is determined through the sharp increase in surface temperature that is normally observed at ignition.

Exemplar surface temperature histories for different airflow velocities are shown in Fig. 5 for PMMA samples. The low-velocity microgravity and normal gravity natural convection was obtained with the KC-135 FIST apparatus described earlier. Because the airflow velocities in the KC-135 FIST apparatus are limited to low values, the large-velocity data (> 1 m/s) was obtained with the FIST apparatus described in Ref. 20. From these data, it can be seen that, as the forced-flow velocity is decreased, there is an increase in the rate of surface temperature rise and a decrease in the surface temperature at which ignition occurs and of the time for ignition. The former is due to the decrease in the heat transfer coefficient and in its turn the convective cooling of the surface. The latter is due to the lower pyrolyzate mass flux needed for ignition to occur as the flow velocity is decreased.[20]

Although here ignition is considered to occur when sustained burning occurs, the time at which flame flashing first occurs is also recorded, if this time is differentiable from that of sustained flaming. The presence of flashing is of significance because it indicates the presence of a flammable mixture near the igniter, although the fuel supply rate is not high enough to support sustained flaming. Flame flashing can be viewed as equivalent to the flash point, and sustained flaming as the fire point in liquid fuels. During the flame flashing, the additional heat from the flame to the sample surface accelerates the fuel pyrolysis rate and often leads to sustained burning. It has been observed that the flashing frequency increases as the sample surface approaches the time of sustained flaming.

The results of Fig. 5, together with video data of the corresponding tests, are used to obtain the variation of the ignition delay with the flow velocity. The results for PMMA and for 30% PP/GL, with air as oxidizer, are presented in Figs. 6 and 7, respectively. The microgravity experiments are conducted at radiant fluxes of 25 and 35 kW/m^2, and air velocities ranging from 0.02 to 0.25 m/s. The experiments at velocities larger than 1 m/s were obtained using a larger scale laboratory FIST apparatus[20] than that used in the KC-135. It is seen that for both fuels, the ignition delay decreases as the flow velocity is decreased. This is due primarily to the decrease of the convective heat losses at the fuel surface together with the

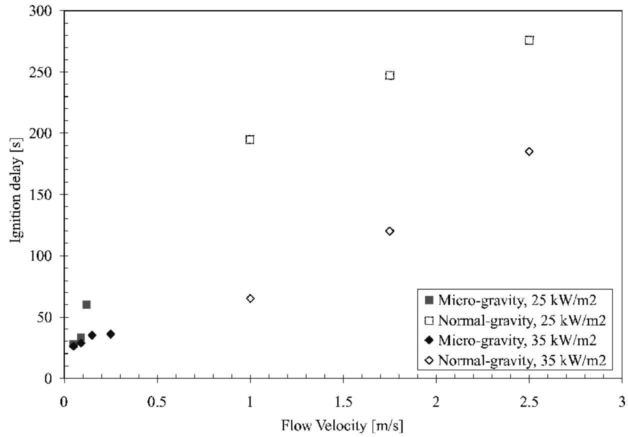

Fig. 6 PMMA ignition delay variation with the airflow velocity.

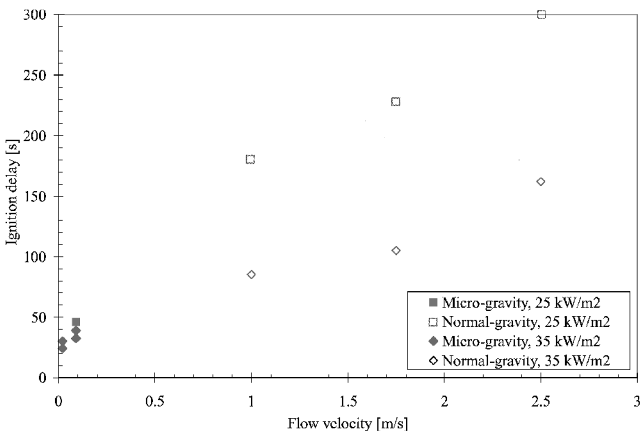

Fig. 7 Composite 30% PP/GL ignition delay with the airflow velocity.

decrease in the minimum pyrolyzate heat flux needed for ignition. The former is due to the dependence of the convection heat transfer coefficient on the flow velocity. Concerning the latter, theoretical predictions and phenomenological arguments indicate that ignition occurs at a fixed value of the equivalence ratio.[28] Thus, as the flow velocity decreases, the amount of pyrolysate needed for ignition also deceases. The results of Figs. 6 and 7 indicate that convection heat losses at the fuel surface seem to play a significant role in the fuel ignition process, even at the high radiant fluxes used in the experiments. This is partly due to the geometric configuration of the experiment. The radiant panel is parallel to the solid surface, has a larger area than the sample, and is separated 40 mm from it. As a consequence, surface reradiation is small (approximately 30%) in comparison to the convective heat losses, which in turn play an important role in determining the critical heat flux for ignition and the ignition delay.

