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Two-sided ignition of a thin PMMA sheet in microgravity

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Abstract

Numerical computations and a series of experiments were conducted in microgravity to study the ignition characteristics of a thin polymethylmethacrylate (PMMA) sheet (thicknesses of 0.2 and 0.4 mm) using a CO_2 laser as an external radiant source. Two separate ignition events were observed, including ignition over the irradiated surface (frontside ignition), and ignition, after some delay, over the backside surface (backside ignition). The backside ignition was achieved in two different modes. In the first mode, after the laser was turned off, the flame shrank and stabilized closer to the fuel surface. This allowed the flame to travel from the frontside to the backside through the small, open hole generated by the laser's vaporization of PMMA. In the second mode, backside ignition was achieved during the laser irradiation. The numerical calculation simulating this second process predicts fresh oxygen supply flows from the backside gas phase to the frontside gas phase through the open hole, which mixes with accumulated hot MMA fuel vapor which is ignited as a second flame in the frontside gas phase above the hole. Then, the flame initiated from the second ignition travels through the hole to ignite the accumulated flammable mixture in the backside gas phase near the hole, attaining backside ignition. The first backside ignition mode was observed in 21% oxygen and the second backside ignition mode in 35%. The duration of the laser irradiation appears to have important effects on the onset of backside ignition. For example, in 21% oxygen, the backside ignition was attained after a 3 s laser duration but was not observed after a 6 s laser duration (within the available test time of 10 s). Longer laser duration might prevent two-sided ignition in low oxygen concentrations.

Keywords: Ignition; Microgravity; PMMA

1. Introduction

A series of experiments was conducted to study ignition, and the subsequent transition to flame spread over a thin polymethylmethacrylate (PMMA) sheet in microgravity. A CO_2 laser was used as an ignition source due to its well-controlled, non-intrusive nature. The intended fire scenario is ignition and subsequent flame spread over a thin plastic material close to momentary burning of a small overheated wire. The results are intended for application to insuring a fire safe environment in spacecraft, including the

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International Space Station. Since the experiments were conducted in a drop tower with limited available test time (10 s), the focus of this study was on the ignition process. Two ignition events were observed in the experiments: the first was ignition on the sample surface exposed to the incident laser beam (frontside ignition), and the second was ignition on the backside sample surface (backside ignition). The presence of two flames over two sample sides significantly increases heat release rate (at least twice from that of one side burning) and fire hazard. Therefore, this paper focuses on the mechanism of backside ignition. Although numerous ignition studies have been previously published, they were with a thermally thick sample (only frontside ignition) [1–3] or with a thermally thin sample (simultaneous ignition on both sides) [4]. Although the relationship between the one-side flame spread and the two-side flame spread was studied [5], few studies have been made on delayed backside ignition resulting from frontside ignition. The mechanism of backside ignition is reported in this paper, as are the effects of the sample thickness, external flow velocity, and oxygen concentration on the time delay between frontside and backside ignition.

2. Experimental study

The experiments were conducted in the 10 s drop tower at the Japan Microgravity Center (JAMIC). The experimental rig consisted of a large rectangular chamber filled with an oxygen–nitrogen test gas. A 12 cm tall, 16 cm wide, and 18 cm long flow duct was mounted inside the chamber with a fan to draw the gas mixture through the test section. Ignition of a PMMA sheet (14 cm long × 10 cm width) was initiated at its midpoint by a CO_2 laser beam having a total power of about 28 W with a Gaussian distribution (half-width at half-maximum value was about 2 mm and the peak flux was 1600 kW/m^2). The sheet was mounted in the center of the flow duct which provided an initially uniform slow flow of up to 10 cm/s on both sides of the sample. Two different sheet thicknesses, 0.2 and 0.4 mm, were used. Color video images were recorded, one of the surface view over the irradiated front surface, and another of the edge view. These allowed observations of the onset of ignition and subsequent transition to flame spread over the two sides (front and back) simultaneously.

