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Effect of Pressure and External Heating on Microgravity and Earth Gravity Fires

By
Christina Liveretou

A dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy

in

Engineering - Mechanical Engineering

in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:

Professor Michael Gollner, Co-Chair
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Professor Ömer Savaş
Professor Joan Walker

Summer 2025

Abstract

Effect of Pressure and External Heating on Microgravity and Earth Gravity Fires

By

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Doctor of Philosophy in Engineering- Mechanical Engineering

University of California, Berkeley

Professor Michael Gollner, Co-Chair
Professor Carlos Fernandez-Pello, Co-Chair

While fire behavior on Earth has been studied for centuries, fire research in microgravity conditions is still in its infancy. The frequency of human space travel and length of individual missions have resulted in a greater need to understand microgravity fire safety. There is particular concern about reducing the flammability risk inside a spacecraft, as the consequences of a fire could be catastrophic in an enclosed environment where egress is difficult or impossible.

The flammability of a material is greatly influenced by the environmental conditions that surround it. Spacecraft environments generally feature reduced ambient pressures, low velocity flows, and potentially elevated oxygen concentrations, and understanding how these conditions affect combustion is an important aspect of flammability assessments. This work aims to compare the flame spread and limiting oxygen concentration (LOC) for opposed flame spread extinction of polymethyl methacrylate (PMMA) in sub-atmospheric microgravity and earth-gravity environments under the influence of an external radiant heat flux, using ground and ISS experiments. The radiant heating ranges from 0 to 3.3 kW/m² and the subatmospheric pressures tested are as low as 40 kPa. Special attention is paid to the influence of a diminishing oxygen concentration on the flame spread rate and process of flame extinction.

Experiments show that the ambient pressure and external heat flux have parallel effects on the rate of flame spread over a solid combustible. Reducing the pressure reduces the flame spread rate and increases the LOC. At the same time, reducing the external radiant flux also reduces the flame spread rate and increases the LOC. It appears that an increased external radiant flux influences flame spread more strongly, and it counteracts the deterring effect of reducing the ambient pressure. The LOC in microgravity is far lower compared to normal gravity, emphasizing the gravity of this research.

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1 Introduction

1.1 Motivation and Scope

Humans have had an innate curiosity about what lies beyond planet Earth for as long as we have existed, and beginning with the 1950's when developments to send the first human to space first began, engineering interests in developing spacecraft have accelerated. Nowadays, with the creation of competing commercial aerospace companies and reusable rockets, launches are becoming increasingly more frequent. Particularly within the years of 2008-2017, there were on average 82 launches per year, whereas after that the average number of space launches increased to over 133 [1]. There are almost 300 launches planned for the year 2025 [2].

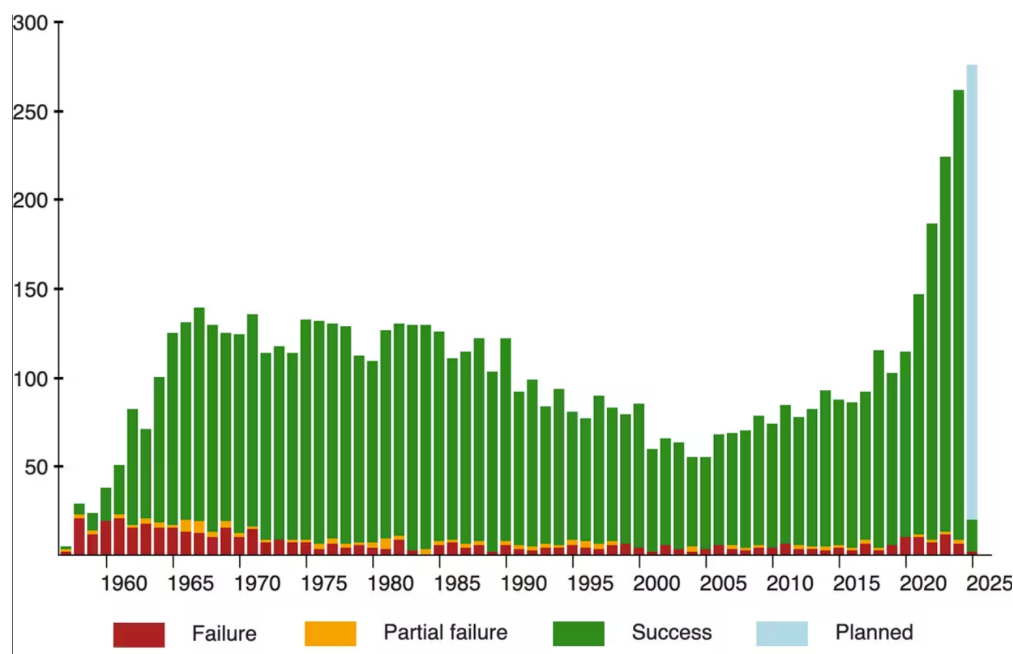


Figure 1: Bar chart showing number of launches per year starting from the 1950's. [3]

The largest share is made up by telecommunications satellites launched by private companies. This is because up to 95% of the revenue from the aerospace sector was from low-orbit satellites that support our communication and internet infrastructure [4]. In recent years, launching a satellite has become significantly cheaper and easier to do, thanks to the commodification of microelectronics. These smaller electronics enable the production of physically smaller and lighter satellites, meaning that even teams working with a small budget are now able to launch [5].

Additionally, there still is significant government investment into building space habitats on surfaces like the moon and Mars, as well as developing vehicles for more distant space exploration. NASA has set forth a Lunar Surface Innovation Initiative [6], which plans to grow the lunar economy [7]. These investments are motivated in large by academia's interest in challenging the frontier of human habitats. In theory, launching spacecraft from the moon will be simpler and cheaper compared to the earth, as the moon has a lower force of gravity, so further space exploration would only become easier [8]; and having a permanent station within which low-gravity experiments can be conducted would be a significant advantage for science. Furthermore, resources found on the moon can be mined for use by humans [9], and private companies have already started developing lunar excavation procedures.

It is important to highlight the increasing relevance of space tourism. The first space tourist was Dennis A. Tito, who arranged for an 8-day trip to low Earth orbit (LEO) through the Russian commercial spaceflight company MirCorp [10]. Since then, opportunities for private space travel have increased significantly, allowing people to buy tickets to space. It is projected that the space tourism industry will continue to grow by 18-26% per year until 2030 [11].

Given that spacecraft launches are becoming more commonplace, and now we are even seeing the rise of private citizens visiting space for tourism purposes, it is natural to worry about the dangers that may arise from the harsh environments found in space. The information presented in this report serves as an exploration of flammability in microgravity, and is motivated by a concern for the fire risks that may arise in the small, confined environments of spacecraft, where escape is unlikely.

1.2 Background

1.2.1 Past Incidents Related to Fire in Space

A fire is an inevitable outcome when heat sources, oxygen, and fuel combine. In a spacecraft, available space is limited and flammable components such as electronic equipment, instrumentation, and incidentals required for daily life (such as food and clothes) are all located in close proximity to each other. Additionally, due to the lack of gravity in space, there is no natural convection, so electrical equipment cannot cool down as easily and are prone to overheating. Combining this with the potentially elevated oxygen concentrations found in some manned spacecraft, which are designed to ease extra-vehicular activities, the risk of a fire igniting and spreading is significant [12]. Below are discussed some well-known fire accidents that have shaped the way spacecraft are designed and tested to this day.

In January 27, 1967, the Apollo 1 mission was preparing for a launch rehearsal test on the pad. The cabin was filled with pure oxygen, and the pressure was purposefully maintained at 110.3 kPa, which is above 1 atm, for the take-off process in order to avoid outside gases leaking in. The pressure was planned to be reduced to 34.5 kPa once in orbit, because the engineers were aware of the fire risk at elevated pressures due to the pure oxygen environment. Unfortunately, these conditions of high oxygen and pressure created extremely favorable conditions for fire, and just 30 seconds after an unidentified ignition event, the atmosphere within the command module was lethal [13]. This unfortunately killed all three astronauts aboard the craft.

At the time of the accident, there was no fire detection system in the vehicle because it was assumed that the astronauts would put out any fire in its developing stages using their drinking water. Additionally, the issue of increased fire hazard on the launch pad due to the overpressure was completely overlooked by the engineers [14]. This high pressure also served to trap the astronauts inside the vehicle because the hatch door opened inwards [12]. As a result of the tragedy, over 100 experiments using full-scale mock-ups of the craft were conducted to investigate the atmospheric conditions that lead to fire growth. This event kickstarted our understanding of fire safety during space exploration missions.

The first known fire incident in microgravity occurred in 1970, two days into the Apollo 13 mission. The spacecraft operated with conditions similar to those planned for Apollo 1: 34.5 kPa pressure, and pure oxygen. The accident was caused by a wire in the oxygen tank which short circuited, providing enough energy to ignite the Teflon wire insulation, and causing the pressure to rise until the tank exploded. Thankfully there were no casualties, as the crew managed to escape into the Lunar Module and perform a rescue operation [12].

Investigations following the accident discovered that NASA had not considered the fuel and heat sources coexisting within the supercritical oxygen tank as a major hazard. This event lead to changes in pre-flight testing and design for future spacecraft, such as reducing the presence of combustible fuels in areas that have potential ignition sources [15]. The report of the Apollo 13 mission concludes with an acknowledgment of the little understanding about fire behavior in the absence of buoyancy.

In June of the year after the Apollo 13 accident, a fire broke out in the Soviet Salyut-I Space Station due to an overheated fan motor [12]. Possibly what saved the cosmonauts was the ambient conditions (21% oxygen concentration, atmospheric pressure) being unfavorable to rapid flame spread, as the source of the smoke was behind a wall panel and was thus inaccessible. The cosmonauts were able to turn off all equipment in due time, which put out the fire, as verified by the on-board fire detection system relying on a CO_2 gas analyzer.

Smoke events have occurred a few times since 1970 (two more cases in the Salyut-VI, and five incidents in the NASA Orbiter fleet). In all these cases, the smoke was caused by overheating electronics and electrical equipment, generally due to a short circuit. In all cases, the equipment was turned off and the issue was resolved without harming the crew.

Two further incidents occurred on the Mir space station, which was operated at atmospheric conditions similar to those found on Earth: a gas mixture of 21% oxygen and 79% nitrogen, and 101.3 kPa pressure. In both cases, the fire ignited due to a malfunctioned oxygen canister [12]. The first incident occurred in 1994, when cosmonaut Valeri Polyakov noticed that the cloth covering the canister was on fire. He turned off all power to the unit, and suppressed the flame by covering it with a jumpsuit. The next time the oxygen canister malfunctioned and ignited was in 1997. This time, the fire rapidly grew to flames over one meter long and smoke filled the cabin, hindering the visibility of the crew [16]. Initial attempts to spray the base of the flame were unsuccessful due to the inertia of the flame jet, but eventually the crew managed to minimize the area of the fire until all the solid fuel was consumed and the fire naturally extinguished. This event was eyeopening due to the sheer lack of preparation for a real emergency: (1) the alarm system was used both for emergencies and for regular operations such as waking up, so the crew did not instantly realize the emergency on board, (2) the fire extinguishers were bolted into place and the astronauts and cosmonauts had to dedicate valuable time to unscrewing them before they could use them, (3) it was found that many oxygen masks onboard were faulty.

The frequency of fires occurring in spacecraft, and the potential for severe harm caused by them, highlights the need to study the effects of microgravity on flame spread, and implement pre-flight flammability safety testing for all materials aboard.

1.2.2 Flammability Tests

Material flammability tests are used ubiquitously in everyday life. Flammability is defined based on how easily a material can ignite and burn, with tests generally focusing on ignitability. Most materials that go into building enclosures people spend time within, such as buildings, cars, trains, etc., have been thoroughly tested to ensure their fire behavior is deemed safe [17]. Regulations have been developed in order to quantify a material’s ease of ignition, flame spread, heat release rate, toxicity of combustion byproducts, and more [18]. In this way, the focus is not only on fire prevention, but also on suppression and human health outcomes.

In the field of manned space travel, material flammability testing is extremely limited due to the complexity and cost of conducting a large-scale combustion experiment in microgravity [17]. However, the first step to reducing fire risk in space is to ensure every material that is used in a habitable spacecraft passes a flammability test. The first formalized test used by NASA was fire safety standard STD-6001B, which was initially drafted in 2008 and to this day remains the primary means of testing materials for their fitness in space [19]. For this test, the material that is to be brought aboard a spacecraft is cut to a size of 30 cm by 5 cm placed vertically and exposed to the same conditions expected to be found in the spacecraft. The material is ignited from the bottom and is allowed to burn while its propagation and dripping is monitored [20]. This is a pass/fail test, and if a material passes, then it can be brought aboard. There are two conditions for passing the test: (1) that the flame does not propagate more than 15 cm along the length of any of the tested samples, and (b) that the fuel does not drip onto a piece of paper that is placed 20 cm below the sample, thereby igniting a spot fire. One limitation of the STD-6001B test is that because this is a binary test, it does not give any information as to the flammability limits of the fuel in question. For each new pressure or oxygen concentration the fuel is expected to experience, additional tests must be conducted [21, 22].

Some limitations of the above test can be avoided by using the LOI (Limiting Oxygen Index) test, which follows ASTM standard 2863 [23]. This testing method utilizes a mixture of oxygen and nitrogen gases to measure the minimum oxygen volume fraction that will support self-sustained flame spread. A plastic fuel is placed vertically in the test column and allowed to burn in opposed flow while the oxygen concentration is slowly reduced, until the flame spread slows down enough to no longer be considered sustained. The test defines self sustaining flame spread as a flame that spreads for at least 50 mm or longer than 180 s at any given ambient condition. Although the LOI test can reveal information about material extinction limits, it was originally developed specifically for plastic fuels and has not been widely adopted by the aerospace industry because opposed flame spread may not be conservative enough for materials intended to be used in microgravity [20].

Konno et al. expressed concern that the LOC of a material varies depending on the flow velocity incident on it, with flammability being suppressed at both very low and very high velocity flows [24, 25]. Therefore, they proposed that instead of using the LOI test, which reveals the LOC of a material under its given conditions, it would be more appropriate to find the minimum limiting oxygen concentration (MLOC), which corresponds to the harshest flow conditions, therefore giving the smallest possible LOC for each fuel. A test for the MLOC was subsequently developed, called ISO 4589-4. Originally this test had only been used for thermally thin sheet fuels, but it is now being expanded to electrical wires, and the authors hope to validate the procedure against a larger variety of samples in the future.

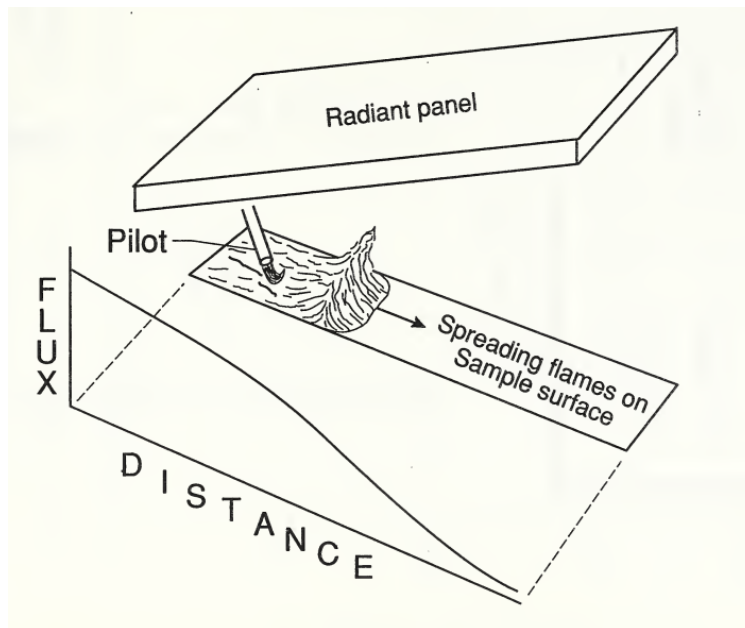


Figure 2: Schematic of LIFT test setup. Figure courtesy of [26].

Another limitation of the STD-6001B and LOI, and MLOC tests is that they do not consider the extra risk imposed by an additional energy source. The LIFT (Lateral Ignition and Flame Spread Test) test, also known as ASTM E-1321 [27], considers the effects of an external radiant heat flux on flame spread. The configuration of this standard involves a linear radiant heater that is placed at an angle over the horizontally aligned fuel, such that the heat flux incident on the sample decreases along the fuel’s length; see Fig. 2. Through this test, it is possible to find the effect of the added heat flux on flame spread properties of materials. Testing materials with an added heat flux is important, as fires rarely exist in isolation, and are often made up of a complex of overheated fuels.

A significant limitation of using any of these tests as pre-spaceflight flammability verifications is that they are conducted at earth gravity, and the fuel is presumed to behave similarly in microgravity, which is often not the case. In fact, flammability risk in microgravity can be heightened compared to normal gravity, as discussed further in this work.

1.2.3 Effect of Pressure

A sub-atmospheric ambient pressure affects the flame by reducing the gas density in accordance with the ideal gas equation $PV = \rho RT$, where P is the ambient pressure, V is volume, ρ is the density R is the universal gas constant, and T is the temperature. As the density decreases, the velocity and thermal boundary layers of the flame widen, causing the flame to expand further away from the fuel surface, i.e. a greater standoff distance. This phenomenon can be observed in Fig. 3 below. Visually comparing the flame at 40 kPa with that at 100 kPa, it can be seen that the base of the low-pressure flame is wider and pulled further away from the sample, and tending towards a spherical shape, whereas the high-pressure flame is longer and features a smaller standoff distance.

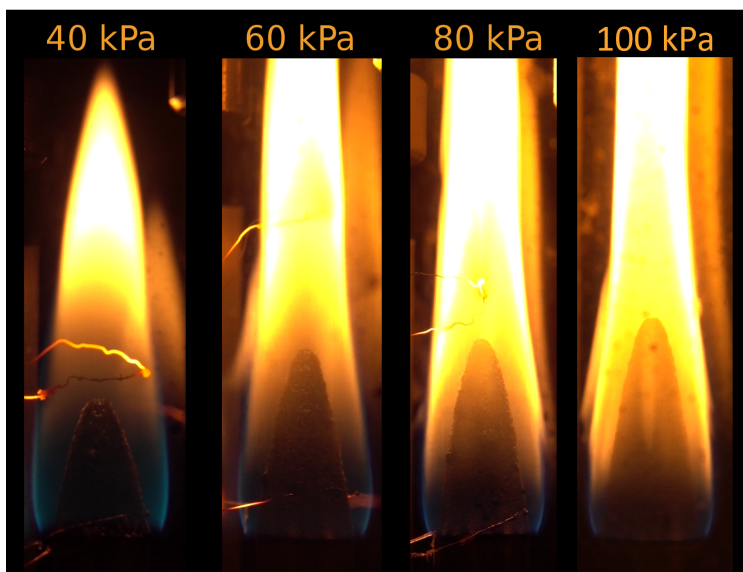


Figure 3: Collage of PMMA burning under four different pressures: 40 kPa, 60 kPa, 80 kPa, 100 kPa. The samples shown are 12.7 mm in diameter and the oxygen concentration is 21%.

Increasing the flame standoff distance directly affects flame spread rates through the rate of heat transfer. As the thermal boundary layer increases, the rate of convective heat transfer in the pyrolysis region decreases. Therefore, it takes a longer time for the flame to heat up the solid to its pyrolyzation temperature and continue the flame propagation process.

Several researchers have studied the relationship between flame spread and pressure in opposed flame spread configurations. Zhu et al. [28] studied opposed flow flame spread over thick PMMA slabs. They concluded that, under a constant oxygen concentration and flow velocity, the flame spread rate increases as the pressure is increased. Thomsen has devoted much of her career to studying the effects of sub-atmospheric pressure on flame spread [29, 30, 31]. In 2021, Thomsen et al. correlated the fuel regression rate, and thus burning rate

of PMMA cylinders, to pressure, and found a positive relationship between the two [30].

[32] studied the effect of sub-atmospheric pressure on the flame spread rate under concurrent flow. The researchers tracked the flame tip, pyrolysis front, and the burnout front of thermally thin PMMA sheets and found that the spread rate of all three decreased as the ambient pressure decreased. Furthermore, Thomsen et al. suggested that reducing the ambient pressure can successfully simulate low gravity concurrent-flow flame spread [31]. They used a thin composite fabric (75% cotton, 25% fiberglass) burned in two gravity conditions: at earth gravity in a sub-atmospheric pressure chamber, and in microgravity at a constant pressure of 100 kPa. Comparing the data from the two environments, it was found that the flame spread rate at 30 kPa on earth was similar to that in microgravity. Similar experiments using thick PMMA slabs further validated the theory that low pressure is a good predictor of microgravity flame spread [29].

In experiments conducted by Thomsen et al. using vertical PMMA cylinders with 100 mm/s opposed flow, the flame velocity was measured at different ambient pressures [30]. In these experiments, the oxygen concentration was varied between 19% and 23%. Figure 4 shows the results of these experiments. The maximum flame spread rate for each condition clearly follows a pattern of increasing ambient pressure corresponding to a faster flame spread, regardless of the oxygen concentration.