The reduction of the ignition delay times indicates that, under these low flow conditions, the ignition process is more affected by the reduction in surface heat loss than the corresponding oxygen transport reduction. Furthermore, it is apparent that the process does not enter an oxygen-limited regime in the case of either tested material as might be conceivable at these low velocities. Such a transition would be signaled by an increase in the ignition delay time with further decrease of the flow velocity. This did not seem to be the case here. In fact, tests conducted under quiescent conditions (with the inlet flow to the combustion chamber turned off) yielded respectively shorter ignition times.

In piloted ignition experiments similar to the present ones but conducted in normal gravity,[19,20] it is observed that the ignition time increases with decreasing heat flux until a critical heat flux is reached, below which ignition can no longer occur. It is also observed that for a given heat flux the ignition delay decreases as the oxidizer flow velocity is decreased. However, as the forced-flow velocity is reduced below approximately 1 m/s, natural convection starts to dominate over the forced flow, and it is not possible to conduct tests at velocities smaller than approximately 0.5 m/s (Ref. 20). In the KC-135 reduced-gravity experiments, because of the time constraints associated with the parabolic flight, ignition tests are limited to high heat fluxes, and it is not possible to determine the entire ignition curve, or the critical heat flux. In spite of this limitation, the reduced-gravity experiments are still important because they allow for the determination of the ignition delay at flow velocities that are not masked by buoyancy, and are smaller than those attainable in normal gravity. By comparison with the normal gravity data, together with the predictions from current models of the problem, it is possible to infer the ignition characteristics of materials in environment expected in space-based facilities.

The current experiments provide information about high heat flux, short ignition delay conditions and must be significantly extrapolated to lower heat flux values to determine a critical heat flux for ignition.[22] However, the normal gravity experiments[20] have shown that the oxidizer flow velocity affects not only the ignition temperature and ignition delay, but also the critical heat flux for ignition, decreasing them as the flow velocity is decreased. Thus, from the present data, it can be inferred that the critical heat flux for ignition will also be reduced at these low flow velocities and that it will be at a minimum when the heat losses are minimized without entering an oxygen-limited regime.

Model Predictions

A theoretical numerical model recently developed to simulate the present problem[29,30] can be used, together with the present data, to predict the ignition curve and critical heat flux for ignition at low flow velocities in microgravity. The numerical model predicts the endothermic pyrolysis and piloted ignition delay of solid combustible materials exposed to an external radiant heat flux. It considers only the coupled thermochemical processes that take place in the condensed phase, with the gas-phase processes being replaced by the assumption that ignition occurs when a critical pyrolysate mass flow is reached at the fuel surface.[28,31,32] The implication is that the ignition of the material is subjected to the attainment of a minimum concentration of fuel in the gaseous mixture adjacent to the pilot (lean flammability limit). The analysis, therefore, describes the piloted ignition of solid combustible materials only under conditions of fast chemical kinetics in the gas phase.

The condensed-phase processes considered in the model include oxidative and thermal pyrolysis, phase change, radiation absorption, and heat and mass transfer in a multiphase and multicomposition medium. The pyrolysis processes are considered to occur following first-order Arrhenius laws with different kinetic parameters for oxidative or thermal pyrolysis. The resulting transient heat and mass transfer problem is described by the solid phase mass and energy equations, which are solved numerically together with the initial and boundary conditions using a Newton iteration method. An enthalpy–temperature hybrid method[29] is employed to model the fuel melting process. The implementation of the model is as follows. For given oxidizer flow conditions and external radiant flux, the predicted variation with time of the surface temperature is compared with the experimental temperature data to verify that the model predicts well the temperature history. Then the experimentally observed time for ignition is used in the model to obtain the pyrolysate mass flux at which ignition occurs. When it is assumed that the pyrolysate mass flux for ignition (critical pyrolysate rate) is dependent on the oxidizer flow conditions, but independent of the radiant flux, the model is used to predict the ignition delay for varied external radiant fluxes. These data are then used to develop the ignition curve of the flammability diagram for a given flow velocity and oxygen concentration. It has been shown that the model predictions agree well with the available normal gravity experimental data.[30]