The ignition and flame spread phenomena were quantified from the video images. Frontside ignition of the PMMA sample was observed shortly after the start of the laser irradiation but subsequent backside ignition was significantly delayed. Frontside ignition delay times for 0.4 mm thick samples were shorter than those of 0.2 mm thick samples. We noticed that a thinner PMMA sample was more difficult to ignite due to rapid consumption of the sample before the onset of ignition in normal gravity but the mechanism of shorter ignition for a thicker sample cannot be explained at present. (Our numerical calculation does not confirm this trend.) Backside ignition delay increased with the thicker sample or lower oxygen concentration as shown in Fig. 1. Backside ignition was attained at two different relative times, one during the laser irradiation, and the other, shortly after termination of the laser irradiation. The former case was observed in 35% oxygen and the latter case was observed in 21% oxygen. This trend was not affected by the changes in external flow velocity and sample thickness that were studied in this work.

As shown in Fig. 2, in 21% oxygen, with the onset of frontside ignition at 0.43 s from the start of irradiation, the flame began as a relatively bright flame and then was reduced to a faint blue color. At 2.55 s (just before the termination of the laser beam at 3 s), the frontside flame was a faint blue color with a localized bright region due to absorption of the laser beam by the flame. It is estimated that, by this time, a small (laser beam diameter or less) hole had formed through the sample due to the degradation of the sample by the continuous laser irradiation as well as flame heat feedback. Since the flame was lifted away from this hole (4–5 mm), it appears that the flame could not travel through the open hole to the backside. By 3.48 s (after the laser beam was turned off), a small, faint blue color flame had shrunk (having a lesser fuel supply after the termination of the laser beam to the sample) and moved closer to the sample surface and the open hole. At 3.54 s, ignition was observed on the backside surface, and at 4.45 s, a flame was visible on each side, both moving upstream. As the initial small flame moved toward the sample surface and toward the open hole after the termination of the laser irradiation, the flame was able to propagate through the open hole and to cause ignition over the backside. Since the formation of an open hole is a critical process for backside ignition, a thicker sample retards the hole formation, increasing the backside ignition delay, as shown in Fig. 1 for the 35% oxygen and 5 cm/s flow tests.

The duration of the laser irradiation could have significant effects on the backside ignition. This was demonstrated in tests with an external velocity of 5 cm/s, 21% oxygen, and two different irradiation durations. A laser duration of 6 s did not ignite the backside within the available test time of 10 s but a 3 s duration did ignite the backside within 1 s *after the termination of irradiation*. This raises a question why backside ignition did not occur when the laser irradiation was turned off at 6 s instead of at 3 s, as shown in Fig. 2. Figure 3 shows the frontside flame at 0.06 s before

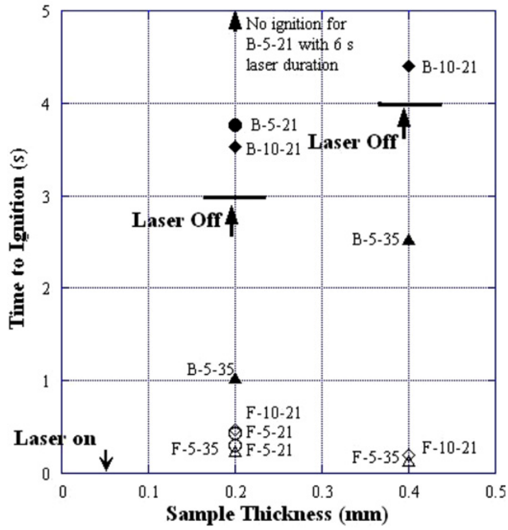

Fig. 1. Effects of sample thickness on ignition delay time of PMMA in microgravity. (F, frontside/B, backside)-flow velocity (cm/s)–O_2 (%).