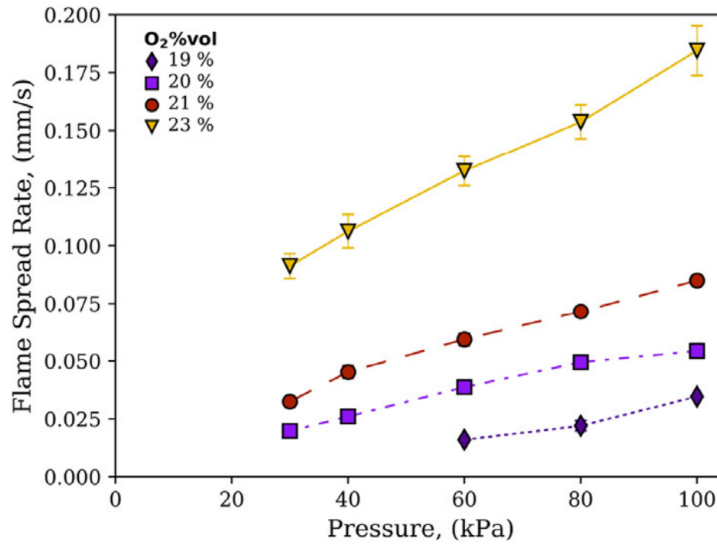


Figure 4: Effect of pressure on flame spread rate of opposed-flow flame on vertical PMMA cylinders under different oxygen concentrations. Figure courtesy of [30].

1.2.4 Effect of External Heat Flux

The presence of an external heat source, whether it be overheated electrical wiring or a nearby fire, can preheat a fuel prior to ignition or serve as an aid to promote faster fire spread. It is particularly important to understand the effect of external heat flux on flame spread in small or confined environments, such as spacecraft, because any fire can quickly become catastrophic. Because the ISS serves as a research laboratory, there are numerous electronic devices present beyond the necessary equipment for the vessel's operation, making it especially vulnerable to fire risk.

Based on prior research [33, 34, 35] and material testing [27, 36], the influence of an externally applied radiant heat flux on fire spread is primarily thermal in character at low heat fluxes, preheating the solid fuel prior to flame arrival. Flame propagation can be described as a series of ignition processes: through convection and radiation from the flame onto a section of the unburned fuel, the fuel heats up to its pyrolysis temperature, at which point that section will ignite and transfer heat onto another section of the fuel. The introduction of an external radiant flux serves to preheat a much larger section of the solid. As the solid fuel is heated, its surface temperature approaches its pyrolysis temperature, which reduces the ignition time of the material and enhances its gasification process. This decreased heating time therefore lends to an increase in the flame spread rate.

Fig. 5 displays the effect of heat flux on flame spread rate. In this work by Thomsen et al. the flame spread rate is plotted over the flame position with different incident radiant heat fluxes for experiments conducted using black cast PMMA cylinders of diameter 12.7 mm [37]. The profile of the incident heat flux varied along the length of the sample similar to the LIFT test, and in these experiments the maximum incident heat flux was roughly 45 mm below the top of the sample and it decreased with distance from that point.

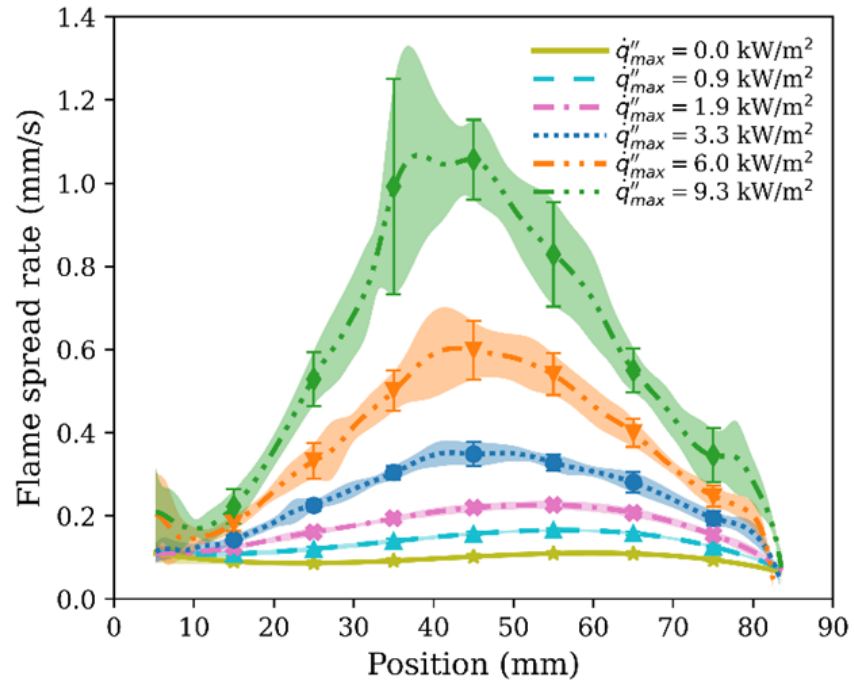


Figure 5: Effect of heat flux on flame spread rate over 12.7 mm PMMA cylinders at 100 kPa. Figure courtesy of [37].

1.2.5 Effect of Oxygen Concentration

It is widely accepted that when all other parameters remain the same, increasing the oxygen concentration causes the flame to propagate faster and consume more fuel [38, 39, 40, 41, 42]. Many scientific fields use concentration, leading to the term having a non-uniform definition. It can be defined through the mass, m_i/V , and moles, N_i/V , or the volume of a substance within a mixture, V_i/V . In this work, oxygen concentration refers to the volume fraction of oxygen, V_O/V , and is expressed as a percentage. This quantity is equivalent to the mole fraction of oxygen, N_O/N , and the partial pressure fraction, P_O/P .

It has been found that the oxygen concentration is proportional to the flame temperature, meaning that an increase in oxygen will cause the flame temperature to increase as well [38]. Naturally, a greater flame temperature leads to a more rapid rate of heat transfer from the flame to the solid fuel. Consequently, through the faster pyrolyzing and igniting of the unburned solid, the flame spread rate increases. Additionally, a greater oxygen concentration affects the chemical reaction rate through Equation 1, where for a single-step reaction $a = b = 1$:

$$q_r = A_0 \exp\left(-\frac{E_a}{R_u T}\right) [Fuel]^a [O_2]^b \quad (1)$$

Understanding the effect of oxygen concentration is particularly important for microgravity combustion, where the fire can only take place in enclosed environments of a given oxygen concentration, such as spacecraft or space habitats. Humans are able to survive in a wide range of pressures, as long as their surroundings are under normoxic conditions, which are conditions that balance the oxygen with the ambient pressure such that the partial pressure of oxygen equals 21 kPa. Therefore, all habitable spacecraft must be operated according to the normoxic curve shown in Fig. 6.

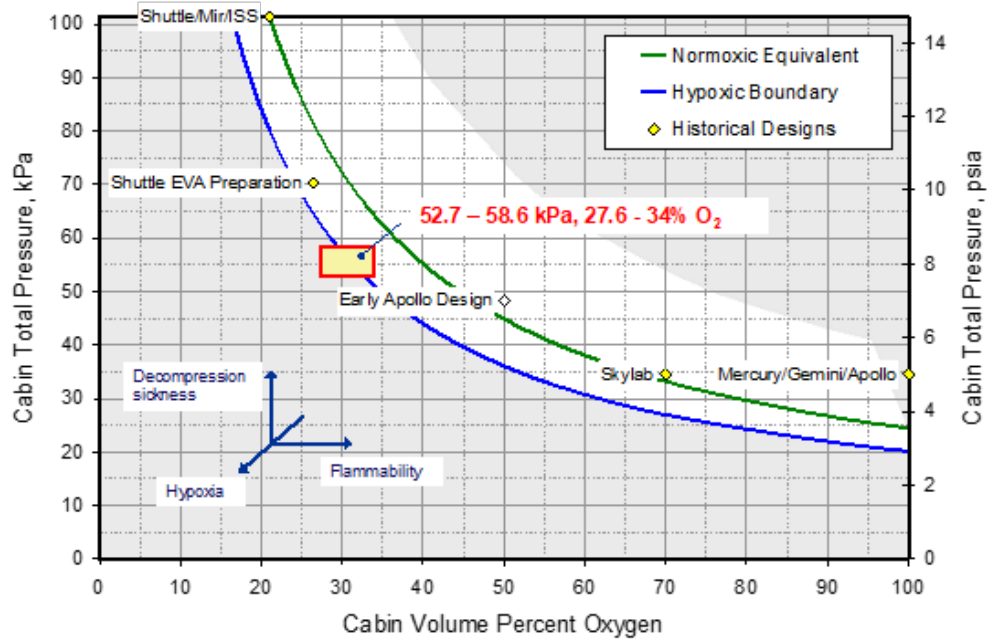


Figure 6: Normoxic curve, showing the balance of oxygen concentration with ambient pressure such that the partial pressure of oxygen will remain at 21 kPa [43].

As seen from the schematic on the bottom left part of Fig. 6, spacecraft designers have to balance the risks of flammability, decompression sickness, and hypoxia when planning the ambient conditions of the vessel. On first thought, it would be ideal to operate at very low pressures, because that decreases the stress put on the exterior walls. Another benefit of operating vessels at low pressures is that it decreases the amount of preparation time needed before an astronaut undertakes Extra-Vehicular Activities (EVA) such as a space walk. To allow for dexterity, space suits are maintained at low pressures and consequently very high oxygen concentrations. To transition into a spacesuit, an astronaut must slowly rid their body of nitrogen and increase the amount of oxygen in the bloodstream - a process that can take hours in order to avoid decompression sickness. It is therefore appealing to aerospace engineers to design low-pressure, high-oxygen spacecraft.

However, such a decision can affect the flammability risk significantly, as seen from the accidents that occurred during the early Apollo missions.

1.2.6 Effect of Gravity

The primary environmental difference in microgravity is the absence of buoyancy. Buoyancy, which opposes gravity, is the upward force acting on an object that is immersed in a fluid, and its magnitude is related to the object's density relative to the density of the fluid. [44]. It is due to buoyancy that, within a fluid, heavier objects will sink lower than lighter ones. On Earth, buoyancy creates convective currents that affect every aspect of our lives: from weather patterns, to cooking dinner, to the physics that dictate flame spread behavior.

The effect of the microgravity environment on flame behavior can be seen visually via the shape of a candle flame. Figure 7 is a collage of two diffusion flames, one in Earth-gravity and one in microgravity. The spherical shape that characterizes a microgravity flame is a consequence of the lack of buoyancy. Additionally, in microgravity the flame standoff distance is significantly larger than that seen in normal gravity, which is a similar behavior to that observed at sub-atmospheric pressures. Furthermore, the microgravity flame is a light blue color, indicative of a complete combustion that does not leave behind unburned sooty particles. Gas mixing is very minimal, which allows the candle flame to burn slowly and combust all of the available fuel. However, the reduced gas mixing may also affect the presence of oxygen within the pyrolysis zone. Therefore, buoyancy leads to opposing effects on a flame: On the one hand there could be fewer oxygen molecules available to pyrolyze, while on the other hand the flame burns slowly and maintains a hot temperature, leading to a complete combustion.

Of key concern is the ease of overheating in microgravity due to the lack of buoyant cooling. Electrical equipment are often designed to take advantage of natural convection through the use of extended surfaces such as fins in order to avoid overheating. In microgravity, forced convection exists in vehicles that feature an HVAC system, such as the ISS's Environmental Control and Life Support System which circulates a gentle flow of 10 cm/s within the cabins. Therefore, it is vital that the design of spacecraft, and especially those intended for human habitation, include fans for forced convective cooling of equipment likely to overheat. Additionally, as was discovered in the aftermath of the Apollo 13 mission, combustible fuel should be placed away from ignition sources wherever possible [15].

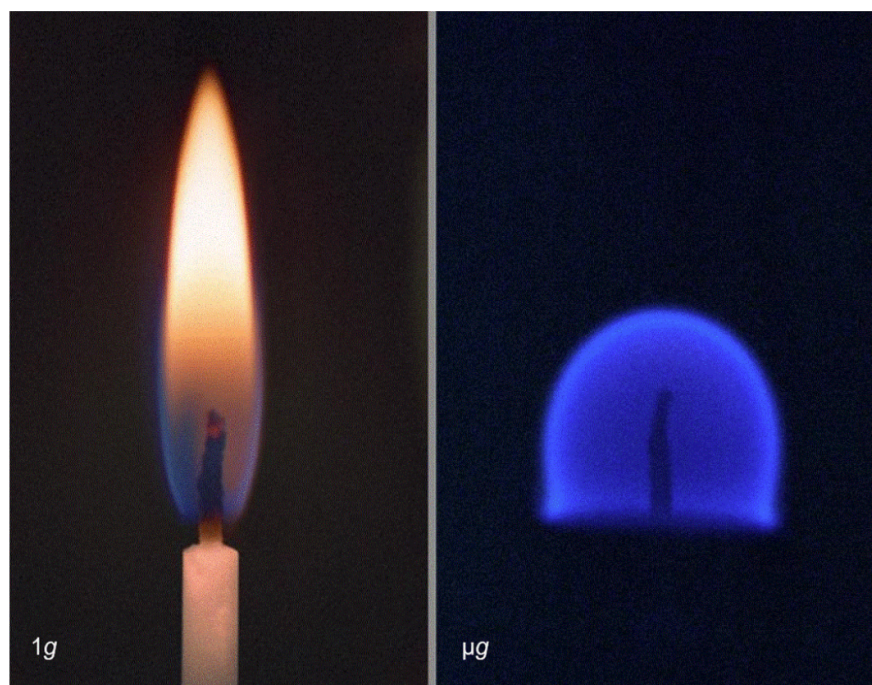


Figure 7: Candle flame in Earth-gravity and in microgravity [45].

1.2.7 Opposed Flow Flame Spread Theory

Opposed flow or counter-current flame spread is characterized by a forced flow with a velocity that is against the direction of flame spread. This configuration is used extensively in lab-scale combustion experiments because it is both a canonical configuration in fire safety and because it can be representative of limiting conditions of flammability [46].

One of the first researchers to study opposed flow flame spread is de Ris [47]. He studied a laminar diffusion flame in counter-current flow using either a solid or liquid fuel, arranged as a thin sheet or as a semi-infinite fuel bed. Through theoretical analysis of heat transfer, he created two flame spread formulas, one for thin-sheet fuel beds, and one for semi-infinite fuel beds. Thermally thin materials are defined as those thin enough where the temperature across the width of the object can be assumed to be uniform. Specifically, a body is thermally thin if it has a Biot number, Bi , of less than 0.1, where $Bi = hL_c/k$ with h being the coefficient of convection, L_c is the characteristic length, and k is the thermal conductivity.

For thermally thin fuel beds, the heat transfer rate needed to heat the fuel bed to its vaporization or pyrolysis temperature (left side of Eqn. 2) is approximately equal to the rate of conductive heat transfer from the flame to the fuel in the gas phase (right side of Eqn. 2). Using ρ_w , C_{pw} , and τ for the fuel-bed density, specific heat, and thickness, respectively, V for the flame spread velocity, and T_{vap} and T_∞ the vaporization and quiescent temperature, and λ for the thermal conductivity,

$$\rho_w C_{pw} \tau V (T_{vap} - T_\infty) \approx \sqrt{2} \lambda (T_f - T_{vap}). \quad (2)$$

As for the semi-infinite solid, the guiding equation for flame spread is

$$\rho_w C_{pw} \lambda_{wy} V / \rho C_p \lambda V_a = \left(\frac{T_f - T_{vap}}{T_{vap} - T_\infty} + \frac{2R_1 F (2\lambda / \rho C_p V_a l_1)}{\rho C_p V_a (T_{vap} - T_\infty)} + \frac{2R_2}{\pi \rho C_p V_a (T_{vap} - T_\infty)} \right)^2 \quad (3)$$

where V_a is the forced flow velocity, R_1 and R_2 are the radiative heat transferred onto the fuel bed, upstream and downstream, respectively. l_1 is the characteristic length of forward radiation, and F is defined as

$$F(z) = [0.5\pi - \sin^{-1}(z - 1) / \pi(2z - z^2)^{1/2}] \quad \text{for } [0 < z \leq 2] \quad (4)$$

$$= [0.5\pi(z^2 - 2z)^{1/2}] \cdot \ln \left[\frac{z - 1 + (z^2 - 2z)^{1/2}}{z - 1 - (z^2 - 2z)^{1/2}} \right] \quad \text{for } [2 \leq z] \quad (5)$$

The velocity is in the left term of Eqn. 3. The first term on the right side represents the conductive heat transfer, while the second and third terms are for the forward and downstream

radiation, respectively. Therefore, it can be seen that there is a correlation between V and V_a ; deRis concluded that increasing the flow velocity leads to an increase in flame spread rate.

In 1977, Williams added onto deRis's work with his paper titled "Mechanisms of Fire Spread" [48]. He studied the propagation of smoldering and flaming combustion over solid and liquid fuels. Williams extended this work through his collaboration with Fernandez-Pello, suggesting that the finite-rate gas phase kinetics are linked with the opposed flow velocity through the Damkohler number. The present work draws from these investigations to explore low pressure and low gravity flame spread and extinction behavior under an opposed flow, and connect them through the Damkohler number.

1.3 Outline of the Dissertation

The work presented in this dissertation, supported by NASA, consists of a comprehensive experimental study into the flammability of solid acrylic fuels in microgravity conditions. The goal of this project is to enhance our understanding of low pressure combustion in the absence of buoyancy, to reduce the risk of a fire catastrophe occurring during a space mission. One of the primary questions investigated in this dissertation is the validity of using Earth-based flammability tests for materials that are intended to be used aboard spacecraft.

The dissertation is organized into six chapters, with this introduction being the first one. The introduction offers some background on existing material flammability tests, and on the effect of key variables such as ambient pressure, external radiant heat flux, oxygen volume fraction, and buoyancy, on flame spread. The chapter concludes with a summary of the theoretical models that guide flame spread under opposed flows.

Chapter 2 explores the effect of a sub-atmospheric ambient pressure and an external radiant heat flux on the extinction limits of PMMA rods. All the experiments were conducted on Earth, so this work is not isolated from the effect of buoyancy. An analysis of the limiting oxygen concentration data is conducted, and a correlation is offered to estimate the limiting oxygen concentration based on the environmental pressure and external heat flux incident on the sample. A phenomenological discussion follows, connecting the experimental results with existing theories in the literature.

Chapter 3 extends the previous topic to include microgravity combustion. For this investigation, experiments were conducted on the International Space Station (ISS) with the help of our colleagues at NASA Glenn Research Center (GRC) and the astronauts at the ISS National Lab, as well as in the Fire Research Lab at UC Berkeley. No external radiant flux was used here, and the combustion chamber was sealed, with all inlets and outlets closed, so the oxygen concentration was decreasing naturally as the fuel gasified and combusted. It is found that the ambient pressure has a similar effect on flammability in the two gravity levels. The limiting oxygen concentration between normal and microgravity is compared, and the risk of flammability fires occurring even at low oxygen volume fractions is highlighted.

Chapter 4 delves into the differences between flame spread rate between normal and microgravity, using the same data as in Chapter 3. It is found that the maximum flame spread rate in microgravity is approximately the same as in normal gravity. However, the flame can be sustained to much lower oxygen concentrations and continue to propagate along the sample for twice as long in microgravity as it can on Earth. A theoretical analysis of flame velocity equations is given and compared with the experimental data to conclude that microgravity flames differ from those on Earth both in their propagation behavior but also in their mode

of extinction.

Chapter 5 examines flame spread over clear PMMA sheets under normoxic conditions. In these environments characterized by low pressure and elevated oxygen volume fractions, the flame is preferentially sensitive to the increased oxygen concentration despite the counteracting effects of a sub-atmospheric pressure. The flame tip, pyrolysis front, and burnout front are compared, and a numerical relationship between flame velocity and ambient pressure is provided. Lastly, using experimental results from other researchers, the heat release rate of PMMA sheets is compared to that of cotton sheets, finding that PMMA released approximately 50% more heat compared to the cotton samples, with the most heat being released in the low pressure and high oxygen environments.

Chapter 6 serves as the conclusion of this work, with a brief summary of the key results from the previous chapters and a discussion on research gaps that still need to be addressed.

2 The Limiting Oxygen Volume Fraction For Opposed Flame Spread Extinction

2.1 Introduction

Fire safety in spacecraft environments is an important concern [49, 17], particularly because of the criticality of such an event inside spacecraft. Inside a spacecraft cabin, or a space facility, there are combustible materials and conditions that can ignite them, thus posing the risk of initiating a fire. Also, the enclosed nature of space facilities, where egress is difficult or impossible, means that the consequences of a fire could be catastrophic for the crew's safety. The fire risk will increase as the time spent in space is increased with the operation of proposed long space missions and the establishment of facilities on the Moon and Mars. A further challenge is that the environmental conditions encountered inside the cabin of a spacecraft are very different from those encountered on Earth, including microgravity or reduced gravity, low velocity flows, and potentially low pressure and elevated oxygen concentration [50]. These atmospheric conditions are referred to as Space Exploration Atmospheres (SEA) and are designed to reduce the preparation time required before Extra Vehicular Activities (EVA) [43]. Although few fire accidents have occurred in spacecraft, and most were extinguished quickly [12], the unique conditions in a spacecraft require that all materials are held to strict flammability standards. Consequently, understanding solid material flammability in the cabin environments expected inside space facilities is necessary to better characterize their fire risk.