The described methodology is used here to predict the PMMA ignition curves in microgravity, low-velocity flows. The surface temperature data of Fig. 5 is first used to verify the model predictions at low-velocity flows. It is found that, using a heat transfer coefficient based on laminar flow[33] to describe the convective heat losses at the solid surface, the model predicts well the experimental surface temperature histories. The ignition delay as obtained from Fig. 5

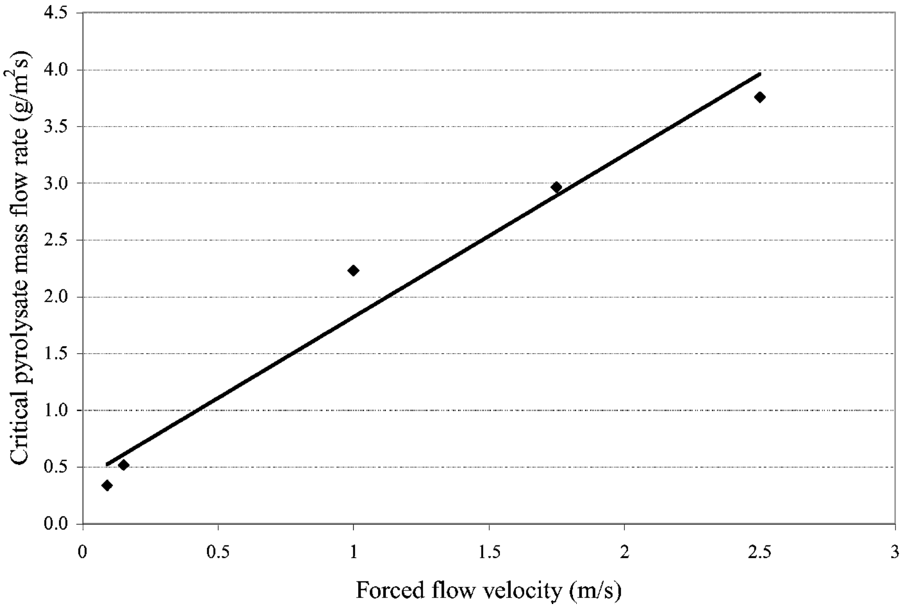

Fig. 8 Critical PMMA pyrolysate rate as a function of the airflow velocity.

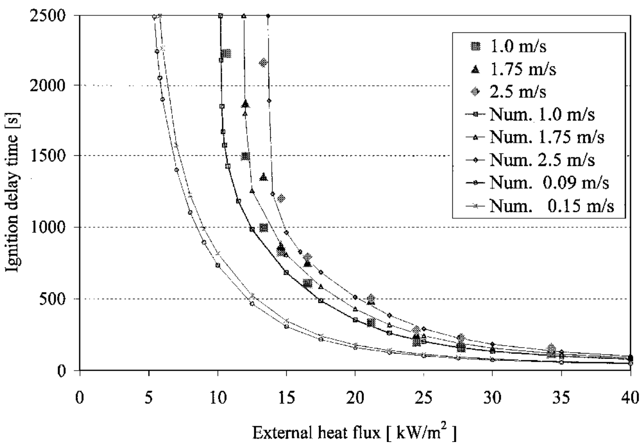

Fig. 9 Predicted PMMA ignition delay curves for several flow velocities.

is then used to determine the pyrolysate mass flux at the different flow velocities. The results, presented in Fig. 8, show that the predicted critical pyrolysate rate increases almost linearly as the airflow velocity is increased. This result is important because it implies that, at the low flow velocities expected in space facilities, the condition that a certain mass of pyrolysate must be released by the solid for ignition to occur is less stringent than in normal gravity.

Using the critical pyrolysate rate of Fig. 8, the model is then used to predict the ignition curves for PMMA for different flow velocities. The results, presented in Fig. 9, show that the predicted ignition delay for a given radiant flux decreases as the flow velocity is decreased. What is more important is that the critical heat flux for ignition also decreases as the flow velocities are decreased. It is predicted that the critical heat flux for ignition at the flow conditions expected in space facilities could be as much as half the value measured in normal gravity natural convection (LIFT). If these predictions are confirmed by long-term microgravity testing, they will have significant implications for the fire safety design of space facilities.