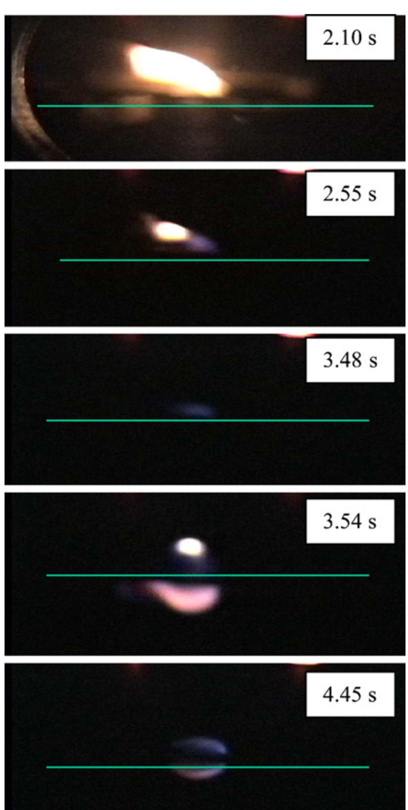

Fig. 2. Selected edge view video images of flame behavior over 0.2 mm thick PMMA sheet (green line) in 21% O_2 at 5 cm/s flow from right to left. Laser irradiation from top.

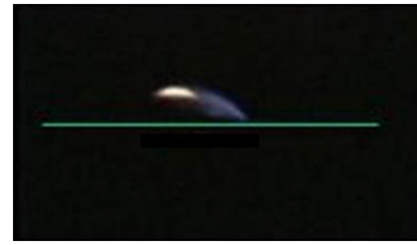

Fig. 3. Selected edge view image of flame over 0.2 mm thick PMMA (green line) in 21% O_2 at 5 cm/s with 6 s laser duration. $t = 0.06$ s before laser termination.

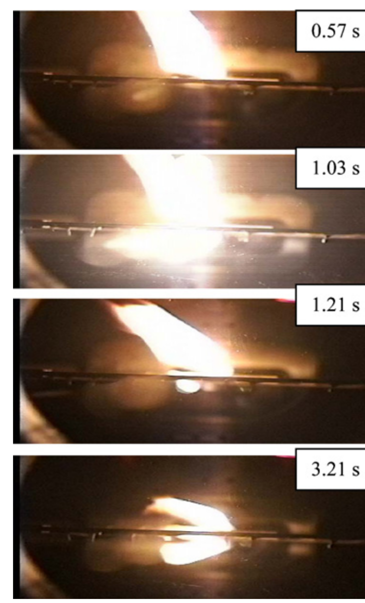

Fig. 4. Selected edge view video images of flame behavior over 0.2 mm thick PMMA sheet in 35% O_2 at 5 cm/s flow from right to left. Laser irradiation from top.

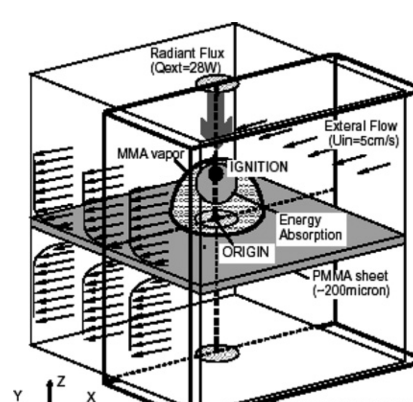

Fig. 5. Schematic illustration of the computational domain.

the termination of the laser irradiation for the case with 6 s laser duration. The bright region of the flame (caused by absorption of the laser beam by the flame) was located at the tail end of the traveling flame instead of being near the leading edge of the flame, as shown in the 2.55 s picture of Figs. 2 and 3 (both pictures were just before the termination of the laser irradiation). After the termination of the laser irradiation, the flame shown in Fig. 3 shrank (toward the traveling flame front) and moved closer to the sample surface. However, the surface view images show that the distance between the flame front and the edge of the open hole was about 4 mm for the 6 s laser duration case (due to 3 s longer traveling time) compared to about 2 mm for the 3 s laser duration case. It appears that the flame front for the former might be too far away to propagate through the open hole. This indicates that longer laser duration might prevent two-sided ignition in lower oxygen concentrations for the two reasons: (1) the frontside flame stands far off from the surface due to the intense fuel blowing and cannot propagate through the hole, and (2) the frontside flame spreads away from the hole during irradiation and at some point it will be too far from the hole to allow the flame to propagate after the laser is turned off.