The flammability of a solid combustible material is often determined from its ease for ignition, flame spread, heat release, extinction, and toxicity. Extinction of a spreading flame is an important fire safety issue since it reduces the spread of the fire. It is used to rank the fire hazard of materials using the Limiting Oxygen Index (LOI) apparatus (ASTM 2863) [23] that determines the limiting volume fraction of oxygen for fuel burning. It has also been studied in more fundamental works, particularly to determine the effect of ambient pressure, and velocity of a gas flow on the extinction of the flame. McAllister et al. [51] tested the ignition of PMMA at air and along the normoxic curve at various pressures and observed that the ignition time decreased as the pressure was reduced until it reached a minimum, after which it increased until ignition no longer occurred. This minimum was between 40 kPa and 27.6 kPa depending on the conditions because that region is where the gas-phase chemical kinetics regimes becomes significant. Thomsen et al. [52] tested Nomex and a blend of cotton, nylon, and Nomex at pressures 40-100 kPa and external radiant heat fluxes of 0-5 kW/m² and presented results similar to Osorio [53], who tested flame resistant materials and found a volume fraction of oxygen above which a flame can spread without the addition of an external radiant flux. Below this oxygen volume fraction, the flame can spread if the added heat flux is sufficient.

In this regard, it should be pointed out that there is some ambiguity with the definition of the limit for flame extinction during burning of a solid fuel. This limit is often referred to as the Limiting Oxygen Concentration or LOC. The oxygen concentration, by definition, is the ratio of the number of moles of oxygen to the total volume (mol/V). However, the LOC as it is referred to in the literature is the volume fraction of oxygen, not the oxygen concentration. Here, to reduce confusion with the terminology of the LOC we will define it as equal to the oxygen volume fraction, and consequently also equal to the molar fraction of oxygen and the partial pressure fraction, i.e., $LOC = \frac{V_o}{V} = \frac{N_o}{N} = \frac{P_o}{P}$. Furthermore, there are two LOC's that can be identified for thick solids: the limit for flame spread and the limit for mass burning [54].

In this work, we are specifically interested in determining the effect of sub-atmospheric pressure and external radiant heating on the extinction limits for flame spread rate over PMMA rods based on the oxygen volume fraction for no flame spread. PMMA is often selected in fundamental flammability studies because is a good “laboratory” solid fuel, with well characterized properties, an abundant data base and is being considered for spacecraft viewing ports. Sub-atmospheric pressures are present in various environments such as spacecraft with SEA atmospheres, commercial aircraft, and high-altitude earth locations. External radiant heating is used to simulate the effect of heating from a nearby fire or overheated equipment. This aspect of material flammability is tested in the LIFT apparatus ASTM E-1321 [27] to rank the flammability of materials according to their ignition and flame spread characteristics. The determination of the extinction requirements is obtained in the LOI apparatus [23]. In this work, we study the LOC for downward opposed flame spread over PMMA rods exposed to an external radiant flux. Thus, the experimental apparatus combines the LOI and Forced Ignition and Spread Test (FIST) tests into one to determine the limiting volume fraction of oxygen of vertical PMMA rods. The PMMA samples are exposed to a mixed (forced and buoyant) low velocity opposed flow and an incident decreasing radiant flux, in sub-atmospheric pressures. In addition to providing information about the flammability of materials in Earth atmospheres, the results of this work also provide data for comparison with experiments to be conducted in the International Space Station (ISS) under the SoFIE-MIST project [55]. The comparison between LOC data in normal and microgravity would provide further understanding of the LOC of materials in SEA, and in turn information about the fire safety in future spacecraft and space facilities.

2.2 Methodology

A laboratory scale combustion tunnel of dimensions 125 mm x 125 mm x 600 mm is placed inside a 105 L pressure chamber that allows for control of ambient conditions at which the

sample is tested and has a flow system that provides a constant supply of fresh gasses and exhausts effluents via critical nozzles (O’Keefe Controls) and a high-capacity vacuum pump (Welch DuoSeal 1376), respectively. The system pressure is continuously monitored with an electronic pressure transducer (Omega Engineering, Inc. PX309-015A5V). This experimental setup has been previously used to study material flammability of combustible solids and further details can be found in Ref. [31].

The forced flow velocity is fixed to 10 cm/s in all the tests, a value which is similar to that induced by the Environmental Control and Life Support System (ECLSS) of a spacecraft. However, because the experiments are performed in normal gravity conditions, the flame is also exposed to a self induced buoyant flow in addition to the forced flow. Thus, during the experiments the flame is exposed to a mixed (free and forced) flow condition, in contrast to only a forced flow in microgravity.

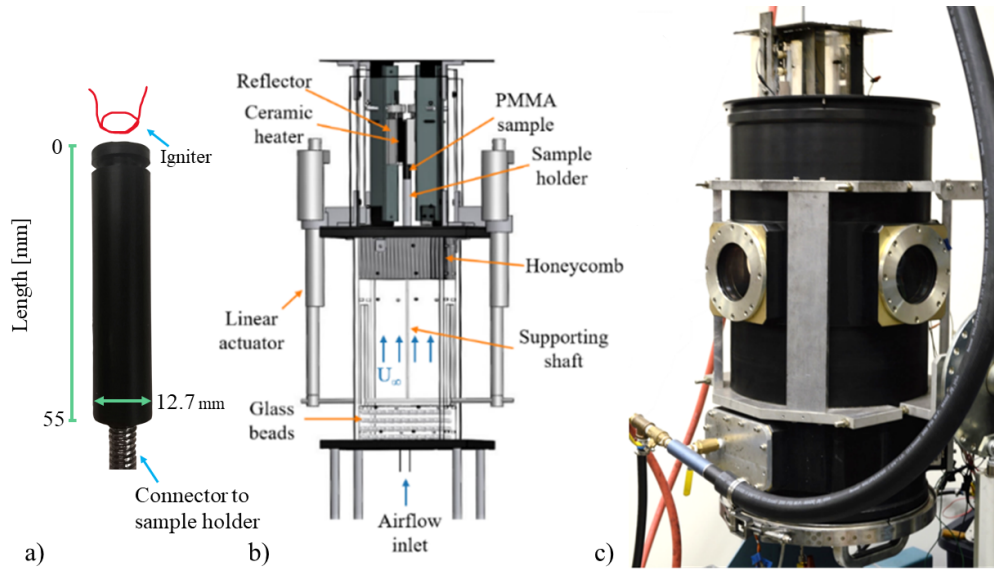


Figure 8: Experimental setup with (a) PMMA sample, (b) test tunnel, (c) pressure chamber.

2.2.1 Procedure

A cylindrical black casted PMMA sample measuring 12.7 mm in diameter and 55 mm in length is placed vertically inside the test section of the flow duct and is connected at the center of the test section using an aluminum sample holder. The black color is selected to maximize the absorbance of thermal radiation at the rod’s surface. A subtracted notch at the top of the sample serves to straighten the flame front right after ignition. The samples

are ignited using a 26-gauge NiCr ignition wire. The wire is shaped into a coil and hovers just above the sample, such that when a current is passed through it, it will heat up and ignite the sample. The current passed through the ignition wire is energized using a variable transformer (STACO Energy model 3PN1210B). The ignition and subsequent flame spread were video recorded through the chamber windows using a Sony RX10-III camera to visualize the front view of the sample.

Four equispaced flat ceramic heaters (Bach Resistor Ceramics GmbH), measuring 14.7 mm x 75 mm, with 50 mm being the heated section, surround the sample and are the source of the external radiant heat flux. Placed 18.5 mm behind each heater is a parabolic reflector made of electropolished stainless steel and measuring 51 mm x 70 mm. Although the heaters provide a radially uniform heat flux to the sample, the heating profile is variable along the length of the heater and follows a half-gaussian curve, resembling that of the LIFT test [27]. The peak incident heat flux is at the center of the heater, which corresponds to 10 mm from the top of the sample. The peak heat flux values tested ranged from 0 to 3.3 kW/m². This range was selected to match experiments expected to occur on the ISS, as well as to maintain safe working conditions inside the pressure chamber. The calibration curve of the heaters, which shows the depleting heat flux along the length of the sample, can be found in Fig. A.1 in A.

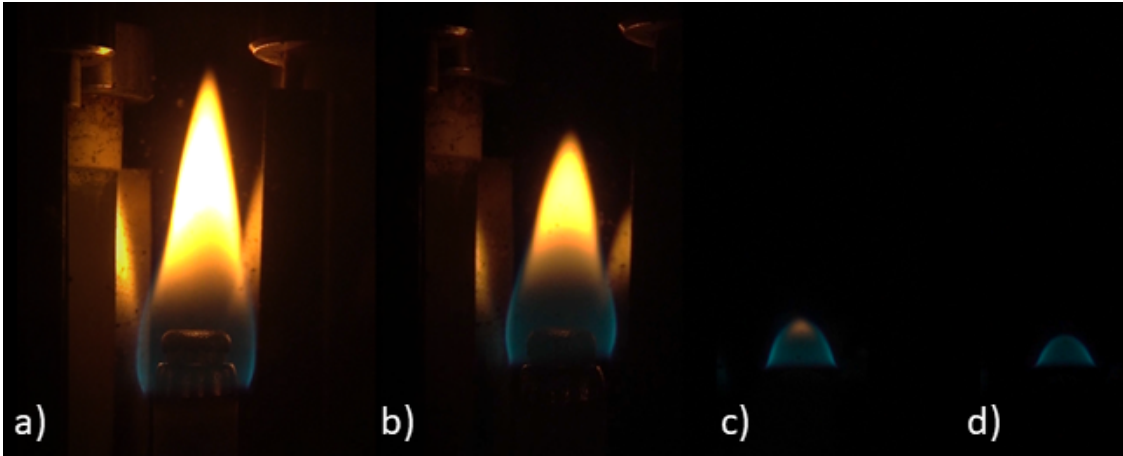


Figure 9: Collage of the process of flame extinction as the oxygen concentration is reduced. Note that the flame is also visible in the heaters' reflector

An experiment begins by starting an inflow of air, 21 vol% oxygen volume fraction, at the desired ambient pressure and switching on the heaters while the sample is raised out of view, until a steady state temperature is reached. Once the sample is ignited, it is subsequently lowered into the view of the heaters using two linear actuators (Firgelli Automations FA-35-S-12-12) that are attached to the sample holder rod. After two minutes, the flame has

stabilized and the oxygen volume fraction is reduced, until extinction of the flame occurs. The ambient pressure is kept constant through each experiment, and only the oxygen volume fraction is changed. Although the oxygen volume fraction is controlled through critical nozzles, an ENERAC 700 portable gas analyzer is used to confirm the oxygen concentration of the gas flowing into the test section. Fig. 9 shows the progression of a flame during an experiment at a given ambient pressure. Frame *a* is taken just after ignition, when the oxygen volume fraction is at 21 vol%. In frame *b*, the oxygen concentration has been reduced, the flame has weakened, and the flame length has decreased. Frames *c* and *d* depict the process of flame extinction. As the oxygen volume fraction is reduced the flame size shrinks considerably, and the temperature of the flame decreases until the flame stops spreading (LOC for flame spread) and becomes a blue semicircle hovering over the flat area at the top of the sample (LOC for fuel burning) [54].

2.3 Results

Experiments were conducted at pressures of 40 kPa to 100 kPa with intervals of 10 kPa and external heat fluxes of 0 kW/m², 0.9 kW/m², 1.9 kW/m² or 3.3 kW/m². The LOC is difficult to identify because as it is approached, any minor perturbation can be enough to extinguish the flame [56, 57]. To reduce the error the oxygen volume fraction was reduced in small intervals and the tests were repeated between three and five times. In Fig. 10, the average of the oxygen volume fraction at which the flame stops spreading or extinguishes (the LOC) is shown as a function of the chamber pressure for each of the different heat flux conditions. The error bars represent the standard deviation of the volume fraction of oxygen from tests conducted. A linear fit is included in the plot to emphasize the observed trends.

It is observed that for all the radiant fluxes, reducing the ambient pressure increased the LOC, although not strongly. This is due to the deterrent effect of reducing the ambient pressure on the flame spread rate [31], and indicates that materials are less flammable as the ambient pressure is reduced. This is in contrast with gas fuel combustion where the flammability limits are independent of pressure. As shown below, this is due to the mole fraction of fuel in the gas phase reaction being dependent on pressure, because the heat flux from flame to solid varies with ambient pressure. Increasing the external radiant flux results in a lower LOC, because the added energy preheats the sample ahead of the flame front, and therefore increases the flame spread rate [58]. It should be pointed out that the results of Fig. 10 would also depend on the thickness of the rods [59], the flow velocity and gravity level [60, 61, 25, 62, 63, 64, 65].

Expressing the LOC in terms of the partial pressure of oxygen is of interest because of its relation to the normoxic oxygen partial pressure for human breathing [50]. In terms of the

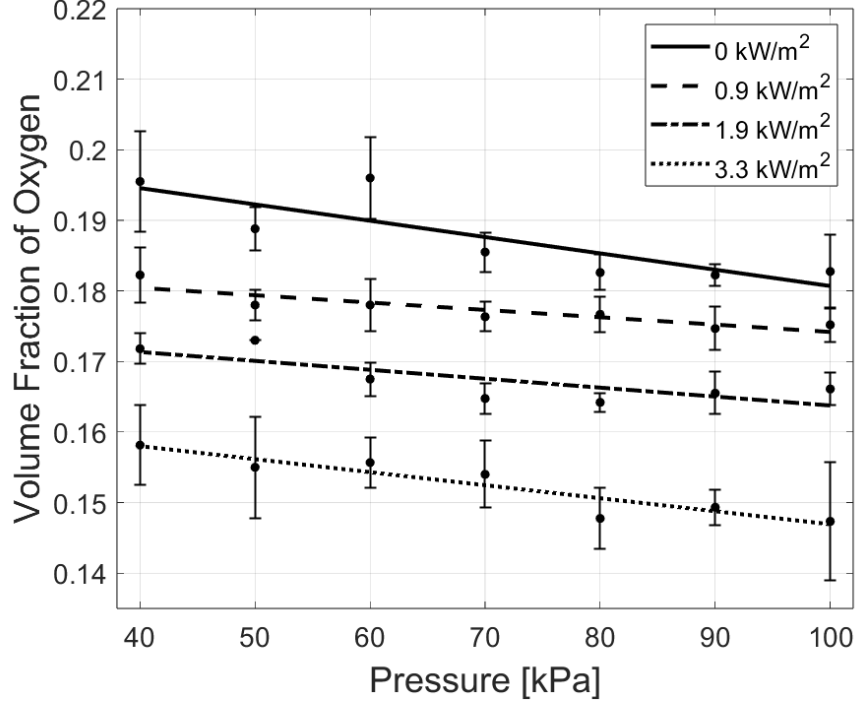


Figure 10: LOC boundaries under sub-atmospheric pressures and varying radiant heat flux conditions.

partial pressure of oxygen, the data of Fig. 10 can be approximately correlated as

$$\frac{P_{O_2}}{P_{amb}} + \frac{q''_{ext}}{q''_{cha}} = (X_O)_a + 0.09 \left(1 + \frac{P_{amb}}{P_{atm}} \right) \quad (6)$$

where $(X_O)_a = 0.183$ (Fig. 10) is the LOC mole fraction of oxygen at normal atmospheric pressure, $P_{atm} = 101.3\text{kPa}$ and zero heat flux, q''_{ext} is the maximum heat flux that the PMMA rods are exposed to, and $q''_{cha} = 100\text{kW/m}^2$ is a characteristic radiant heat flux used to normalize the applied radiant heat flux. From the discussion below it can be inferred that this critical heat flux may be related to the critical heat flux for ignition [58], since flame spread is treated as pilot ignition of the pyrolyzate. Although critical heat flux for PMMA in air is around 11 kW/m^2 [58], which is an order of magnitude smaller, since as the pressure and oxygen concentration decrease the critical heat flux for ignition increases, it seems appropriate to use this as a characteristic parameter of the problem.

The resulting correlation is shown in Fig. 11. Fig. 11 also includes the Lunar Exploration and SEA in air for reference. It is seen that all the data for each heat flux are almost linearly related, with a reduction of the partial pressure of oxygen, and a slight reduction in the slope

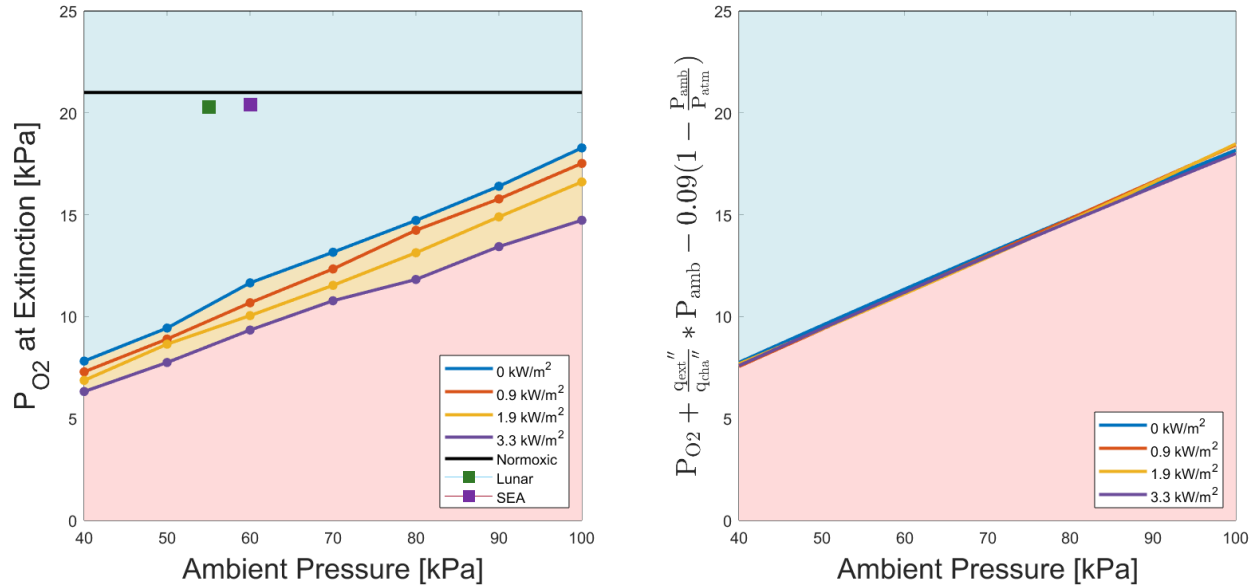


Figure 11: Open chamber LOC boundaries under sub-atmospheric pressures and varying radiant heat flux values. The errorbars are not included in second plot for simplicity, though the average error is 0.24 kPa.

for higher heat fluxes. Since for a given total ambient pressure solid fuels are flammable for partial pressure of oxygen above the LOC, Fig. 11 shows that PMMA is flammable for partial pressures of oxygen well below the oxygen partial pressure of air. Furthermore, in SEA air environments PMMA is flammable for pressures smaller than approximately 110 kPa. The presence of an external heat flux decreases the LOC partial pressure of oxygen even further.

It should be noted that in tests conducted to determine the LOC of different combustible materials and flow conditions, [56, 66, 67, 52] also observed that plotting the LOC data in terms of the partial pressure of oxygen gave a linear dependence on pressure independent of the material and conditions, suggesting that the mole fraction of oxygen may have an important role in the extinction of spreading flames over a solid fuel.

2.4 Discussion

The simplified analysis of flame spread developed by Fernandez-Pello [68, 40] is a possible approach to discuss the above experimental results. In that work, an expression is derived to describe the flame spread over a solid fuel based on the concept that the flame spreads over the solid as a series of ignition steps where the flame acts both as a heat source for

fuel pyrolysis, and as an ignition pilot (the flame) of the pyrolyzate and oxidizer gas ahead of the flame [69, 48, 70, 71, 72]. The analysis provides a simplified analytical formula for the opposed flame spread rate obtained from the ratio of the solid heating length ahead of the pyrolysis front and the time required to heat and pyrolyze the solid and to ignite the resulting flammable gaseous mixture ahead of the flame:

$$V_f = l_h / (t_{igs} - t_{igg}) \quad (7)$$

where V_f is the flame spread rate, l_h is the characteristic heated length ahead of the flame front, t_{igs} is the solid fuel ignition time and t_{igg} is the gas ignition (induction) time. In order to obtain an analytical solution to the solid heating problem, the solid is assumed to be either thermally thin or thick. The rods tested here are between these two limits, but for simplicity of presentation they are considered here as thin, although the same analysis would apply if considered thick. The following expression describes the flame spread rate [52].

$$V_f = Fl_h \left[\frac{\rho_s c_s d (T_p - T_0)}{h(T_f - T_p) + q''_{fr} + q''_{ext} - q''_{rs}} - \mathcal{D} \right]^{-1} \quad (8)$$

$$\mathcal{D} = C_1 \ln(1 - Da_{cr} / Da_x)$$

where, F is a geometrical conversion between a flat and cylindrical body [69], $h(T_f - T_p)$ is the convective heat flux from the flame to the solid surface, $q''_{fr} = F_{12}\epsilon\sigma(T_f^4 - T_p^4)$ is the flame radiant flux to the solid, q''_{rs} the re-radiation from the solid, q''_{ext} the external radiant flux, ρ_s and c_s are the solid density and specific heat and d is the rod diameter. T_f is the flame temperature, and T_p and T_0 are the pyrolysis and initial temperatures of the solid, C_1 is a constant related to the ignition time in the gas, Da_x is the Damkohler number at given conditions, and Da_{cr} is the critical Damkohler number for extinction [68].