Conclusions

The FIST test method has been employed to examine the ignition behavior of test materials subjected to forced-flow velocities lower than those of gravity-induced buoyant flows. Tests have been conducted in normal gravity and ground-based KC-135 microgravity facilities to provide a preliminary indication of the effects of the reduced-oxidizer flow velocity. The results show a reduction of the ignition delay time under microgravity, low flow velocity conditions. Theoretical predictions of the ignition process at low flow velocities indicate that the critical pyrolysate rate for ignition and the critical heat flux for ignition decrease significantly at the low flow velocities expected in space-based facilities.

These preliminary results suggest that the low forced-flow velocity conditions commonly found on spacecraft may, in fact, be more dangerous from an ignition standpoint. These conditions may lead to reduced ignition times and critical heat fluxes. Whether it also leads to increased flame spread rates is to be determined. The flammability of tested materials subjected to a radiant heat flux is enhanced by the reduction in convective heat losses under these conditions. Furthermore, the oxidizer supply still appears to be sufficient to maintain the reaction. Note that because of the geometry of the apparatus, with the radiant flux parallel to the fuel surface, radiant heat loss from the surface is relatively small. If the radiant heat loss were larger, as would occur if the solid radiated to an open environment, the effect of a reduction in convective heat loss would become less significant.

Shortcomings of the ground-based microgravity facilities, which include short reduced-gravity period, g-jitter, and elevated g-levels highlight the need for the conditions afforded by long-term microgravity facilities such as the space station. These facilities would allow for the conduction of low heat flux and low flow velocity tests that would provide more accurate and complete information about the behavior of solid fuels.

Note that the microgravity data presented here should be viewed as a qualitative indicator of the effects of the reduction of the oxidizer flow velocity on ignition delay. The parabolic flight approach to achieving reduced-gravity conditions has its own unique problems, which can affect experimental results. One difficulty concerns g-jitter, which refers to small fluctuations in the g-level due to meteorological and physical events. Buoyant flows induced by such fluctuations may exceed the very low forced-flow velocities (below ~0.09 m/s) and result in increased ignition delay. A second problem that was alluded to earlier is the necessary 2 g pullup period that follows/precedes the reduced-gravity interval. The magnitude of the buoyant flows during pullup is significantly increased when compared to the flows present under normal gravity and can lead to significant heat losses at the sample surface. This effect impacts tests that require the sample to be exposed during the pullup because of an expected long ignition delay. In addition, the residual oxidizer currents from the pullup period can persist into the microgravity period, disrupting the flowfield.

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References

[1]Palmer, H., "Closing Remarks," International Microgravity Combustion Workshop, NASA, Jan. 1987.

[2]Faeth, G., "Closing Remarks," Space Station Freedom Modular Combustion Facility Assessment Workshop, NASA, May 1989.

[3]Friedman, R., "Risk and Issues in Fire Safety on the Space Station," NASA TM 106403, 1994.

[4]Ross, H., "Presentation," Drop Tower Days 1998, JAMIC, Hokkaido, Japan, Oct. 1998.

[5]Tanaka, T. J., Baynes, E., Jr., Nowlen, S. P., Brockmann, J., Gritzo, L., and Shaddix, C., "LDRD Report: Smoke Effects on Electrical Equipment," Sandia National Labs., Rept. SAND2000-0599, Albuquerque, NM, 2000.

[6]Ivanov, A. V., Balashov, Y. V., Andreeva, T. V., and Melikhov, A. S., "Experimental Verification of Material Flammability in Space" NASA CR-1999-209405, 1999.

[7]Olson, S. O., "Mechanisms of Microgravity Flame Spread over a Thin Solid Fuel: Oxygen and Opposed Flow Effects," *Combustion Science and Technology*, Vol. 76, Nos. 4–6, 1991, p. 233.

[8]Sacksteder, K. R., and T'ien, J. S., "Buoyant Downward Diffusion Flame Spread and Extinction in Partial Gravity Acceleration," *Twenty-Fifth Symposium (International) on Combustion*, Combustion Inst., Pittsburgh, PA, 1994, pp. 1685–1692.

[9]Tarifa, C. S., and Juste, L. G., "A Study of the Combustion Problems of Solid Materials at Conditions Existing in Space Stations," Second European Symposium for the Utilization of the International Space Station, ESA, 1998.

[10]"Flammability, Odor, Offgassing, and Compatibility Requirements and Test Procedures for Materials in Environments that Support Combustion," NASA Handbook 8060.1, 1981.

[11]"Materials Selection List for Space Hardware Systems," NASA Marshall Space Flight Center, MSFC-HDBK-527, rev F, 1988.