In 35% oxygen, after the frontside ignition, a bright flame was established as shown in Fig. 4. The flame appears to be closer to the sample surface than in 21% oxygen due to the better oxygen supply to the flame. Backside ignition occurred during the presence of the laser irradiation, even with a thicker sample. However, it is not clear how the backside ignition occurred. Did the frontside flame travel through an open hole through the sample or did a separate ignition occur on the backside surface? A numerical calculation simulating the above described ignition experiment is made to provide some clues for the backside ignition mechanism.

3. Theoretical study

A schematic illustration of the computation domain simulating the experimental configuration is shown in Fig. 5. The enclosure configuration represents the flow duct used in the experiment, with flow in the $-x$ direction. At the inlet, a 5 cm/s uniform flow is imposed parallel to the PMMA sheet. The total laser irradiation energy at the sample surface is 28 W with a Gaussian distribution (half-width at half-maximum value is about 2 mm and its center is on the z-axis). The three-dimensional, time-dependent, gas-phase model used here is quite similar to that in our previous study [6], with the addition of absorption of the external radiation by gas phase methyl methacrylate (MMA) (the degradation product of PMMA). The absorption coefficient of MMA vapor is set to 0.1 $atm^{-1}\,cm^{-1}$.[1] Three species are followed in the calculation: MMA, oxygen, and inert gas. A one-step, irreversible, exothermic gas phase reaction model is used with kinetic parameters from references [8,9]. In the solid phase, the time-dependent conservation equations for mass, energy, and species are solved, and thermal conduction (three dimensional) is included. A one-step pyrolysis reaction is considered for the PMMA decomposition reaction to form MMA [10]. The thermal properties of PMMA are given as functions of temperature [11] and surface radiative properties are from [12]. The absorption coefficient of PMMA at 10.6 μm is 175 cm^{-1} (measured using FTIR). In the flow field, the thickness of the PMMA sheet is only one cell in its depth but, in the condensed phase, there are 20 cells in the depth direction to calculate the processes of thermal conduction, absorption of the external radiation, and thermal decomposition. The MMA vapor from the decomposition of PMMA in the sample is immediately released from the exposed surface. For each PMMA cell, once 95% of the PMMA is consumed, the cell is removed from the condensed phase to become a gas-phase computational cell. The gas-phase quantities (temperature, concentration, and pressure) at the 'newly opened' cell are specified as the averaged quantities between those of the first cell in the frontside and in the backside of the gas phase. The careful observation of the flow field around the hole at the instance of its opening shows a smooth transition without any sudden changes. Then, once the hole is made, the flow starts through the hole.

Simulations are performed with a modified revision of fire dynamic simulator (FDS) [13] with new subroutines for solving solid phase processes as well as absorption processes (gas- and solid-phase). The total number of grid points is 138,000 ($50 \times 40 \times 69$), and a non-uniform grid system is applied in the x- and z-directions. The minimum size grid is placed near the surface and the irradiated center to resolve the local ignition position accurately. Non-slip conditions are applied on the exposed surfaces (enclosure wall, PMMA). A typical computational time for one productive run is about 72 h using a generic personal computer.

A calculated ignition sequence over a 0.2 mm thick PMMA sheet in 35% oxygen at an external flow of 5 cm/s is shown in Fig. 6. The time $t = 0$ s is defined when the sample is exposed to

[1] The value published in [7] was 1.9 $atm^{-1}\,cm^{-1}$. This value appears to be too large (extremely short ignition delay is predicted), and the value used in this study is approximated as 1/1000 of that of PMMA due to the difference in density between PMMA and MMA vapor.