The first term inside the parentheses in Equation (8) describes the heat transfer mechanisms of the flame spread over a thin rod and the second term represents the gas phase chemical kinetics mechanisms [73]. For large Damkohler numbers, i.e. fast reaction rate, the chemical kinetics term is small, and it does not play a role in the flame spread rate. In this case only the first term in Equation (8) determines the flame spread rate. The resulting equation normally is referred to as describing the heat transfer regime of flame spread. The equation is basically the well-known de Ris equation for opposed flame spread [47] for fast chemical kinetics and there exist other similar equations based on models of the heat transfer mechanisms of flame spread [48, 69, 70, 72]. As the Damkohler number decreases, the gas induction time increases and consequently the rate of flame spread also decreases (Equation (8)). The chemical kinetics also affect the heat transfer term through the flame temperature [67]. Under these conditions both terms in Equation (8) play a role in the flame spread process and must be considered. If the Damkohler number decreases even more and it equals the critical

Damkohler for extinction, the flame extinguishes.

2.4.1 Heat transfer mechanism

In this subsection, a summary is presented of how the problem variables affect the first term of Equation (8). The oxygen concentration affects primarily the flame temperature. Considering that the gas behaves approximately as an ideal gas, the flame temperature is proportional to the ambient oxygen concentration and is not strongly dependent on ambient pressure until the pressure is low enough to affect the reaction rate, and consequently the heat release rate at the flame. The adiabatic flame temperature can be obtained with a thermodynamics-based energy analysis of the combustion reaction [32] that approximately gives

$$T_f = T_0 + \Delta H_c X_0 s / c_p \approx C X_0 \quad (9)$$

Where ΔH_c is the heat of combustion per unit fuel, X_0 is the mole fraction of oxygen and s is the stoichiometric fuel to oxygen ratio. From Equation (9) it can be inferred that since extinction occurs at a given X_0 , it would also occur at a given flame temperature, as observed in the study of Dehghani et al. [74]. As the oxygen mole fraction is reduced, the flame temperature decreases, the heat flux from the flame to the solid decreases and so does the flame spread rate. As the pressure decreases the flame moves away from the surface [72], the heat from the flame to the solid decreases and the heat transfer term decreases quickly, under infinitely fast rate kinetics. Consequently, the flame spread rate decreases as both the pressure and the oxygen concentration are decreased, particularly in the latter case [52].

2.4.2 Chemical kinetics mechanism

The chemical kinetic mechanisms affect the flame spread rate primarily through the second term of Equation (8). The Damkohler number, Da , is the ratio of the flow time to the chemical time. The flow time can be defined as $t_{fl} = l_c / U_m$ if convection is dominant (where U_m is the mean flow rate) or $t_{fl} = l_c^2 / \alpha$ if diffusion is dominant (where α is the thermal diffusivity). The chemical time is defined as $t_{ch} = \rho / q_r$, where q_r is the reaction rate, which for a single step, the overall reaction can be expressed as [17]

$$\begin{aligned} q_r &= A_0 \exp\left(-\frac{E_a}{R_u T}\right) [Fuel]^a [O_2]^b = \\ &= A_0 \exp\left(-\frac{E_a}{R_u T}\right) X_F^a X_O^b \left(\frac{P}{R_u T}\right)^{a+b} \propto P^{a+b} \end{aligned} \quad (10)$$

For a second order reaction, $a = b = 1$, and the reaction rate is proportional to P^2 . In Equation 10, A_0 is the pre-exponential constant, E_a is the activation energy, and R_u the universal gas constant. For a convective dominated flow, the Damkohler number is

$$Da = \left(\frac{l_c A_0}{U_m \rho} \right) \exp \left(- \frac{E_a}{R_u T} X_F X_O \left(\frac{P}{R_u T} \right)^2 \right) \quad (11)$$

The ambient oxygen concentration affects the Damkohler number through the flame temperature, and the oxygen and fuel mole fractions. Because of the exponential term, the effect of the temperature is very strong and consequently very sensitive to the value of the X_O . The mole fraction of fuel is also affected by the environmental conditions since is determined by the mass gasification rate, or burning rate, of the solid, which depends on the heat flux at the fuel surface. In a boundary layer the fuel gasification rate and the fuel mole fraction is approximately determined by [75]

$$X_F = C \ln(1 + B) \approx 2C X_O \quad (12)$$

where C is a constant and B is the mass transfer number [76]

$$B = [\Delta H_c X_O s - c_p (T_p - T_0)] / [L_p + q_s'' / m''] \quad (13)$$

with L_p being the solid heat of pyrolysis. Thus, the fuel gasification rate, and consequently the mole fraction of fuel, also depends on the oxygen mole fraction through the heat release rate and the heat flux at the surface. From Equation (11) it is inferred that for a second order reaction the Damkohler number is approximately linearly dependent on pressure $Da \sim P$.

2.4.3 LOC for flame spread

In this work, the LOC is experimentally determined by observing when there is no flame propagating or it extinguishes as the oxygen volume fraction is decreased for a given pressure and external heat flux. From Equation (8) it is seen that this can occur from three different mechanisms; 1) when the heat transfer term in Equation (8) is zero, i.e. the solid doesn't ignite; 2) when the problem Da equals the Da_{cr} , i.e. the chemical kinetics term is zero; 3) when the heat transfer and chemical kinetics terms balance each other, i.e. the solid may burn but the flame doesn't propagate. Reducing the oxygen volume fraction reduces the flame temperature and consequently can reach the LOC from any the three mechanisms above. This is the marker of the LOC for flame spread.

2.4.4 Heat transfer limit

The LOC occurs when the numerator in the heat transfer term is zero. Considering that in opposed flame spread the radiation view factor from flame to fuel is small and that the flame temperature is low near the LOC, the flame radiation may be neglected. Thus

$$h(T_f - T_p) - q''_{rs} + q''_{ext} = 0 \quad (14)$$

This non flame spread limit has been defined as the radiation limit of flame spread, [72, 25, 63, 64], since the heat flux from the flame to the fuel cannot balance the heat lost by the solid by radiation to the surrounding. Combining Equation (9) and Equation (14) it is deduced that

$$T_f = CX_0 = (q''_{rs} - q''_{ext})/h + T_p \quad (15)$$

Thus the heat transfer LOC occurs at a determined flame temperature or mole fraction of oxygen, as given by Equation (15).

2.4.5 Chemical kinetics limit

The LOC occurs when the Damkohler number of the problem equals the critical Damkohler number for extinction Da_{cr} , in which case the flame is extinguished. Assuming that the critical Damkohler number for extinction is constant, Equation (10) with $Da = Da_{cr}$ being constant gives the chemical kinetics conditions for the LOC. Since the flame temperature and the mole fraction of fuel depends on the oxygen mole fraction, it can be concluded that the chemical kinetics limit is also determined by the oxygen mole fraction, although it is not possible to derive an analytical formula of the limit.

2.4.6 Combined heat transfer and chemical kinetics limit

This limit is given by a combination of effects on the heat transfer and chemical kinetic processes leading to the spread of the flame over the solid surface [77, 78]. In this limit the heat transfer and chemical kinetics terms in Equation (8) balance each other and the flame spread rate is zero. Since both the heat transfer and chemical kinetic limits in Equation (8) are dependent on the oxygen mole fraction, it is possible to extract from the equation the value of oxygen mole fraction that gives a zero flame spread rate, i.e. the LOC. This is constrained by the difficulty in determining the values of the different parameters in Equation (8) and is beyond the scope of this work.

2.4.7 Effect of pressure on the LOC

If the pressure is reduced at a fixed oxygen volume fraction, the heat transfer from flame to solid decreases because the boundary layer thickness increases as the density decreases [72, 76]. The effect is similar to the flow velocity being reduced. In addition, the chemical kinetics term increases because the reaction rate decreases as pressure decreases, and so does the Da (Equations (10, 11)). Thus, reducing pressure increases the LOC although the effect is relatively weak, as shown in Fig. 10.

2.4.8 Effect of the external heat flux on the LOC

The addition of an external heat flux counteracts the decrease of the convective and radiative heat transfer from the flame to the solid, as the oxygen concentration and/or pressure are reduced. It also counteracts the lower mass gasification rate as the heat flux from flame to the solid decreases. Consequently, applying an external heat flux reduces the LOC for flame spread, as shown in Equation (15).

2.4.9 Effect of the flow velocity on the LOC

If the flow velocity is increased at a fixed oxygen volume fraction and pressure, the heat transfer from the flame to the solid increases because the boundary layer thickness decreases. This results in an increase in the flame spread (Equation (8)). At the same time the Damkohler number decreases and the chemical kinetics term increases (Equations (8, 11)). Thus, in the latter case, increasing the flow velocity is another potential mechanism for the LOC that takes place at elevated flow velocities. This is often referred to as the blow off limit [63, 78]. Decreasing the mole fraction of oxygen results in the LOC to occur at lower flow velocities.

From the above phenomenological analysis, it can be concluded that the flame temperature or the oxygen mole fraction are the determining parameters of the LOC for flame spread. It supports the observed experimental results of Fig. 10 and of reference [38]. Also interesting is that from Equation (12) it can be inferred that there is an “extinction” B number for the LOC that is based on the mole fraction of fuel.

2.5 Conclusion

In this paper, the limiting oxygen volume fraction for no flame spread is studied as a function of ambient pressure and external heat flux for flames spreading downward over the surface

of cylindrical PMMA samples. Correlating the LOC data in terms of the partial pressure of oxygen shows that the partial pressure of oxygen at the LOC is linearly dependent on the ambient pressure, with a slope that is the LOC at earth atmospheres, and weakly dependent on the ambient pressure and radiant flux. Thus, the partial pressure of oxygen at the LOC, and by extension the molar fraction of oxygen, is instrumental in determining the conditions below which flame spread cannot be sustained. Over the ranges tested, this relationship can be described to an acceptable degree of accuracy through a simple linear equation, which evades the need for detailed experimentation at each condition. The combustion mechanisms leading to this result are discussed based on simple equations and phenomenological arguments to predict the dependence of the LOC on the molar fraction of oxygen. Also, a critical B number for no flame spread is identified in terms of the molar fraction of oxygen at the LOC. The relevance of these results is that they are specific to an aspect of the combustion of solid fuels, since extinction is determined by the interaction between the solid and gas phases. This is in contrast with gaseous fuel combustion where both the mole fraction of oxygen and fuel are prescribed, and extinction is independent of pressure. Thus, the mechanisms controlling the flammability limits in the combustion of solid fuels are significantly more complicated than those for gaseous fuels. Consequently, care should be taken when applying the concepts traditionally used for gaseous fuel combustion to solid fuel combustion.

Future research should consider the transient characteristics of the extinction process at each oxygen volume fraction because reducing the oxygen in a cabin to put out a fire can only be used as a temporary safety measure. It is also worth studying the probability of fire extinction at oxygen volume fractions slightly above the LOC.

2.6 Acknowledgments

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3 Flame Extinction of Thermally Thick PMMA in Earth Gravity versus Microgravity: A Comparison of Earth and On-Orbit Space Experiments

3.1 Introduction

The frequency of human space travel has increased over the past decade with the growth of private companies participating in space programs and increasing opportunities for non-astronauts to buy a ticket to space. At the same time, governmental organizations such as NASA are proposing longer space missions with the establishment of facilities on the Moon and Mars. With increased time spent in space, microgravity fire safety is of increasing importance. Environmental conditions inside the cabin of a spacecraft, termed Space Exploration Atmospheres (SEA), are very different from those encountered on Earth: besides the reduced gravity and therefore buoyancy, there are also low velocity flows from ventilation systems, and potentially low pressures and elevated oxygen concentrations [50]. Given that egress or rescue from a spacecraft are difficult or impossible, the consequences of a fire could be catastrophic. Therefore, reducing the flammability risk is key to improving spacecraft fire safety.

The first step to reducing fire risk in space is to ensure every material that is used in a habitable spacecraft passes a flammability test. The primary test used by NASA is fire safety standard STD-6001B, in which the material is exposed to the same conditions expected in the spacecraft and an upward flame spread test is conducted [19]. This is a pass/fail test, and if a material passes, then it can be brought aboard. In addition to this binary test, it would be important to know the material flammability limits to reduce the need for retesting at each new condition. Another limitation is that the STD-6001B test is conducted at Earth gravity and that the material is presumed to be less flammable in microgravity, which is not always the case. Although microgravity fire research is limited due to the difficulty with performing such experiments, several researchers have studied the differences in flammability in normal gravity versus microgravity and environmental factors that affect it [21, 22].

In reduced gravity airplane experiments involving upward flame spread over thin solids for a short duration of time, Sacksteder et al. [22] noticed a significant reduction in the flammability limits of thin cellulosic fuel at reduced gravity levels. This result is consistent with the findings of Mizutani et al. [79] who mapped the Limiting Oxygen Concentration (LOC) of EFTE-insulated wires in microgravity versus Earth gravity at different external opposed flow velocities. In these tests, the LOC in microgravity is found to be 5-10% lower than in Earth gravity. Takahashi et al. [65] experimentally showed the extinction limits of LDPE insulated nickel-chrome and copper wires in both gravity levels at different external opposed

flow velocities. For both materials, across all flow velocities, they found that the LOC in microgravity is approximately 3-4% lower than on Earth. Lastly, Olson et al. [80, 81] used a centrifuge system inside a drop tower to simulate upward spread on three flame retardant materials in Mars [80] and lunar [81] gravity conditions. They found that the LOC in Martian gravity was up to 5.75% lower than normal gravity, and lunar gravity LOCs were even lower. This indicates that PMMA flammability is highest not in microgravity, but in partial gravity conditions, which is consistent with the predictions of Nakaya et al. [82]. The authors highlighted that Earth-based flammability tests may not be conservative enough and some materials may still be flammable under spacecraft conditions, recommending the inclusion of a factor of safety on Earth flammability limits.

Recently, Rivera et al. [83] outlined the existence of two different flammability limits: LOC for flame spread (LOC-FS) and LOC for flame regression (LOC-FR). Following the observation that in a sealed chamber of continuously decreasing oxygen concentration, the flame initially spread along the length of the sample and later regressed into the core of the sample, LOC-FS represents the oxygen concentration at which the flame stops spreading along the length of the sample, while LOC-FR is the oxygen concentration at which regression ends and the sample extinguishes. In this work, the LOC is denoted as the oxygen concentration at which the flame visually extinguishes.

The present work seeks to combine the effects of pressure, oxygen concentration, and the influence of buoyant forces by comparing experiments conducted in a laboratory scale combustion tunnel on Earth with tests performed aboard the International Space Station (ISS), where the force of gravity is negligible. The experiments presented here concentrate on the flame behavior as the oxygen concentration is reduced, and the differences in the subsequent flame extinguishing process between normal and microgravity. The ambient gas initially is air (21% oxygen volume fraction), but as the flame consumes the available oxygen in the combustion chamber, the oxygen concentration decays. Only sub-atmospheric pressures are considered because future spacecraft are expected to operate at low pressures and increased oxygen conditions in order to reduce stress on exterior walls and expedite astronaut preparation time before any extra-vehicular activity (EVA) [43]. Furthermore, experiments discussed in this paper deviate from the normoxic curve, which pairs low pressures with elevated oxygen concentrations, because the goal of the study is to characterize the extinction process of a vitiated environment. On Earth, the PMMA samples are exposed to an upward mixed (buoyant and forced) low velocity opposed flow, whereas in microgravity there is only the opposed low velocity forced flow. The comparison between LOC data and extinction processes in normal and microgravity can advise ways to improve Earth-based flammability standards for materials in SEA.

3.2 Methodology

Ground normal gravity experiments were conducted in a laboratory scale combustion tunnel measuring 125 mm x 125 mm x 600 mm which is placed inside a 105 L pressure chamber (see Fig. 12). A high-capacity vacuum pump (Welch DuoSeal 1376) was used before each experiment to reduce the chamber pressure to the desired value. The system pressure was then continuously monitored with an electronic pressure transducer (Omega Engineering, Inc. PX309-015A5V). A fan below the test section recirculated gases and produced a forced flow velocity of 10 cm/s, a value which is similar to that induced by the Environmental Control and Life Support System (ECLSS) of a spacecraft. However, during ground experiments the flame induced a buoyant flow, so it was exposed to a combination of forced and free convection conditions.

The microgravity experiments were performed in a similar setup aboard the International Space Station (ISS), in the Combustion Integrated Rack (CIR), containing a 100 L combustion chamber [84]. Inside the combustion chamber was the SoFIE insert enclosing the Material Ignition and Suppression Test (SoFIE/MIST) apparatus, within which the samples were allowed to burn. Similarly to the combustion chamber in normal gravity, the MIST apparatus was equipped with inlets to allow for the addition of oxygen and nitrogen gas into the test section, and an outlet connected to a vacuum pump. A fan was placed at one end of the test section, below the sample, and recirculated gases towards the sample to create an opposed forced flow of 10 cm/s.

The samples used in all tests were black cast PMMA cylinders, 55 mm in length and 12.7 mm in diameter. The black color was selected to maximize the absorbance of thermal radiation at the rod's surface. The material used in this study, PMMA, is used extensively in flammability research because it is a well characterized fuel. Besides its plentiful uses on Earth, it is also utilized for aerospace applications such as airplane windows and is being considered for future spacecraft viewing ports. The sample was fixed at the center of the test section and ignition was achieved with a coil-shaped NiCr ignition wire that hovers just above the sample such that when a current was passed through it with a variable transformer, it heated and ignited the tip of the sample. The ignition, flame spread, and extinction were video recorded through the chamber windows, both on Earth and in microgravity, using a digital camera.

Before starting an experiment, the pressure chamber was filled with air at the desired ambient pressure. The pressures tested are 40 kPa, 60 kPa, 80 kPa, and 100 kPa. Then, all gas inlets and outlets were closed. Once the ignition wire was energized and the sample ignited, the sample was allowed to burn and naturally consume the available oxygen. The volume fraction of oxygen in the chamber was recorded at a frequency of 1 Hz with an FDO2 optical gas sensor from PyroScience GmbH.

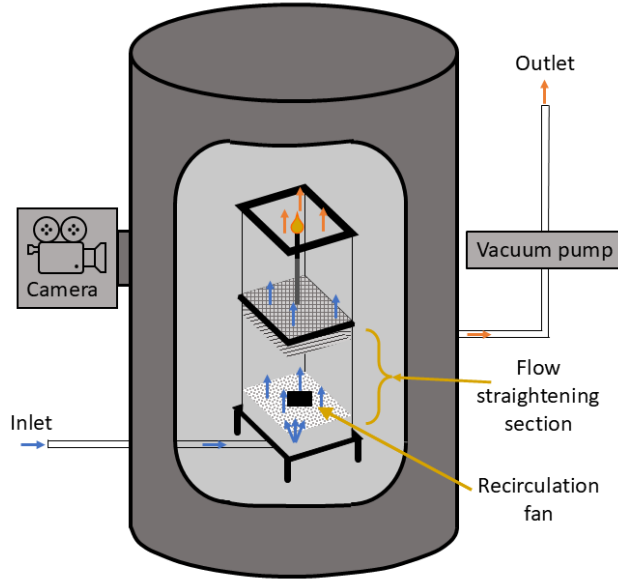


Figure 12: Illustration of the pressure chamber with a cutout showing the combustion tunnel.

In each experiment, the flame eventually stopped spreading along the sample and regressed, shrinking to a blue hemisphere hovering at the top of the sample, flickering with increasing intensity until extinction. In order to keep the ambient pressure constant for the duration of each experiment, the chamber was vented occasionally to offset the pressure increase caused by the combustion process [54].

3.3 Results

Experiments were conducted at pressures of 40 kPa to 100 kPa with intervals of 20 kPa. For all pressures and particularly at lower pressures, once the sample is ignited the flame is often weak and is slow to establish in size and luminosity. Following ignition, the flame begins spreading along the length of the PMMA sample in the presence of the opposed flow oxygen gas mixture. The combustion process then accelerates initially and the flame becomes larger, consuming oxygen at a faster rate as it further pyrolyzes the unburned fuel. As the oxygen in the chamber decreases due to the combustion of the PMMA, the flame spread rate decreases, and the flame becomes weaker. Approaching extinction, the oxygen concentration is relatively low and only a small, dim flame is sustained, as seen in Fig. 13. It should be noted that in the top row of Fig. 13, depicting the microgravity flame spread and extinction, the brightness and contrast in the images have been enhanced to make the

flame more visible, as it is very dim in the original images. The LOC is difficult to pinpoint because at low volume fractions of oxygen, any minor perturbation can be enough to extinguish the flame [57]. Therefore, it is necessary to repeat each experiment between three and five times to reduce the uncertainty and ensure variability. In this work, normal gravity experiments are repeated following this recommendation. However, due to the limitations of conducting experiments in space, each condition in microgravity was only tested either once or twice. Special attention was paid to ensure the experiments were conducted in a precise manner and equipment fully calibrated to minimize sources of systematic and random errors.