[12]Friedman, R., *Proceedings of the 2nd International Microgravity Combustion Workshop*, NASA CP-10113, 1993, p. 163.

[13]Friedman, R., "Fire Safety in Extraterrestrial Environments," NASA TM-1998-207417, 1998.

[14]Friedman, R., "Fire Safety in Low-Gravity Spacecraft Environments," Society of Automative Engineers, SAE TP 99-01-1937, 1999.

[15]Ohlemiller, T. J., and Villa, K. M., "Material Flammability Test Assessment for Space Station Freedom," NISTIR 4591, NASA CR-187115, 1991.

[16]Ohlemiller, T. J., "An Assessment of the NASA Flammability Screening Test and Related Aspects of Material Flammability," NISTIR 4882, NASA CR-189226, 1992.

[17]"Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter," *Annual Book of ASTM Standards*, ASTM E 1354-99, 04-07, American Society for Testing and Materials, 1999.

[18]"Standard Test Method for Determining Material Ignition and Flame Spread Properties," *Annual Book of ASTM Standards*, ASTM E 1321-93, 04-07, American Society for Testing and Materials, 1996.

[19]Cordova, J. L., Zhou, Y. Y., Pfaff, C., and Fernandez-Pello, A. C., "Test Method for Ranking the Fire Properties of Materials in Space Based Facilities," *Prevention of Hazardous Fires and Explosions*, edited by V. E. Zarko, V. Weiser, N. Eisenreich, and A. A. Vasil'ev, Kluwer Academic, Norwell, MA, 1999, pp. 49–59.

[20]Cordova, J. L., Walther, D. C., Torero, J. L., and Fernandez-Pello, A. C., "Oxidizer Flow Effects on the Flammability of Solid Combustibles," *Combustion Science and Technology*, Vol. 164, 2001, pp. 253–278.

[21]Quintiere, J., and Harkleroad, M., "New Concepts for Measuring Flame Spread Properties," U.S. Dept. of Commerce, NBSIR 84-2943, 1984.

[22]Quintere, J., Harkleroad, M., and Walton, D., "Measurement of Material Flame Spread Properties," *Combustion Science and Technology*, Vol. 32, 1983, pp. 67–89.

[23]Goldmeer, J. S., "A Users Guide for the Spacecraft Fire Safety Facility," NASA TM-2000-210375, 2000.

[24]Long, R. T., Torero, J. L., Quintiere, J. G., and Fernandez-Pello, A. C., "Scale and Transport Considerations on Piloted Ignition of PMMA," *Proceedings of the 6th International Symposium on Fire Safety Science*, International Association for Fire Safety Science, 1999, pp. 567–578.

[25]"Plexiglas, Design and Fabrication Data," Rohm and Hass Co., Philadelphia, 1971.

[26]Orloff, L., De Ris, J., and Tewarson, A., "Thermal Properties of PMMA at Elevated Temperatures," Factory Mutual Research Corp., TR 22355-2, Norwood, MA, 1974.

[27]"BJ22GC Data Sheet," Montell Polyolefins, Montell Higlass, Elkton, MD, 1993.

[28]Zhou, Y. Y., Walther, D. C., and Fernandez-Pello, A. C., "Numerical Analysis of Piloted Ignition of Solid Materials," 2nd Joint Meeting of the U.S. Sections of the Combustion Inst., Paper 63, March 2001.

[29]Zhou, Y., and Fernandez-Pello, A. C., "An Enthalpy-Temperature Hybrid Method for Solving Phase Change Problems and Its Application to Polymer Pyrolysis and Ignition," *Combustion Theory and Modeling*, Vol. 4, 2000, pp. 477–493.

[30]Zhou, Y., and Fernandez-Pello, A. C., "Numerical Modeling of Endothermic Pyrolysis and Ignition Delay of Composite Materials Exposed to an External Radiant Flux," *Proceedings of the Combustion Institute*, Vol. 28, 2000, pp. 2769–2775.

[31]Drysdale, D. D., and Thomson, H. E., "Flammability of Plastics. II. Critical Mass Flux at the Firepoint," *Fire Safety Journal*, Vol. 14, 1989, pp. 179–188.

[32]Atreya, A., "Ignition of Fires," *Philosophical Transactions of the Royal Society of London, Series A: Mathematical and Physical Sciences*, Vol. 356, 1998, pp. 2787–2813.

[33]Incropera, F. P., and DeWitt, D. P., *Fundamentals of Heat and Mass Transfer*, 4th ed., Wiley, New York, 1996.

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