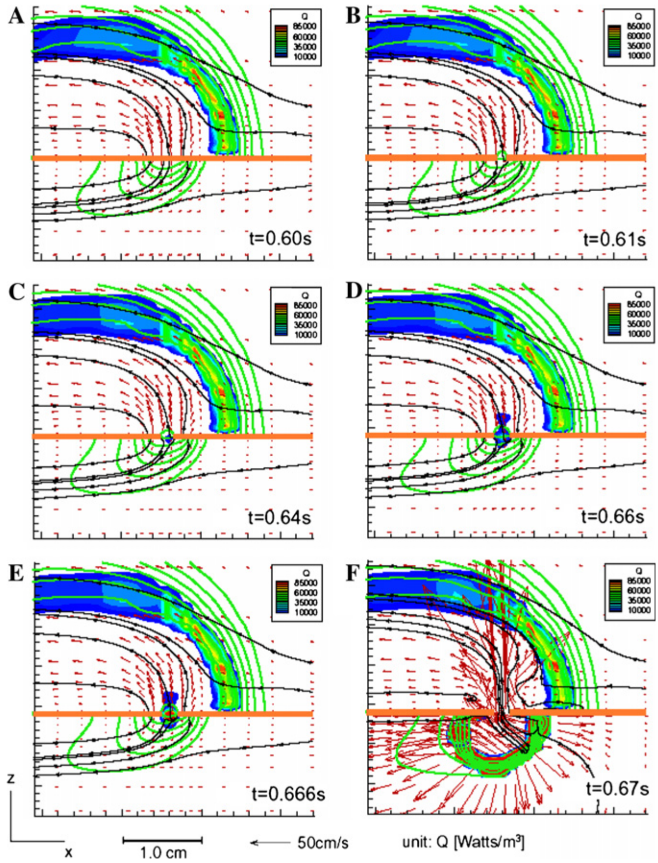

Fig. 6. Calculated two-dimensionally sliced contours, along the centerline, of heat release rate (Q), oxygen mass fraction (green), stream line (black), flow vectors (red arrows) over 0.2 mm thick PMMA (orange sheet) with laser irradiation from top in 35% O_2 at flow velocity of 5 cm/s from right to left at various times from the start of laser irradiation.

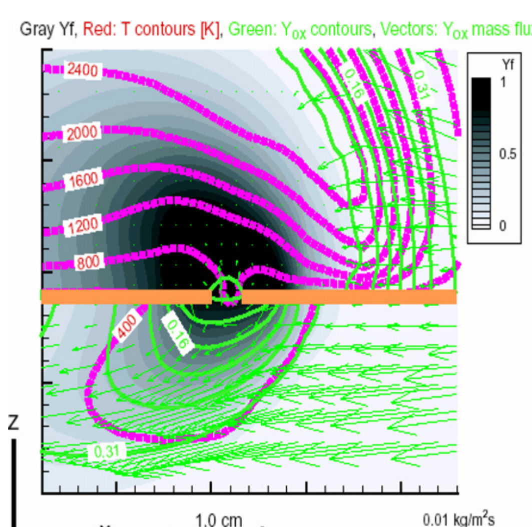

Fig. 7. Enlarged image of contours of fuel mass fraction, gas phase temperature, oxygen mass flux, and oxygen mass flux vectors near the open hole over 0.2 mm thick PMMA with laser irradiation from top in 35% O_2 at 5 cm/s flow from right to left at 0.64 s after the start of laser irradiation, shortly after a hole is formed in the fuel sheet.

the external radiation. Frontside ignition is predicted at 0.193 s. At 0.60 s, the frontside flame is well established and is slowly spreading upstream. The backside near the irradiated area is heated and producing a small amount of MMA. At 0.61 s, a small hole through the sample is formed and the frontside gas phase near the irradiated surface is hot and fuel rich but heat release rate from the gas phase reaction is negligible due to a lack of oxygen.