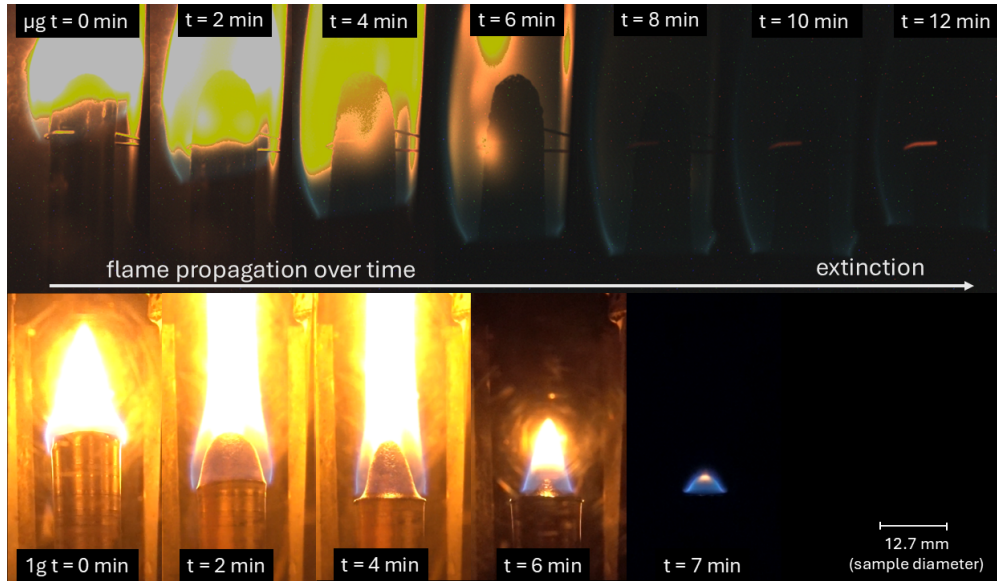


Figure 13: Collage of flame propagation over time at 100 kPa. In microgravity (top row, images are edited to enhance the colors and facilitate the visualization of the flame) the flame becomes dimmer and bluer and shrinks in size, and flickers just before extinguishing. The Earth gravity experiment (bottom row) follows a steady trend decreasing in size to extinction without flickering.

The flame front position along the PMMA over time is shown in Fig. 14, with microgravity experiments being on the left plot and normal gravity on the right. The flame spread further along the length of the fuel in microgravity compared to earth gravity. For this figure, coordinate (0,0) corresponds to the time and position of the flame when the sample is lowered into position, which happens a few seconds after ignition. By that point, the flame was technically propagated by a small distance already, consuming the outer diameter of the sample, which is why some experiments present a flame regression below the 0 mm index.

The consumption of oxygen over the duration of an experiment is shown in Fig. 15. Mi-

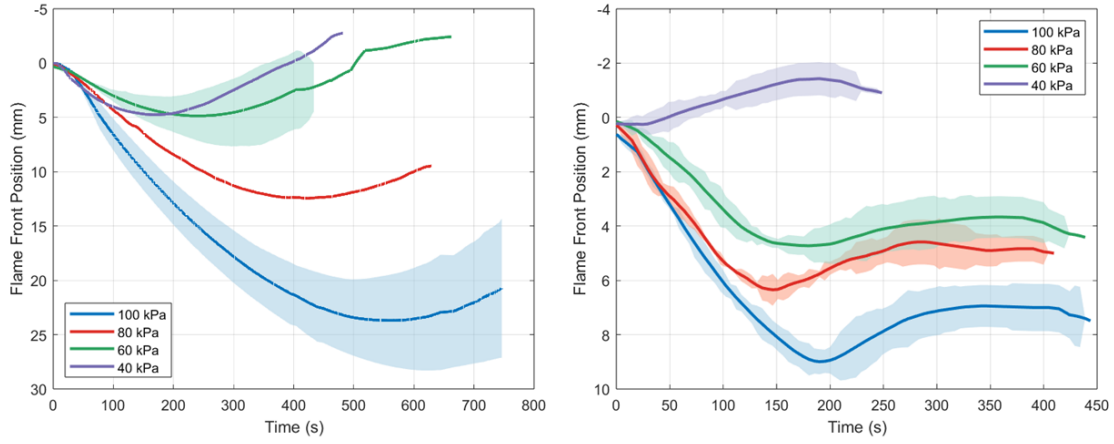


Figure 14: Flame propagation in microgravity (left) and normal gravity (right) over time. All conditions, except for 40 kPa in normal gravity, displayed flame spread along the length of the sample, followed by flame regression. The exception is 40 kPa in normal gravity, in which the average flame spread was less than 0.5 mm, and most of the combustion took place in the flame regression phase.

crogravity experiments occasionally started at oxygen volume fractions lower than 21% to ensure that the low-oxygen extinction limits are reached before the end of the sample is ignited. The transparent shaded regions represent the standard deviation of the data, while the opaque curves depict the average value. In Fig. 15, unlike Fig. 14, time=0 s corresponds to the moment the flame is ignited.

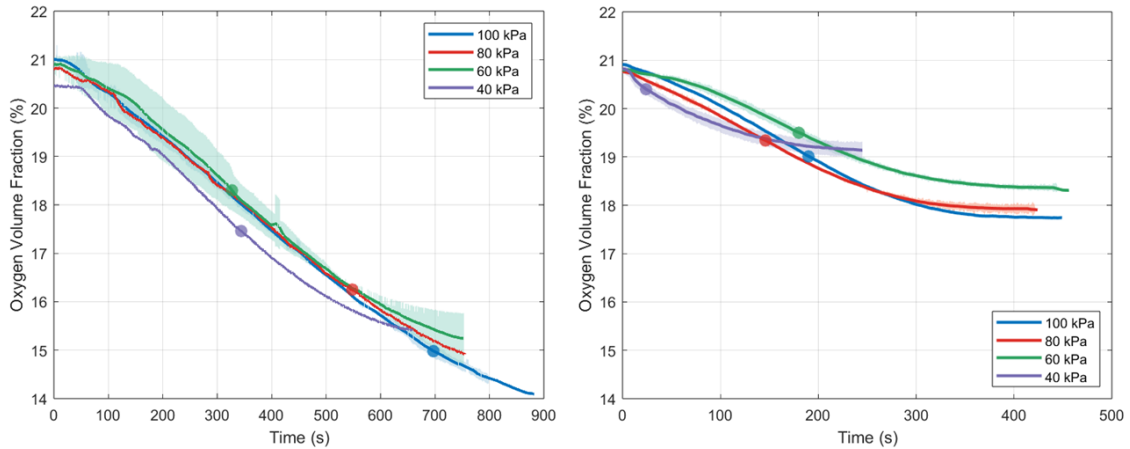


Figure 15: Curves showing the depletion of oxygen over time in microgravity (left) and normal gravity (right) for four ambient pressures. The dots on each curve signify the LOC of the flame spread phase.

In Fig. 16 the oxygen volume fraction at extinction is shown for both microgravity and normal gravity, with the former being significantly lower than the latter. That is, microgravity combustion can be sustained in environments with oxygen concentrations approximately 3-4% lower than on Earth. In microgravity, all samples were flammable at oxygen volume fractions greater than the Earth gravity LOC. Similarly, below the microgravity LOC, none of the samples were flammable. The primary difference between the normal gravity and microgravity environments is the presence of a buoyant convective current induced by the flame. At the scale of the Earth experiments, the buoyant flow is as large as 30-40 cm/s and acts on top of the 10 cm/s forced flow. At the beginning of an experiment, the large flame produces a larger buoyant flow, and then decreases with decreasing oxygen concentration as the flame length decreases. However, in microgravity the only flow past the sample is the forced flow. Past studies have shown that a small to moderate opposed flow helps the flame spread by mixing the gasified fuel and oxygen around the pyrolysis zone, transporting the oxidizer to the flame while increasing the convective heat transfer from the flame to the solid [63, 85, 86]. However, higher flow rates have the opposite influence on the spread rate, reducing the flame heat release rate. The transition between the two effects depends on the ambient oxygen concentration [77].

Both in the absence and presence of gravity, it is observed that for opposed flow flame spread the LOC is lower at higher ambient pressures. This implies that materials are less flammable as the ambient pressure is reduced. As the ambient pressure is reduced, the gas density decreases, the boundary layer grows thicker, resulting in the flame moving away from the surface, as seen in Fig. 17 and Fig. 18 [32]. This in turn affects the spread of the flame because the heat transfer rate from the flame to the solid decreases [87].

	HRR (kW)			
Pressure (kPa)	40	60	80	100
Microgravity	0.53	0.90	1.24	1.89
Earth Gravity	0.18	0.39	0.61	0.85

Table 1: Average heat release rate of each condition from ignition until flame extinction.

The average heat release rate (HRR) can be calculated using the oxygen depletion data from the duration of the tests shown in Fig. 15, together with the heat release per unit mass of oxygen consumed, which is approximately 13.1 kJ/g [88]. Table 1 includes the values of the average HRR for each condition tested. It can be seen that the HRR increases with increasing pressure for all conditions tested which is aligned with the ambient pressure's effects on the LOC. Reducing the gravity level appears to have the strongest effect, with microgravity experiments having a larger HRR compared to those in Earth gravity. The difference between the microgravity and Earth gravity HRR is a direct result of the larger

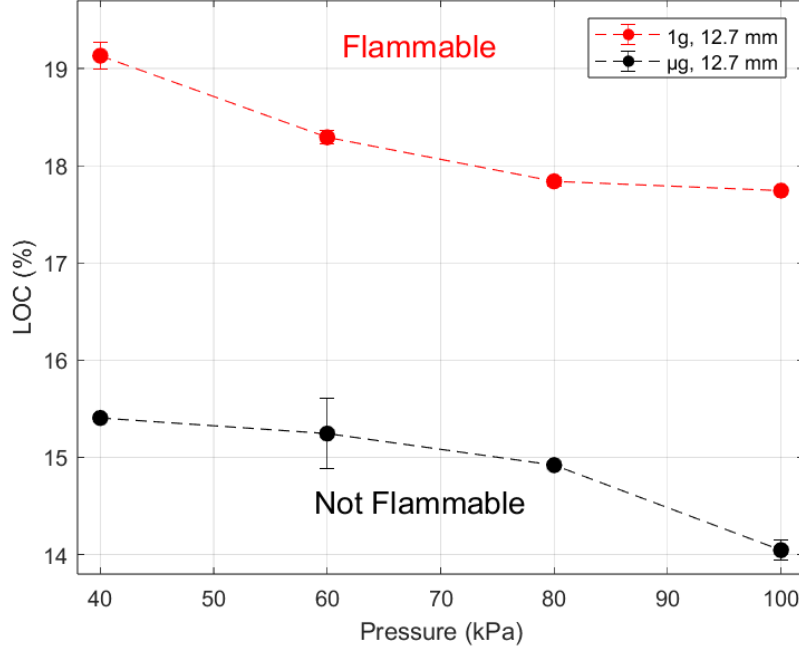


Figure 16: Limiting Oxygen Concentrations at tested pressures. The region where all samples are flammable in normal gravity and the region where no sample is flammable are marked explicitly in the figure. In between the “normal gravity flammable” and “not flammable” regions, the oxygen concentration is low enough such that flames could be sustained only in microgravity.

oxygen consumption in microgravity due to the slower flame spread rate and longer time to extinction (Fig. 19). Therefore, not only is PMMA more flammable in microgravity because of its low LOC, but more total energy is released during the longer burning times, making PMMA more dangerous in microgravity compared to Earth gravity.

3.4 Discussion

The process of flame spread over a solid fuel can be characterized by a series of ignition steps. The flame acts as an ignition pilot, transferring heat to and preheating the unburned fuel until it pyrolyzes, at which point the flame propagates to continue this process with more unburned fuel. This procedure involves chemical kinetics and heat transfer mechanisms, as well as mass and heat transport processes which must all be analyzed [87, 30, 77].

Thermal transport and chemical kinetics processes are influenced by the mean flow velocity,

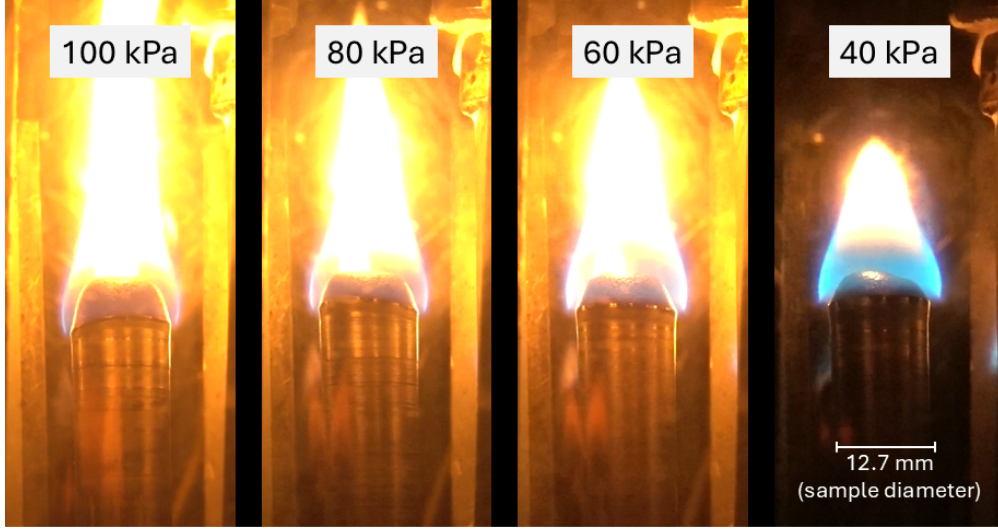


Figure 17: Collage displaying how the standoff distance increases with decreasing pressure. Each frame shown is taken exactly 1 minute after sample ignition, in normal gravity.

U_m , past the surface at which burning is occurring. Earth gravity flames can be described as convection dominant because of the 40 cm/s mixed flow incident on the sample in the pyrolysis region, whereas the flow velocity is severely dampened in reduced microgravity. Using $U_m = \sqrt{g\beta\Delta T l_c} + 10$ cm/s, where g is the force of gravity and $\beta \approx 1/T$ is the volumetric thermal expansion coefficient and the constant represents the 10 cm/s forced flow, decreasing gravity will reduce the flow velocity, which will in turn affect the rate of flame spread.

To characterize the influence of the chemical kinetics and heat transfer on flame spread, a mathematical expression for flame spread rate over a thermally thick rod is used [77, 89]:

$$V_f = Fl_c \left[\frac{C_1 \rho_s c_s k_s (T_p - T_0)^2}{(q''_{f,conv} + q''_{f,cond} + q''_{f,rad} - q''_{s,re-rad})^2} - C_2 \frac{\ln(1 - Da_{cr}/Da)}{t_{fl}} \right]^{-1} \quad (16)$$

where F is a geometrical conversion between a flat and a cylindrical shape [69], C_1 is a constant related to the solid ignition time, ρ_s , c_s , and k_s are the solid density, specific heat, and thermal conductivity, and T_p and T_0 are the solid pyrolysis and initial temperatures. $q''_{f,conv}$ is the convective heat flux from the flame to the solid, $q''_{f,cond}$ is the heat conducted ahead of the flame, $q''_{f,rad}$ is the flame radiant flux, and $q''_{s,re-rad}$ is the re-radiation from the solid surface. The second term of the flame velocity equation utilizes C_2 as a constant related to the ignition time of the gas, t_{fl} as the flow time, Da_{cr} the critical Damkohler number for extinction, and Da the Damkohler number at the given conditions.

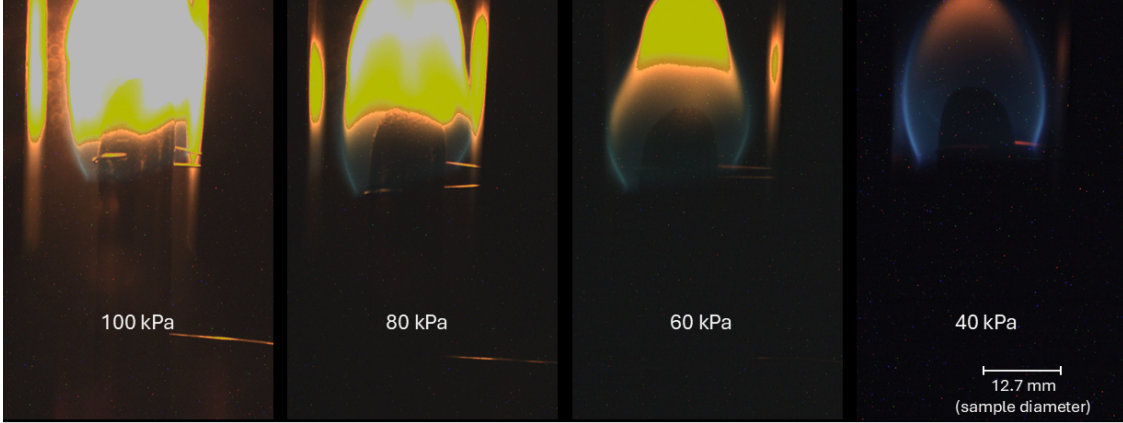


Figure 18: Microgravity flames at different pressures. All figures are taken exactly 1 minute after ignition. The color intensity in the images is edited to allow for better visualization of the flame.

The LOC is reached when $V_f = 0$, which can occur in three ways: when the denominator of Eqn. 16 approaches infinity. This may occur when the pyrolysis time is infinite and the solid never ignites; when the Damkohler number is equal to the critical Damkohler number for extinction thereby making the chemical kinetics term on the right side of Equation 16 approach infinity; or when the sum of the two terms together is infinite [90, 30].

Following the analysis in [90], the first condition of an infinite heat transfer term is possible if the energy balance at the solid ahead of the flame approaches zero. For an opposed flow configuration, the view factor from the flame to the solid is small, so that $q''_{f,rad}$ may be neglected. This leaves the convective heat flux, the heat conducted ahead of the flame, and re-radiation from the solid in the energy balance.

$$q''_{f,conv} + q''_{f,cond} - q''_{s,re-rad} = 0 \quad (17)$$

Equation 17 can be further broken down by expressing the mixed convection heat flux as

$$q''_{f,conv} = h(T_f - T_p) = C_3 k_g \rho_g c_p U_m / x (1 + Fr)^{1/2} (T_f - T_p) \quad (18)$$

where Fr is the Froude number $Fr = Gr/Re$, which is the ratio of the Grashof number divided by the Reynolds Number. It is appropriate to use a mixed convection heat flux as the normal gravity flames are exposed to mixed (forced and natural) convection [77]. For reduced gravity flames the reduction in natural convection will be reflected in the Froude number, which will be smaller, leading to a decrease in convective heat transfer. The conductive heat flux can be expressed as $q''_{f,cond} \approx \gamma_s Q''_{rr}$ where γ_s is the fraction of the heat release rate conducted

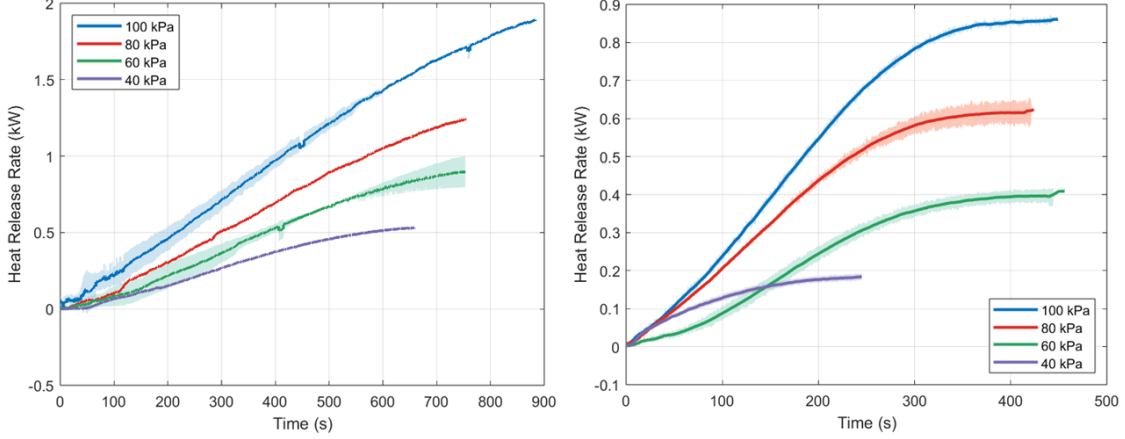


Figure 19: Heat release rate over time in microgravity (left) and normal gravity (right).

through the solid, $Q''_{rr} = q_r \Delta H_c$ is the gas phase heat release rate, q_r is the chemical reaction rate, and ΔH_c is the heat of combustion. Finally, the re-radiation from the solid can be expressed as $q''_{s, re-rad} = F_{s, \infty} \epsilon \sigma (T_p^4 - T_0^4)$. Equation 17 is then rewritten as [90]:

$$C_3 k_g \rho_g c_p U_m / x (1 + Fr)^{1/2} (T_f - T_p) + \gamma_s Q''_{rr} - F_{s, \infty} \epsilon \sigma (T_p^4 - T_0^4) = 0 \quad (19)$$

Given that the convective and radiative terms of Equation 19 are primarily driven by the flame temperature, even when the convective heat flux is decreased at reduced gravity, the flame temperature is the key factor for flame extinction in the case of an infinite pyrolysis time. Conducting a thermodynamic analysis of the combustion reaction, the adiabatic flame temperature can be approximated as [91]:

$$T_f = T_0 + \frac{(1 - \phi) \Delta H_c X_{O_2} S}{c_p} \quad (20)$$

Where ΔH_c is the heat of combustion per unit fuel, X_{O_2} is the oxygen mole fraction, S is the stoichiometric fuel to oxygen ratio, and ϕ is the fraction of the heat lost to the surroundings by the flame. Equation 20 demonstrates that the flame temperature decreases with a decreasing oxygen mole fraction and thus so does the flame spread rate which reaches zero when the conditions of Equation 19 are met. Thomsen et al. [90] were able to obtain an explicit expression for the LOC for flame spread by combining Equation 19 and Equation 20:

$$X_{O_2} = \frac{F_{s,\infty}}{C_3} \frac{\epsilon\sigma(T_p^4 - T_0^4) - \gamma_s Q''_{rr}}{\left(\frac{k_g P}{RT_f}\right)^{1/2}} \left(\frac{U_m}{x}(1 + Fr)\right)^{1/2} \frac{c_p^{1/2}}{(1 - \phi)\Delta H_c S} + (T_p - T_0) \frac{c_p}{(1 - \phi)\Delta H_c S} \quad (21)$$

Equation 21 shows the dependence of the LOC on the heat transfer mechanisms controlling flame spread. Variations in the parameters in Equation 21 that result in the decrease of the flame temperature will decrease the oxygen volume fraction.