At 0.64 s, a hole is formed due to continued irradiation. An enlarged image near the hole is shown in Fig. 7. It shows clearly that the frontside gas phase near the hole is hot (above 800 K due to convected hot flow from the upstream flame front) and has a high MMA concentration caused by continuous irradiation. The small green arrows indicate a slow oxygen flow from the backside to the frontside through the open hole. Since the backside gas phase temperature near the hole is low (slightly over 400 K), backside ignition does not occur even with a flammable mixture of MMA and oxygen there. The incoming cool external flow and low absorption of the external radiation (external radiation is strongly absorbed by high concentration of MMA in the frontside gas phase above the hole) keep the backside gas phase near the hole at a relatively low temperature.

As the fresh supply of oxygen continues to flow through the hole, an exothermic gas phase reaction is accelerated above the hole and second ignition appears around 0.666 s in the frontside (Fig. 6). The flame from the second ignition rapidly travels through the hole from the frontside to the backside and it ignites the accumulated flammable mixture in the backside gas phase. A sudden expansion caused by the heat release from the backside ignition can be seen at 0.67 s. Thus, the calculation predicts that backside ignition is achieved via the second flame formed on the frontside gas phase near the hole (beneath the spreading flame). Although this predicted ignition process in 35% oxygen has not been experimentally confirmed yet, a similar ignition process is also predicted for several configurations (various sample orientations) in normal gravity.

4. Conclusions

Ignition of a thin PMMA sheet (thicknesses of 0.2 and 0.4 mm) was experimentally studied using a CO_2 laser as an external radiant source in microgravity. At first, ignition of the irradiated surface (frontside ignition) was observed, followed, with significant delay, by ignition of the backside surface (backside ignition). To attain backside ignition, the formation of a small open hole through the PMMA sheet generated by the continuous laser irradiation is critically needed. Backside ignition was achieved by two different modes. In one, when the laser was turned off, the flame initiated by the frontside ignition shrank closer to the sample surface. Subsequently this flame traveled through the open hole from the frontside to the backside. In the other mode, backside ignition was achieved in the presence of the laser irradiation. The numerical calculation simulating this second mode predicts that fresh oxygen supply flow from the backside gas phase to the frontside gas phase through the open hole, mixes with accumulated hot MMA vapor and ignites a second flame in the frontside gas phase above the hole. This flame travels back through the hole to ignite the accumulated flammable mixture in the backside gas phase near the hole and to generate ignition there. The first backside ignition mode was observed in 21% oxygen, and the second backside ignition mode was observed in 35% oxygen. The duration of the laser irradiation appears to have important effects on the onset of backside ignition. The backside ignition was attained after a 3 s duration in 21% oxygen but the backside ignition was not observed after a 6 s laser duration within the available test time of 10 s because the flame had already propagated too far from the hole. Longer laser duration might prevent two-sided ignition in low oxygen concentrations.

Acknowledgments

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Comments

Carlos Fernandez-Pello, University of California—Berkeley, USA. What is the role of the hole in affecting (delaying) the ignition time?

Reply. A hole through the thin sample has two competetive effects for the front-side ignition; one is that it implies a limited supply of the fuel and the other is it provides an increase in air supply from the backside to the irradiated side through the hole. A hole is necessary for the *backside ignition* of thin, non-char forming polymeric materials.

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James T'ien, Case Western Reserve University, USA. Is it possible to ignite the backside without a hole or a hole that is smaller than the quenching distance?

Reply. Without the formation of a hole, backside ignition can occur only with a thin char forming material. The temperature of a char gets high enough (due to continuing external thermal radiation) to be able to ignite the backside (backside char surface acts as a self-induced pilot) if a flammable mixture consisting of the degradation products and air is available near the hot surface. For a non-char forming material, a hole is necessary for the backside ignition. In the case of a hole smaller than the quenching distance, backside ignition is still possible but only when the laser beam through the hole is absorbed by the flammable mixture *on the backside* and thereby initiates runaway reactions. Such a case is predicted in the ceiling configuration in normal gravity (with an upward laser beam on a thin horizontal, downward facing PMMA sheet). A paper based on this result has been submitted to Combustion and Flame (under review).