The second condition to reach the LOC relates to the chemical kinetics term and is fulfilled when the Damkohler number decreases to equal to the critical Damkohler number for extinction [90]. The Damkohler number, Da, is defined as the ratio of the flow time to the chemical time. If convection is dominant, as in this case, $t_{fl} = l_c/U_m$, where U_m is the mean flow velocity, and the Damkohler number is $Da = t_{fl}/t_{ch} = (l_c/U_m)/(\rho/q_r) = (l_c q_r)/(U_m \rho)$. For a single step chemical reaction, the reaction rate is expressed as:

$$q_r = A_0 \exp\left(\frac{-E_a}{RT}\right) [Fuel]^a [O_2]^b = A_0 \exp\left(\frac{-E_a}{RT_f}\right) X_F^a X_O^b \left(\frac{P}{R_u T_f}\right)^{(a+b)} \quad (22)$$

where A_0 is the pre-exponential factor, E_a is the activation energy, R is the universal gas constant, T_f the flame temperature, X_F is the mole fraction of fuel and X_O the volume fraction of oxygen, and P is the ambient pressure. From the above equation, the reaction rate is proportional to both the pressure and oxygen concentration. For a first order reaction, $a = b = 1$, and $q_r \propto X_O \cdot P^2$. Therefore, decreasing the volume fraction of oxygen, or the ambient pressure, will reduce the Damkohler number, and bring the flame spread closer to extinction. Reductions in oxygen concentration (and consequently flame temperature) and ambient pressure, will slow down the reaction rate, which in turn reduces the Damkohler number for both normal and microgravity.

These two mechanisms can be combined for condition three, which stipulates that the sum of the heat transfer and chemical kinetics terms must be infinite, leading to an infinite ignition time, and therefore no flame spread [90]. The oxygen mole fraction, through the flame temperature, plays a critical role in the flame extinction process in all gravity conditions, as it directly affects both terms. Decreasing gravity reduces the flow velocity and serves to increase the pyrolysis time, through the slowed rate of heat transfer. However, at the same time it increases the Damkohler number through the increase of flow time. This means that as the mixed flow velocity (forced and buoyant) increases, the flame spread process is transitioning from a thermal regime, influenced by the balance between heat transfer from

the flame to the fuel and solid re-radiation, to a chemical regime in which flame dynamics are influenced by the chemical kinetics [90]. At the former regime, at very low velocities the solid re-radiation may become larger than the heat flux from the flame to the solid, causing its extinction. This mechanism is sometimes referred to as the “radiation limited” extinction. In the chemical kinetics regime, as the flow velocity increases the oxidizer may not be available long enough to mix with the fuel and the flame will shrink in size to its extinction. This limit is referred to as the “blowoff limit” for extinction.

The correlation of the results presented in Fig. 16 in terms of the above analysis shows that the LOC for both normal gravity and microgravity fall in the region where both heat transfer and chemical kinetic mechanisms affect the spread of the flame and its extinction.

3.5 Conclusion

This work explores the different mechanisms driving flame extinction in microgravity and Earth gravity in order to assess the feasibility of Earth-based flammability testing standards for materials intended for use in spacecraft. The results show that the LOC is lower (3-4% difference in oxygen volume fraction at extinction) in microgravity compared to Earth gravity when all other experimental parameters are the same. This implies that buoyancy, or lack thereof, is an important factor in flame spread under a low velocity opposed flow. Whereas at Earth the flame induced a buoyant convective flow of the order of 40 cm/s on top of the 10 cm/s forced flow, in microgravity the flame was exposed only to the forced flow. Regardless of the level of gravity, the flame temperature is a critical factor in influencing the LOC as it drives both the heat transfer and the chemical kinetics mechanisms that control the rate of flame spread.

Reducing the ambient pressure had the effect of the PMMA extinguishing at a higher volume fraction of oxygen compared to experiments conducted at 100 kPa. The justification for this behavior is that as the system pressure is reduced, the boundary layer grows thicker, so the heat transfer rate from the flame to the solid decreases. At the same time the reaction rate decreases and so does the Damkohler number. Therefore, more oxygen is required to maintain the spread of the flame.

The results of this work highlight that there are significant differences between solid fuel combustion in normal gravity and microgravity. Given the large differences in the LOC between the two environments, it might be insufficient to conduct flammability tests on Earth for materials intended to be used in spacecraft. At the very least, the differences in flame spread and extinction behavior must be taken into consideration when analyzing the results of Earth-based flammability tests.

3.6 Acknowledgments

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4 The Effect of Buoyancy on Flame Spread Rate Over PMMA Cylinders

4.1 Introduction

Fire accidents may occur in any environment where heat sources, oxygen and fuel combine, and they pose a great threat to human life and structures that support humans. For this reason, virtually every material that goes into building a structure that humans will spend time in, such as buildings, cars, and trains, has undergone flammability tests [17]. When it comes to space habitats, egress is limited or impossible, so fire safety is of key importance. Manned spacecraft often feature elevated oxygen concentrations, low ambient pressures, and low velocity flows in the cabin, which, coupled with the lack of natural convection in microgravity and the overcrowded environment filled with electrical equipment that is prone to overheating, produce a very risky environment [50]. It is therefore especially important to ensure every material brought aboard a spacecraft is considered safe.

Flammability testing was not always prioritized for missions. During the space race the Apollo 1 crew suffered a fatal accident during a launch rehearsal test in which a fire started from an unidentified ignition source, lending the command module lethal within just thirty seconds. The cabin was maintained at 110.3 kPa and pure oxygen during take-off, and the plan was to reduce the pressure to 34.5 kPa once in orbit [12]. Unfortunately, the ambient conditions in the spacecraft created an ideal environment for uninhibited flame spread. Additionally, there was no fire detection system in the vehicle because it was assumed that the astronauts would put out any fire in its developing stages using their drinking water [14]. This catastrophe prompted the prioritization of fire safety in space exploration missions.

Today, every material used in a habitable spacecraft is thoroughly tested and must pass a ground-based flammability test. The primary test used by NASA is called the STD-6001B fire safety standard and was the first flammability test for materials expected to operate in microgravity [19]. Every fuel that is to be brought aboard the spacecraft is cut to a size of 30 cm by 5 cm, placed vertically, and exposed to spacecraft (pressure and oxygen) conditions while an upward flame spread test is conducted [20]. There are two criteria for passing the test: (a) that the flame does not propagate more than 15 cm along the length of any of the tested samples, and (b) that the fuel does not drip onto a piece of paper placed 20 cm below the sample, thereby igniting a spot fire. Although this test has been widely used for decades, it has a major limitation due to its binary nature: it does not reveal the fuel's flammability limits, so additional tests must be conducted for each new oxygen concentration or pressure that the cabin might have. [21, 22]

Several researchers have devoted their efforts to studying the behavior of and developing rigorous testing methods for the flammability of solid combustible fuels. Williams presents a comprehensive overview of flame spread processes, underlining the fundamental equation of flame spread and dominant spread mechanisms [48]. It is emphasized that the dominant mechanism in downward flame spread over PMMA slabs is gas-phase conductive heat transfer from the flame to the unburned material ahead of the flame front. Link et al. [92] investigated the effect of gravity on flame spread over PMMA cylinders under low opposed-flow velocities, variable oxygen concentrations, as well as variable sample thicknesses. Upon comparing ISS-based data and ground experiment data, they discovered that the difference in flame spread rate arises at low flow velocities due to buoyancy effects. The upward buoyant flow overpowers the opposed flow in normal gravity conditions, rendering the flame spread rate invariant to low flow velocities. The primary difference between microgravity and earth fires is buoyancy. [93] conducted experiments with PMMA rods under reduced ambient pressures and variable oxygen concentrations to study the effect of buoyancy on opposed flame spread behavior. The study revealed that the flame spread rate is slower at lower ambient pressures. The authors correlate experimental data in both gravity environments with previously developed theoretical models of opposed flame spread, revealing that normal gravity results align well with the models, whereas microgravity data shows discrepancies, potentially due to a difference in flow properties due to the lack of buoyancy.

The present work seeks to explore the influence of buoyancy on opposed flow flame spread rate, and combine it with the effects of pressure and oxygen concentration. In order to isolate the buoyancy, experiments are conducted in the microgravity environment aboard the International Space Station (ISS) and compared with results from identical experiments conducted in a laboratory on Earth. Of primary interest are the changes in flame spread rate under a changing oxygen concentration, with most attention paid to the extinction process as the flame is quenched by an oxygen lean gas mixture in the two gravity limits. For this reason, the ambient gas at the beginning of all experiments is air (21% oxygen), and the oxygen concentration is allowed to decay naturally as the sample burns. Furthermore, the pressures used in the experiments were 40-100 kPa, which is within the range of pressures used for habitable spacecraft cabins. There is an upward forced flow of 10 cm/s past the sample, which is equivalent to the flow rate in the ISS from the Environmental Control and Life Support system. Therefore, on Earth the samples are exposed to an upward mixed velocity opposed flow, whereas in microgravity there is only forced flow. This investigation aims to validate the safety of Earth-based flammability standards for materials intended for spacecraft use.

4.2 Methodology

Earth gravity experiments were performed using a laboratory scale combustion tunnel with dimensions of 125 mm x 125 mm x 600 mm, placed inside a 105 L pressure chamber that allows for active control of reduced pressure conditions, achieved using a high-capacity vacuum pump at the outlet (Welch DuoSeal 1376) and continuously monitored using an electronic pressure transducer (Omega Engineering, Inc. PX309-015A5V). The setup is the same as that visualized in Fig. 12. An upward forced flow of 10 cm/s was produced by a fan placed below the test section, which recirculates gases from the chamber to mimic the airflow induced by the Environmental Control and Life Support System (ECLSS) of a spacecraft. This flow velocity was characterized under cold flow conditions using a hot wire anemometer. Besides the forced convective flow, experiments at normal gravity also experienced free convection on the order of 30 cm/s due to the flame induced buoyant flow [87].

Microgravity testing was conducted in a similar configuration aboard the International Space Station (ISS), utilizing the Combustion Integrated Rack (CIR), which houses a 100 L combustion chamber. Located within this chamber, the SoFIE insert encloses the Material Ignition and Suppression Test (SoFIE/MIST) apparatus, where controlled combustion of the samples was carried out. Consistent with the ground combustion chamber, the MIST apparatus included inlets to allow the addition of oxygen and nitrogen gas into the test section and an outlet connected to a vacuum pump. To induce an opposed forced flow with a velocity of 10 cm/s, a fan was placed at one end of the test section, below the sample, helping to recirculate gases. Contrary to normal gravity experiments, the flame was only exposed to forced flow during microgravity testing.

The fuel used for this study is polymethyl methacrylate (PMMA), which is frequently used in flammability research because it has well-defined characteristics in the literature. In addition to its extensive applications on Earth, PMMA is also commonly featured in critical aerospace components such as airplane windows and is being considered for future spacecraft viewing ports. The samples used in all tests were 55 mm long cylinders with a diameter of 12.7 mm, made of black cast PMMA that maximizes the absorbance of thermal radiation at the surface of the sample. The sample was mounted vertically at the center of the test section and ignited using a coil-shaped NiCr ignition wire positioned just above the sample. The ignition wire was heated by a current passing through it with a variable transformer (STACO Energy model 3PN1210B), igniting the sample tip. The entire combustion sequence, including ignition, flame spread, and extinction, was video recorded through the chamber windows with a digital camera, under both gravity conditions.

To initiate an experiment, the pressure chamber was filled with air to achieve the desired ambient pressure, ranging from 40 kPa to 100 kPa in increments of 20 kPa. Just before

ignition, all gas inlets and outlets were turned off. Then, the ignition wire was energized, igniting the sample, which then burned and naturally consumed the available oxygen in the chamber. In all tests, the flame eventually stopped spreading along the sample’s surface and regressed into its core, shrinking to a blue hemisphere at the tip of the burning sample, and flickering with increasing intensity until extinction. To maintain a constant ambient pressure during each test, the chamber was occasionally vented to mitigate the pressure rise caused by the combustion process [54]. The volume fraction of oxygen in the chamber was recorded at a frequency of 1 Hz with an FDO2 optical gas sensor (PyroScience GmbH). A Sony RX10-III camera with a resolution of 1920 by 1080 pixels at 30 frames per second was used to record each experiment from the front of the sample. The videos were processed using an internally developed program called the FlameTracker, which tracks the location of the flame front frame by frame using Python-based image analysis, which is then used to calculate the flame spread rate [94].

4.3 Results

In both microgravity and earth gravity, experiments were carried out at pressures of 40 kPa, 60 kPa, 80 kPa, and 100 kPa. The sample was ignited and allowed to burn within the sealed chamber as the oxygen concentration naturally depleted due to the combustion of the fuel. At the beginning of each experiment, the flame was large and bright, but as the mole fraction of oxygen depleted, the flame length became shorter and the combustion was more complete, indicated by a blue flame. Tracking the flame front over the duration of each experiment revealed the two phases of flame propagation proposed by Rivera et al. [83]: flame spread and flame regression. The flame spread phase is characterized by a rapid combustion of the fuel’s outer surface, in which the flame front propagates in the direction opposite the forced flow, in this counter-current arrangement. In contrast, flame regression is observed near extinction, marked by the radially inward consumption of fuel, while the flame spreads in the same direction as the flow. In the experiment depicted in Fig. 20, which was conducted under an ambient pressure of 100 kPa and normal gravity, the transition from the spread phase to the regression phase occurs approximately 3 minutes after the start of the test. In the first three minutes of the burn, the flame spreads downwards, in the g direction, whereas from minute 4 until extinction, the flame retreats up the sample in the $-g$ direction, and the cone that had previously formed on the sample tip begins being flattened out.

The flame spread and regression phases can be distinguished with ease from a plot of the position data over time. Fig. 21 depicts the location of the flame front through the duration of experiments conducted at 100 kPa in both normal and microgravity. In the figure, the colored curves are smoothed, while the grey dots are the original data. The smoothed data was not used for the calculation of the flame spread rates or in any other figures in this

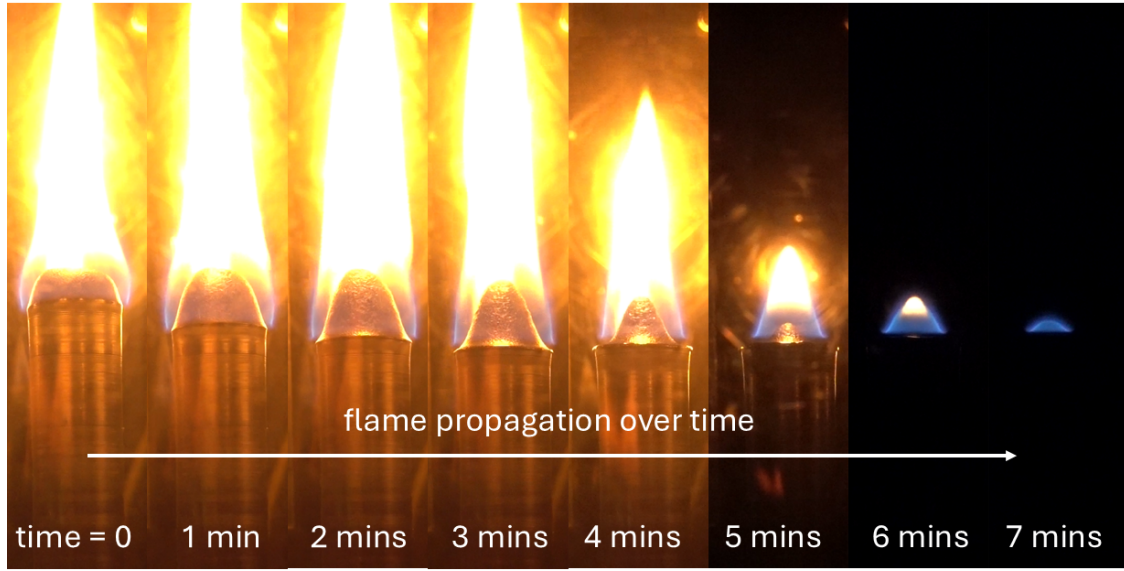


Figure 20: Collage of flame propagation over time at 100 kPa in normal gravity, and under a depleting oxygen concentration. A similar collage of microgravity experiments is shown in Fig. A.4 in A.

work, but it helpful for describing the flame spread and regression phases in this case. The apex of the curves corresponds to the transition from spreading phase to regression. Results show that the curves of flame front position over time for microgravity and normal gravity follow a similar trend during the spread phase, but differ significantly in the regression phase. In the absence of buoyancy, the flame front initially regresses slowly but speeds up approaching extinction, following a concave curve. On the other hand, on Earth the flame initially retreats quickly and slows down just before extinction, which traces a convex shape. For this reason, this work distinguishes the two flaming regions to analyze them separately, noting the commonalities in the flame spread rate (FSR) and differences in the regression rate between the two gravity conditions, and under all pressures tested.

Once the flame spread and regression regions have been identified for each experiment, a second order polynomial curve is fit to each region, ensuring that the fit describes the original experimental data appropriately ($R^2 \geq 0.94$). An example of this fit can be found in A.3, where it can be seen that the polynomial effectively smooths the position data. The derivative of the polynomial with respect to time is the FSR. It was found that following this analytical process, as opposed to taking a numerical derivative, resulted in flame spread rates that were not as sensitive to small environmental disturbances, and therefore less noisy.

The FSR of the spreading phase is tracked over time for experiments of all pressures and

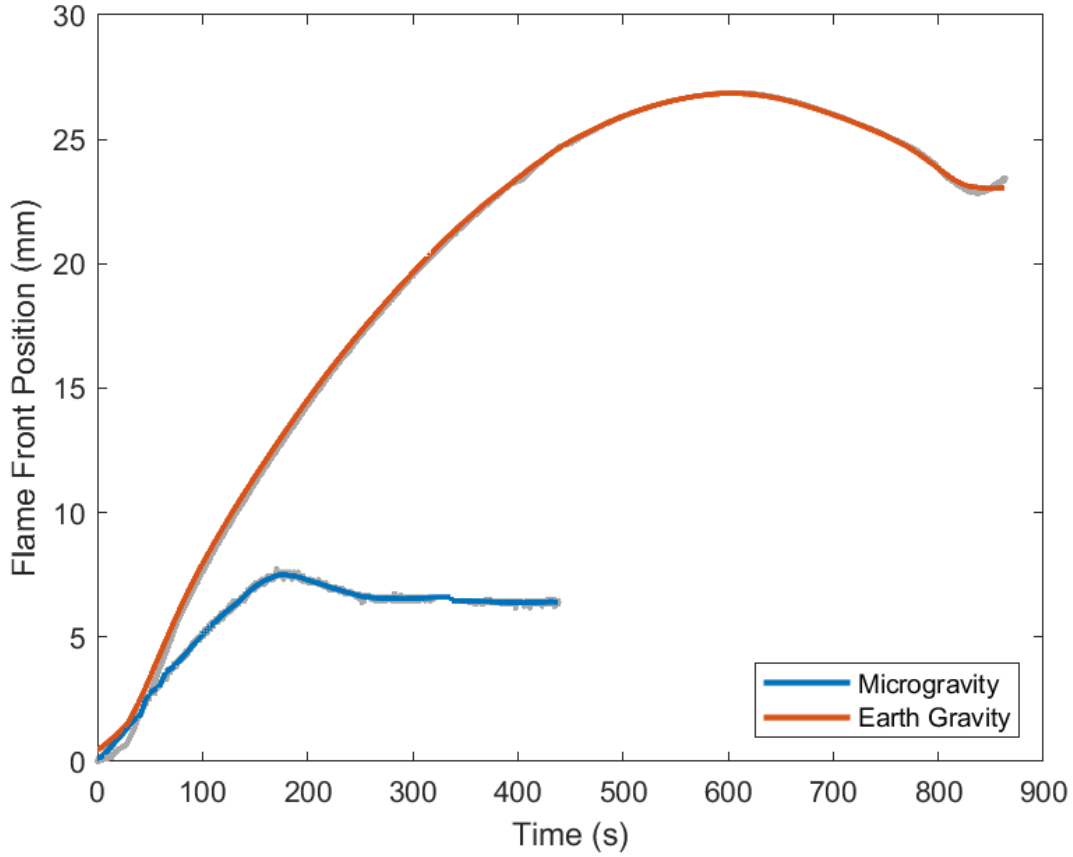


Figure 21: Plot of flame position over time at 100 kPa in microgravity and normal gravity.

both gravity levels, and the results are presented in Figs. 22 and 23. It is seen that the flame spread rate decreases with decreasing ambient pressure, consistent with other works in the literature [28, 30]. This finding suggests that fire may be less dangerous at low pressures because the flames propagate slower, and can be explained by the decreased gas density at low pressures, which causes the flame standoff distance to increase, and in turn slows down the rate of convective heat transfer from the flame to the unburned fuel.

For each given pressure, the spread rates in microgravity and Earth gravity follow the same trend: initially the flame is spreading quickly in the oxygen-rich environment, but the spread rate linearly decreases over time as the flame front approaches the transition to regression, as seen in the right sides of Figs. 22 and 23. Additionally, the maximum FSR appears to be unaffected by the presence or absence of buoyancy. At least for the pressures tested in both gravity conditions, in experiments at similar pressures the maximum FSRs were all within 0.01 mm/s of each other. Instead, reducing the buoyancy lengthened the duration of the experiment and the amount of fuel consumed. Within the pressures that were tested

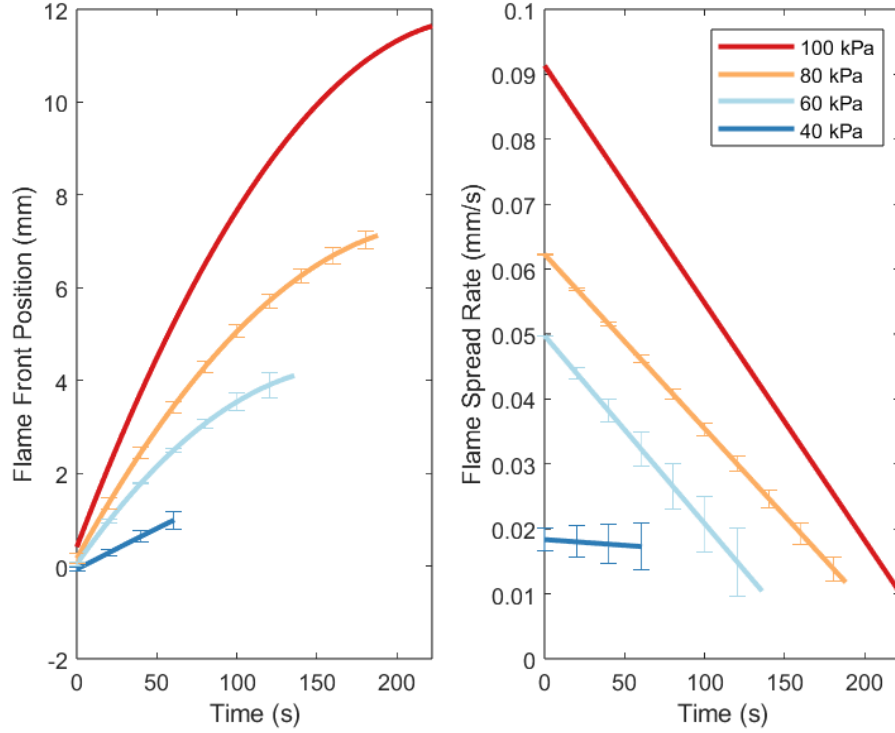


Figure 22: Spread phase position and flame spread rate over time at normal gravity, under four pressures.

both in normal gravity and microgravity, it appears that regarding both the duration of the experiment and the amount of fuel consumed, the effect of microgravity was more evident when the ambient pressure was highest.

Due to the steadily decreasing oxygen mole fraction in the combustion chamber, it is incorrect to assume that the microgravity and Earth gravity flames were exposed to the same amount of oxygen at any given time in Fig. 22. Therefore, it is necessary to characterize the flame spread rate with the oxygen concentration, pairing the time-dependent spread rate with the corresponding measured oxygen concentration at that time.

The results of flame spread rate with oxygen concentration are displayed in Fig. 24. The left plot shows the microgravity data and the plot on the right has the normal gravity data. Some microgravity experiments were started at oxygen concentrations lower than 21% to ensure that low oxygen extinction limits are reached before the entire fuel ignites. Conversely, earth gravity fuels at very low pressures, namely 40 kPa and 60 kPa, had to be ignited at

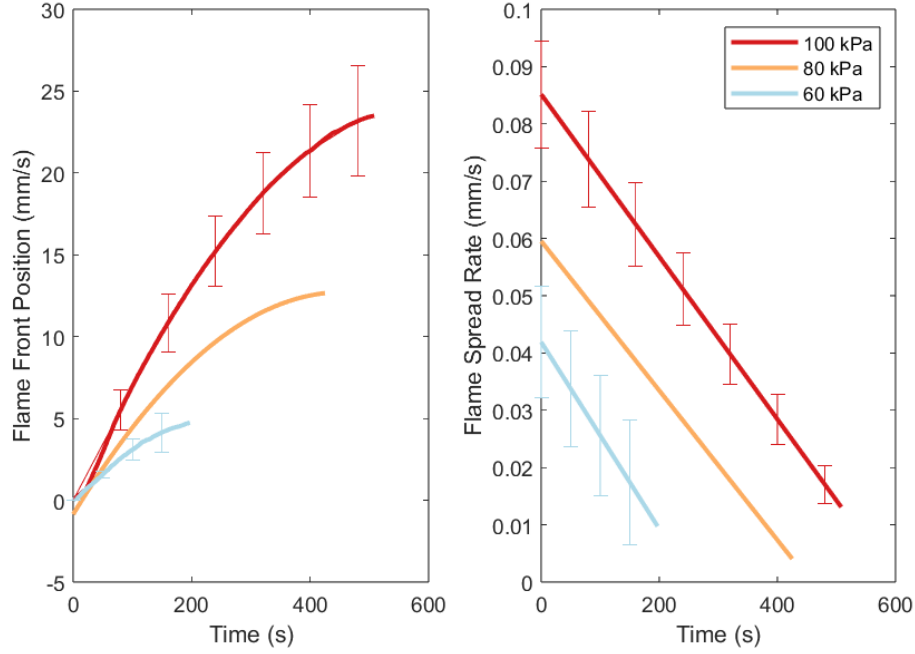


Figure 23: Spread phase position and flame spread rate over time in microgravity, under three pressures.

elevated oxygen concentrations in order to avoid instant flame extinction. The error bars in the figure depict the standard deviation of the oxygen volume fraction and flame spread rate data. Because there are thousands of data points, only a few error bars are displayed so as not to overcrowd the figure. As was observed in Figs. 22 and 23, the initial flame spread rates appear to be independent of gravity, showing a strong correlation with pressure instead. Additionally, it has been shown that the limiting oxygen concentration is much lower in microgravity compared to Earth gravity [87, 83, 95]. This difference in oxygen concentrations is evident even during the flame spread phase, as the transition from flame spread to flame regression occurs at an oxygen volume fraction that is approximately 3% lower in microgravity compared to normal gravity. Earth gravity flames are subject to a mixed flow, due to the 10 cm/s forced flow, and the flame induced buoyant convective flow which is on the order of 30 cm/s. On the other hand, experiments in space experience only the forced flow. It has been shown that a small opposed flow can help mix the gasified fuel with oxygen in the pyrolysis zone, enabling flame spread, whereas high flow rates reduce the flame heat release rate [63, 85, 86, 77].

Fig. 25 compares the differences in microgravity and normal gravity flame behavior in the regression phase for experiments conducted at 100 kPa. The flame is accelerating in micro-

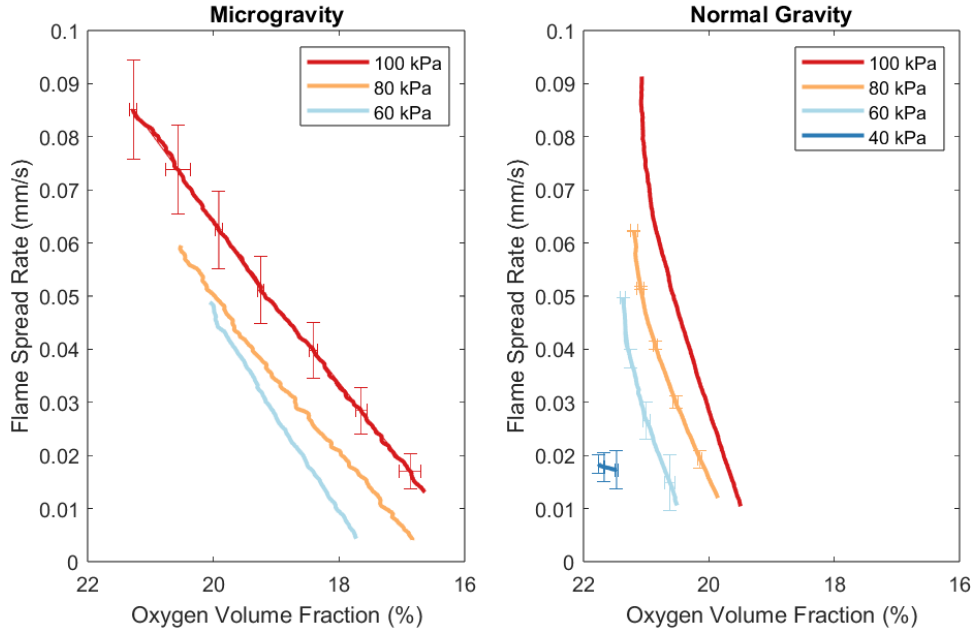


Figure 24: Flame spread rate over the depleting oxygen in microgravity (left) and normal gravity (right) for ambient pressures tested.

gravity, whereas in normal gravity the flame is decelerating, slowing down before extinction. Before extinction, the microgravity flame starts flickering, with the flame front expanding as if to entrap enough oxygen in order to sustain combustion, but eventually experiences blow off extinction. Conversely, in Earth gravity the coupled effect of the forced flow and buoyant flow allows the air in the chamber to mix, bringing oxygen molecules into the pyrolysis region. The gasified fuel burns slowly, with the spread rate decreasing and the flame gradually reducing in size, and eventually quenching due to the oxygen lean gas mixture.

4.4 Discussion

The flammability of solid combustible materials is affected by several environmental parameters, such as ambient pressure and gravity. The two are inherently related, as reducing the ambient pressure has the effect of approximately simulating microgravity opposed flow flame spread [93]. In this work, experimental results reveal a stark difference in flame behavior and characteristics of flame spread between microgravity and normal gravity conditions. In an Earth gravity environment, gravity-induced buoyancy forces generate strong upward convective currents that fundamentally alter the flame structure and dynamics. They cause the flame length to increase, but also convectively cool the gasified fuel in the pyrolysis region, slowing the rate of combustion. Conversely, in microgravity conditions, the lack of buoyant

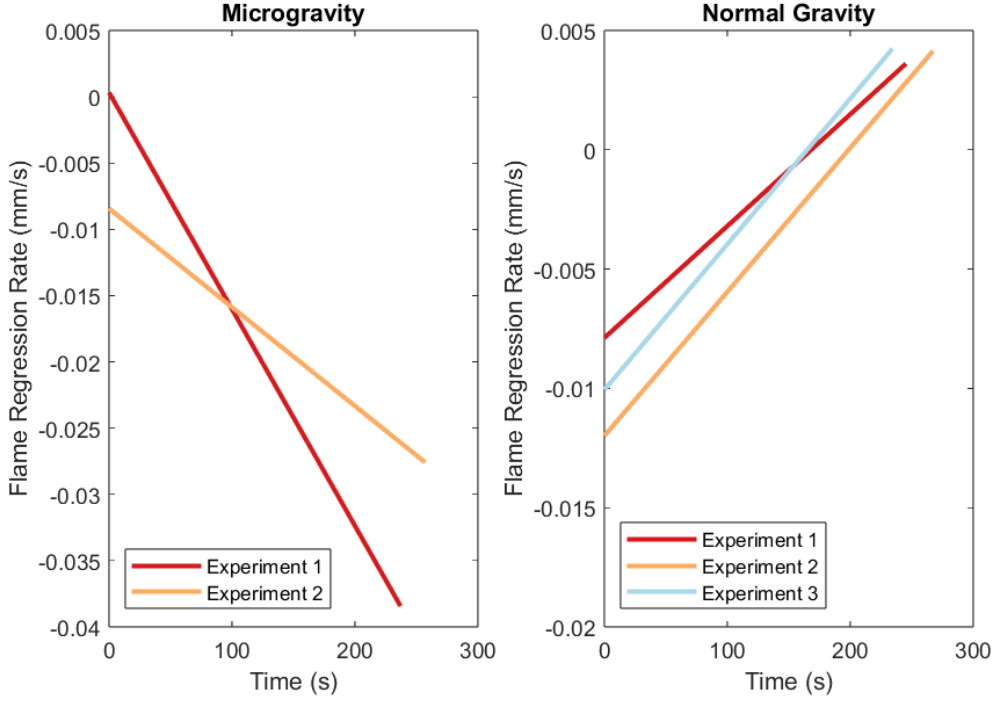


Figure 25: Flame regression rate for all experiments at 100 kPa, in microgravity (left) and Earth gravity (right).

convection causes the flames to be smaller, exhibiting a blue hue which indicates reduced soot formation. This occurs because, with a very low ambient flow, the oxidizer is able to remain in the pyrolysis region for longer periods of time, allowing for complete combustion of the gasified fuel. The buoyant velocity can be estimated as

$$U_m = g\sqrt{\beta\Delta T l_c} + c \quad (23)$$

where g is the force of gravity and $\beta \approx \frac{1}{T}$ is the volumetric thermal expansion coefficient, l_c is the characteristic length and the constant $c = 10$ cm/s represents the forced flow. Therefore, reducing the force of gravity will in turn reduce the flow velocity, which then affects flame spread due to the reduced oxidizer residence time near the pyrolysis region.

Flame spread over a solid fuel can be described as a series of ignition steps, in which the flame acts as an ignition pilot that preheats the unburned fuel until it pyrolyzes. This successive process drives flame spread. In order to further understand the effects of pressure and oxygen on flame spread, it is important to analyze the effects of chemical kinetics in the flame and associated mass and heat transfer mechanisms involved [87, 30].

For a single step chemical reaction, the reaction rate q_r is expressed as

$$q_r = A_0 \exp \left(-\frac{E_a}{RT_f} \right) [Fuel]^a [O_2]^b \quad (24)$$

$$q_r = A_0 \exp \left(-\frac{E_a}{RT_f} \right) X_F^a X_O^b \left(\frac{P}{R_u T_f} \right)^{a+b} \quad (25)$$

where A_0 is the pre-exponential factor, E_a is the activation energy, R is the universal gas constant, T_f the flame temperature, X_F is the mole fraction of fuel and X_O the volume fraction of oxygen, and P is the ambient pressure. Therefore, the reaction rate is proportional to both the pressure and oxygen concentration, and for a first order reaction, $a = b = 1$. Applying this to Eqn. 25, $q_r \propto X_O \cdot P^2$, which implies that both the oxygen concentration and the ambient pressure have a positive relationship with the rate of the chemical reaction. Decreasing either the volume fraction of oxygen or the ambient pressure slows down the flame spread rate along the length of the sample by slowing down the reaction rate.

The chemical reaction rate and mean flow velocity work together to affect the rate flame spread, as described in the mathematical expression for flame spread rate over a thermally thick rod [77]

$$V_f = Fl_c \left[\frac{C_1 \rho_s c_s k_s (T_p - T_0)^2}{q''^2} - D \right]^{-1} \quad (26)$$

where F is a geometrical conversion between a flat and a cylindrical shape [77], C_1 is a constant related to the solid ignition time, ρ_s , c_s , and k_s are the solid density, specific heat, and thermal conductivity, and T_p and T_0 are the solid pyrolysis and initial temperatures. The net heat flux from the flame is $q'' = q''_{f,cond} + q''_{f,conv} + q''_{f,rad} - q''_{s,re-rad}$, where $q''_{f,cond}$ is the heat conducted ahead of the flame, $q''_{f,conv}$ the convective heat flux from the flame to the solid, $q''_{f,rad}$ is the flame radiant flux, and $q''_{s,re-rad}$ is the re-radiation from the solid surface. In the second term, $D = C_2 \frac{1}{t_{fl}} \ln(1 - Da_{cr}/Da)$, with C_2 being a constant related to the ignition time of the gas, t_{fl} the flow time, Da_{cr} the critical Damkohler number for extinction, and Da being the Damkohler number at the given conditions. The flame velocity equation can then be re-written as follows.

$$V_f = Fl_c \left[\frac{C_1 \rho_s c_s k_s (T_p - T_0)^2}{(q''_{f,conv} + q''_{f,cond} + q''_{f,rad} - q''_{s,re-rad})^2} - C_2 \frac{1}{t_{fl}} \ln(1 - Da_{cr}/Da) \right]^{-1} \quad (27)$$

Within the velocity term of Eqn. 27, the effects of gravity and pressure show up within the Damkohler number, Da . $Da = \frac{t_{fl}}{t_{ch}}$ is the ratio of the flow time to the chemical time,

and for a convection-dominant flow, $t_{fl} = \frac{l_c}{U_m}$, where U_m is the mean flow velocity. With $t_{ch} = \rho/q_r$, $Da = \frac{l_c/U_m}{\rho/q_r} = \frac{l_c}{U_m} \frac{q_r}{\rho}$. As discussed previously, reducing the ambient pressure or oxygen concentration will lead to a slower reaction rate, which causes the Damkohler number to decrease for both normal and microgravity. The effect of gravity shows up in the flow velocity term, and reducing the gravity will serve to increase the Damkohler number. This is a primary difference in microgravity versus normal gravity flame spread and extinction. The low pressure and oxygen experiments in Earth gravity give a decreased Damkohler number, meaning that the chemical time is increasing relative to the flow time and the flame dynamics are more impacted by the chemical kinetics than the heat transfer processes. This result is validated experimentally, as shown in Fig. 25, where microgravity flames extinguished with a larger absolute flame spread rate (blowoff extinction) while normal gravity flames extinguished when their spread rate was approximately $0mm/s$ (quenching extinction). The microgravity flames are extinguished via blowoff, because their increased Damkohler number implies that the residence time is slow and the oxidizer availability is compromised, characterized by a weak flame that flickers as it attempts to entrap more oxygen molecules just before extinction [22]. On the other hand, at normal gravity the Damkohler number is decreased and the oxidizer is not available for long enough to mix with the fuel so the flame extinguishes. The combination of variables in the experimental procedure affects the Damkohler number in competing ways: at the beginning of an experiment, $Da_{\mu g} > Da_{1g}$, but as the oxygen volume fraction depletes, $Da_{\mu g}$ decreases and begins to also approach the chemical regime. This was seen in the experiments as the microgravity flames became dimmer and shrank in size slowly, but also experienced flickering for some seconds before extinction.

4.5 Conclusion

This work investigates the effect of gravity on the flame spread rate over PMMA cylinders under sub-atmospheric ambient pressures and an opposed flow with a depleting oxygen volume fraction. The results show that the flame spread rate has a strong correlation with pressure, with the flame propagating slower at lower pressures. This is explained by the decreased rate of heat transfer from the flame to the unburned solid due to the widened thermal boundary layer at low pressures.

Gravity did not appear to have a noticeable effect on the flame spread rate, particularly within the spreading phase. The maximum flame spread rate was the same at a given pressure condition in both normal and microgravity. However, the spread phase of microgravity experiments lasted twice as long compared to Earth gravity, meaning the flame decelerated much faster on Earth. In the regression phase, Earth flames continued decelerating until quenching extinction, whereas microgravity flames accelerated in the opposite direc-

tion and extinguished due to blow off. These extinction patterns are predicted theoretically through the Damkohler number terms in an equation describing the flame velocity: the low pressure and oxygen volume fraction on Earth cause the Damkohler number to decrease meaning that the combustion process is more impacted by the chemical kinetics than the heat transfer processes. On the other hand, reducing the gravity serves to increase the Damkohler number, exhibited by a slow residence time and a compromised oxidizer entrainment process.

The results of this work highlight that there are significant differences between combustion in normal gravity and microgravity. Microgravity flames can be sustained at oxygen concentrations much lower than on Earth [87], propagate over the fuel as quickly as they would on Earth, but burn for twice as long. For this reason, it is imperative that more research is conducted on the flammability tests that are conducted on Earth for materials that are intended for use aboard spacecraft.

4.6 Acknowledgments

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5 Upward Flame Spread over a 0.1 mm Thick PMMA Sheet in Normoxic Atmospheres

5.1 Introduction

Ensuring material fire safety onboard spacecraft is a concern for current and future space missions, as the interplay of various parameters significantly impacts the well-being of astronauts [49, 17]. Flame spread rate and heat release rate are key parameters to determine the flammability of a material. Factors that affect these parameters include the pressure, oxygen concentration, gas flow velocity, and gravity level. In environments characterized by low pressure, such as those found in aircraft, spacecraft, and high-altitude locations, the flame exhibits a tendency to move away from the burning surface [32]. This reduces the rate of convective heat transfer from the flame to the combustible solid, consequently impeding the flame spread rate. Elevated oxygen concentrations result in an increased flame propagation rate primarily due to an increase in the flame temperature [35]. Given that combustion is guided by a series of ignition steps, as the temperature of the flame increases, the time required to heat, pyrolyze, and ignite the solid fuel decreases as the oxygen concentration is increased. In concurrent flame spread, as is the case in this work, as the flow velocity is increased the flame spread rate is increased because the stand-off distance between flame and solid decreases [77]. In the presence of gravity, there are flame-induced buoyant flows opposite to the gravity, with velocities that decrease as the gravity level is decreased, resulting in a larger distance between flame and fuel surface. Thus, reducing gravity has a similar effect on the concurrent flame spread as reducing the ambient pressure [31].

This work analyzes how the upward flame spread rate and heat release rate of thin acrylic samples of polymethyl methacrylate (PMMA) are affected by the ambient pressure and oxygen concentration in normoxic atmospheres. Thin samples of thickness 0.1 mm were selected to explore the behavior of thermally thin fuels at ambient pressure from 80 kPa to 100 kPa. The oxygen concentrations used are selected according to the normoxic atmosphere, that combines the ambient pressure with a corresponding volume oxygen fraction such that the partial pressure of oxygen is always $PO_2 = 21$ kPa (the same as that of normal atmosphere at sea level), as indicated in Fig. 6 [96, 97].

The goal of this paper is to add insight into the flammability of thermally thin fuels under normoxic conditions. This project has been designed to study spacecraft environments, therefore, the pressure and oxygen conditions are selected to specifically follow the normoxic curve shown in Fig. 6. However, the knowledge gained from this study may be applicable to other low pressure environments, such as aircraft, and future work should study further changes in pressure and oxygen volume fraction. The flame spread rate and heat release rate are analyzed at different conditions along the normoxic curve to find a direct link between the pressure, oxygen, and combustion characteristics, and hopefully provide insight into how

to estimate the flame spread rate and heat release rate in cases where it would not be possible to measure these conditions directly.

5.2 Methodology

A laboratory scale combustion tunnel is placed inside a pressure chamber that allows for control of ambient conditions at which the sample is tested. The combustion tunnel is of dimensions 125 mm x 125 mm x 600 mm and has an inlet at the bottom. The first 350 mm of the tunnel are dedicated to straightening the gas flow with glass beads and an aluminum honeycomb mesh, whereas the other 250 mm serve as the test section. The pressure chamber has a volume of 105 L and is equipped with a flow system that allows for a constant, controlled supply and exhaust of gases via critical nozzles from O’Keefe Controls and a high capacity vacuum pump (Welch DuoSeal 1376), respectively. The pressure inside the chamber is monitored in real time with a pressure transducer (Omega Engineering, Inc. PX309-015A5V).

The upward forced flow velocity is fixed to 20 cm/s in all the tests, a value which mimics the airflow induced by the Environmental Control and Life Support System (ECLSS) of a spacecraft. Additionally, since the experiments are performed in normal gravity conditions, the flame is also exposed to a self-induced buoyant flow of the order of 0.2-0.5 m/s in addition to the forced flow, meaning that there is a mixed (free and forced) flow condition.

The oxygen concentration is recorded using an optical oxygen meter from PyroScience GmbH, which measures the partial pressure of oxygen and the ambient pressure in order to calculate the volume fraction of oxygen. The sensor probe is placed on the outlet line downstream of the vacuum pump where the post-combustion flow has been properly mixed. Given that the oxygen concentration inside the combustion tunnel is known, this oxygen meter allows us to monitor the oxygen consumption during an experiment. The fuel samples used are cast PMMA sheets of thickness 0.1 mm, supplied from McMaster Carr. The samples are secured within two flat stainless steel frames that are 0.6 mm thick and which have a rectangular opening of 150 mm length by 50 mm width. This opening serves as our testing area and is placed in the mid-plane of the test section, centering the sample. The samples are ignited from the bottom (concurrent spread) with 26-gauge Kanthal igniter wire which is quickly energized with 50 W using a controlled current power supply (BK Precision 1785) until the sample ignites on both sides, which takes on average 3 seconds. The sample is allowed to burn until the entire testing region fuel is consumed, and at the end of the experiment the system is flooded with nitrogen gas to extinguish the flame.

Two cameras are used to video record the experiments. A Sony RX10-III camera with a

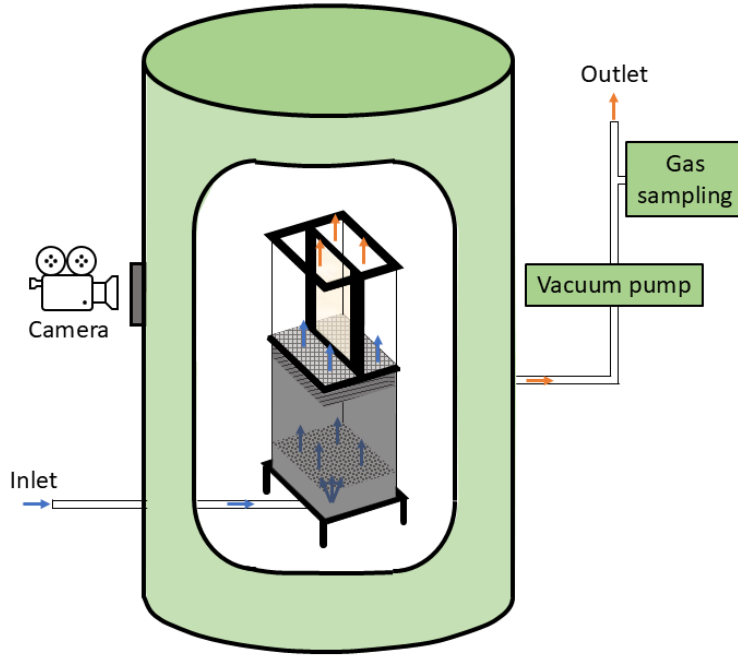


Figure 26: Experimental Setup depicting the test section with the sample inside.

resolution of 1920 by 1080 pixels at 30 frames per second is used to record the front view, and a Nikon D3200 camera of the sample resolution and frame rate is used for the flame side view. The settings for each camera have been selected to optimize the image of the flame at each frame and remain constant throughout the experiments. These videos are processed on an internally developed program called the Flame Tracker which tracks characteristics of the flame on a frame-by-frame basis using Python-based image analysis to separate the flame from the background [94].

An experiment begins by recording the initial mass of the sample on a Radwag WTC 2000 precision balance, and fixing the inlet and outlet gases of the chamber such that the pressure, oxygen concentration, and gas flow rate are at the testing values. The two cameras begin recording, and the igniter wire is switched on until both faces of the PMMA samples have ignited. At the end of the experiment, the final mass of the sample is measured again to be used for the heat release rate calculations.

5.3 Results

Fig. 27 shows the upward propagation of the flame along a PMMA sample over time at atmospheric conditions. Two different regions can be noted through these images. The first

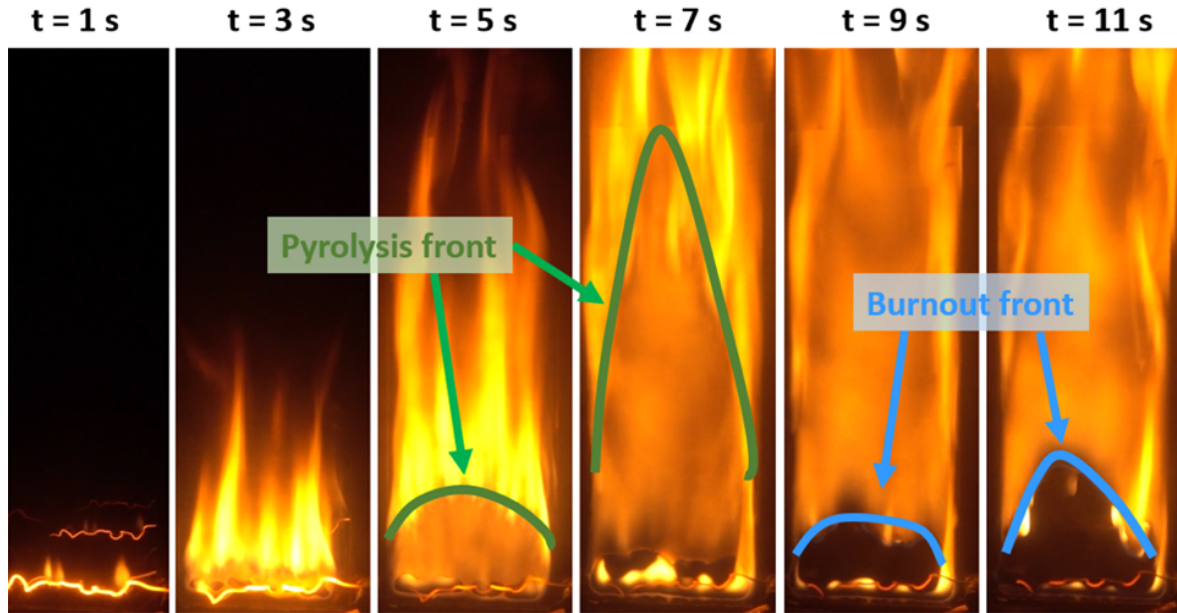


Figure 27: Image sequence showing the flame spread over time at 100 kPa, 21% oxygen by volume conditions.

is the pyrolysis front, which refers to the front of the region created by PMMA pyrolyzing and vapor jetting. The pyrolysis front propagates slowly compared to the flame length that is generated by the gas phase combustion of the pyrolyzate. The second notable region is the burnout front, which is a boundary created by the consumed sample, and it propagates upwards as the PMMA gasifies. The pyrolysis and burnout fronts both trace out an arc, but as can be seen at $t = 5$ s and $t = 9$ s the slope of each arc is initially small but then it gets steeper as the experiment progresses. This behavior is due to air entrainment and heat lost to the metallic sample holder at the edges of the sample causing the center of the flame to propagate faster. The pyrolysis front was reliably imaged for all the experiments. A similar strategy for tracing the pyrolysis front was used by Carmignani et al. [32]. The flames in Fig. 27 and all tests visually appear laminar for the majority of the sample length with some wrinkling occurring due to deformation of the sample during burning. Some transition to turbulence is observed at the tip of the flames, but almost exclusively above the pyrolysis front.

Figs. 28 and 29 show the progression over time of the flame at a pressure of 90 kPa and 23.2% oxygen concentration as well as 80 kPa pressure and 26.2% oxygen volume fraction. Fig. 27 can be qualitatively compared with Figs. 28 and 29 to examine how the flame responds to the ambient conditions along the normoxic curve. The flame appears brightest and largest at normoxic reduced ambient pressures, and it also spreads over the sample faster. This is

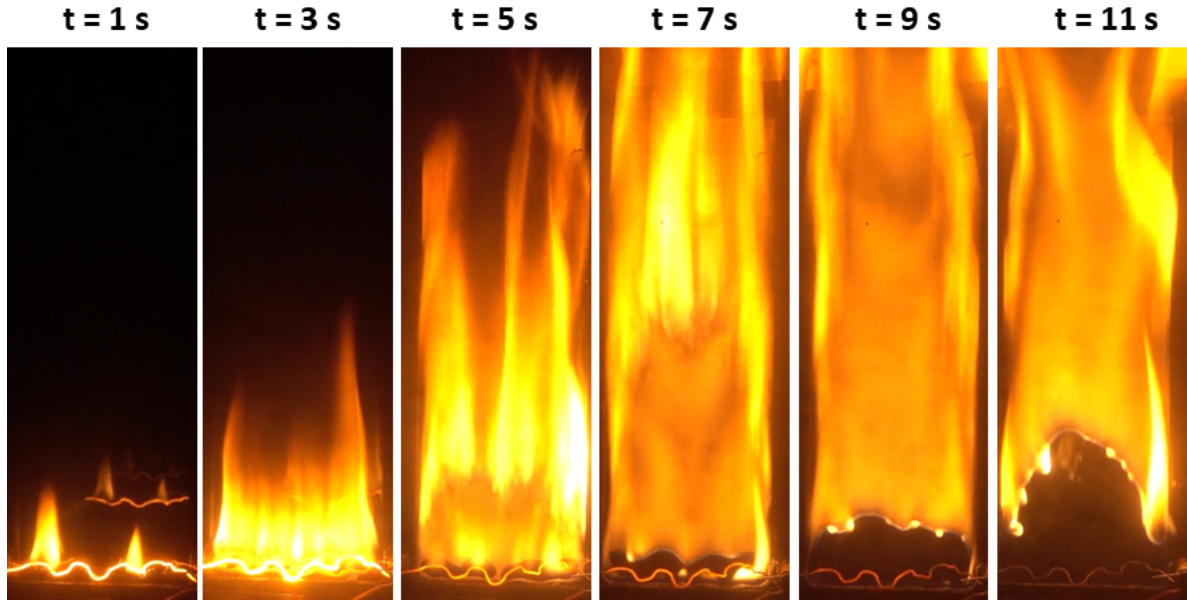


Figure 28: Flame spread over time at 90 kPa 23.2% oxygen by volume.

in agreement with the observations of Thomsen et al. who show that the increased oxygen concentration counteracts the deterring effect on the flame spread of the reduced pressure [98]. The boundary of the pyrolysis front is not outlined in Figs. 28 and 29 so the viewer can observe it unobstructed.

Experiments are limited to pressures higher than 80 kPa due to the risks associated with the higher oxygen environments and hardware limitations. At higher oxygen concentrations, the flame length grows and the temperature of the flame increases to values that cannot be safely accommodated inside the pressure chamber.

The position of the flame tip, pyrolysis front, and burnout front are tracked for every frame of each experiment using the Flame Tracker. As mentioned earlier, the edge effects on the left and right sides of the sample influence the flame characteristics, so samples are tracked only along their vertical centerlines. The pyrolysis and burnout spread rates are fairly constant for the first half of their spread, but then accelerate towards the upper half of the sample, as evidenced by the fast progress of the pyrolysis front between times $t = 7$ s and $t = 9$ s in Fig. 28. Therefore, a one second snapshot of each condition around the sample's midpoint gives an adequate representation of the spread progress. The averaged positions of flame characteristics for each condition tested are shown in Fig. 30, where 0 mm represents the midpoint of the sample. It can be seen that as the pressure is reduced, and thus the oxygen concentration is increased, the flame, pyrolysis, and burnout fronts all advanced faster. The

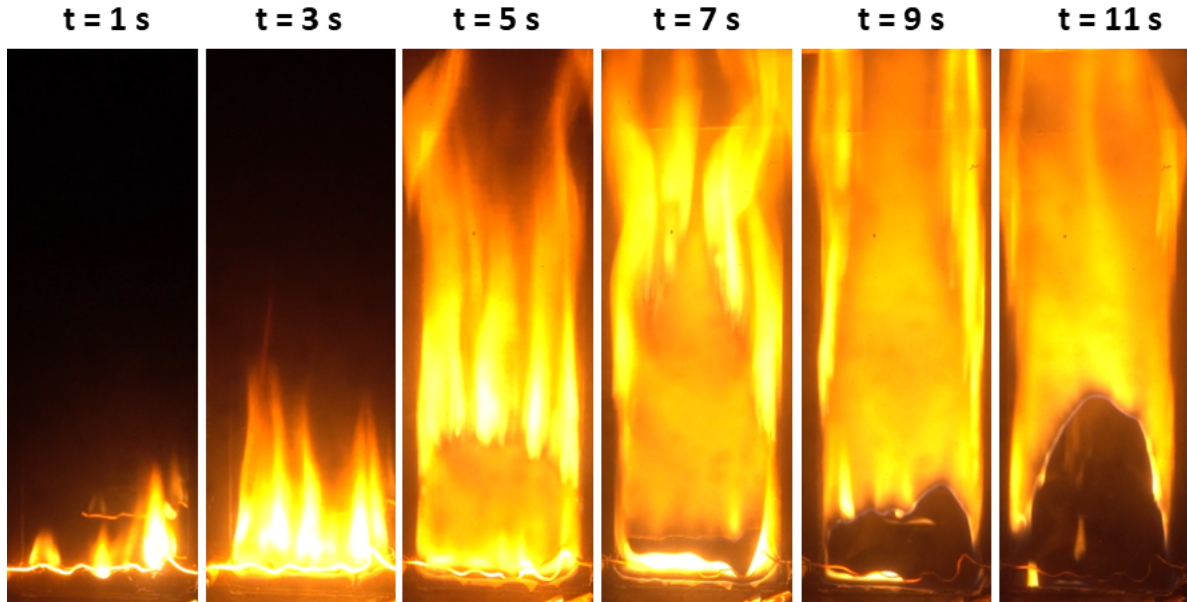


Figure 29: Flame spread over time at 80 kPa 26.2% oxygen by volume.

flame tip progressed the fastest, with only a small difference between each condition tested, whereas the pyrolysis front and burnout front both had a slower spread and a wider gap between the different pressure and oxygen levels. This may be due to decreased oxygen availability during the progression of the pyrolysis front and burnout fronts since much of the oxygen is consumed by the fast spreading flame. Additionally, the pyrolysis and burnout front spread rates are similar at lower pressures. This is likely a result of the competing effects of the increased availability of oxygen and the decreased pressure. The high oxygen volume fraction leads to a greater burning rate, whereas the decreased chamber pressure decreases the rate of convective heat transfer.

The partial pressure of oxygen of the combustion products is measured throughout an experiment, and by matching it with the pressure transducer data and the camera footage, the volume fraction of oxygen is calculated at each second. The results show that during the rapid combustion of the fuel, oxygen is consumed by the flame at a faster rate than is replenished through the inlet of the chamber, so the volume fraction of oxygen decreases until most of the fuel has pyrolyzed and the combustion process slows down (Fig. 31). Interestingly, for each pressure tested, the maximum reduction in oxygen volume fraction was 3%, implying that the oxygen consumption rate remains proportional to the rate of replenishing volume fraction of oxygen at the inlet under normoxic conditions.

Fig. 32 depicts the averaged steady state spread rate along the sample for the flame tip,

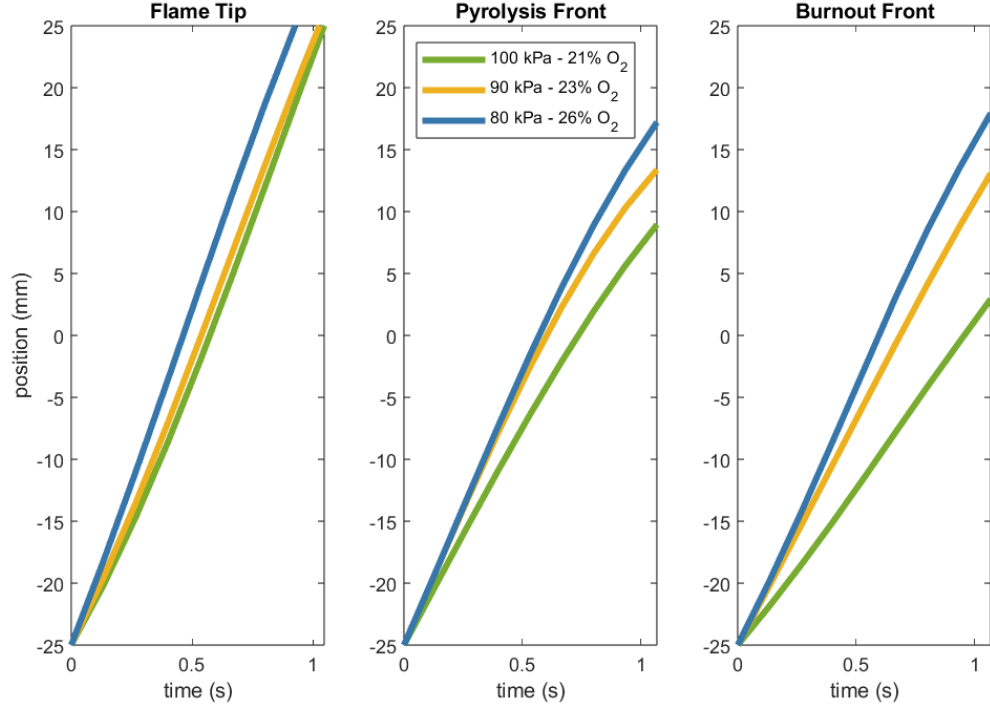


Figure 30: Plots of relative position versus relative time for flame tip, pyrolysis front, and burnout front. Position = 0 mm represents the midpoint of the sample.

pyrolysis front and burnout front for the pressures tested. It is seen that as the pressure is reduced and the oxygen concentration is increased, the spread rate of the three flame locations increases, in agreement with the work of Thomsen et al. which uses cotton samples (included in Fig. 32) [98]. These results indicate that, at normoxic conditions, the increase in oxygen volume fraction has a more important effect on the flame spread rate than the deterrent effect of decreasing the pressure. That is, the increase of the flame temperature as the oxygen volume fraction is increased has a stronger effect on the spread rate than the increase in the flame stand-off distance and decrease of the buoyant velocity as the pressure is decreased.

From Fig. 32 it is seen that the pressure dependence on flame spread rate is stronger for the burnout front than the pyrolysis and flame tip fronts. The relationship between flame velocity and ambient pressure at normoxic conditions is retrieved from the experimental data. The pressure dependence on the flame spread rate of each part of the flame for PMMA is unique, with the flame tip velocity surpassing that of the pyrolysis front by a factor of pressure, and similarly the pyrolysis front velocity is a factor of pressure faster than the burnout front velocity. However for cotton, the relationship was the same for the pyrolysis and burnout fronts, and was very similar to that of the flame base.

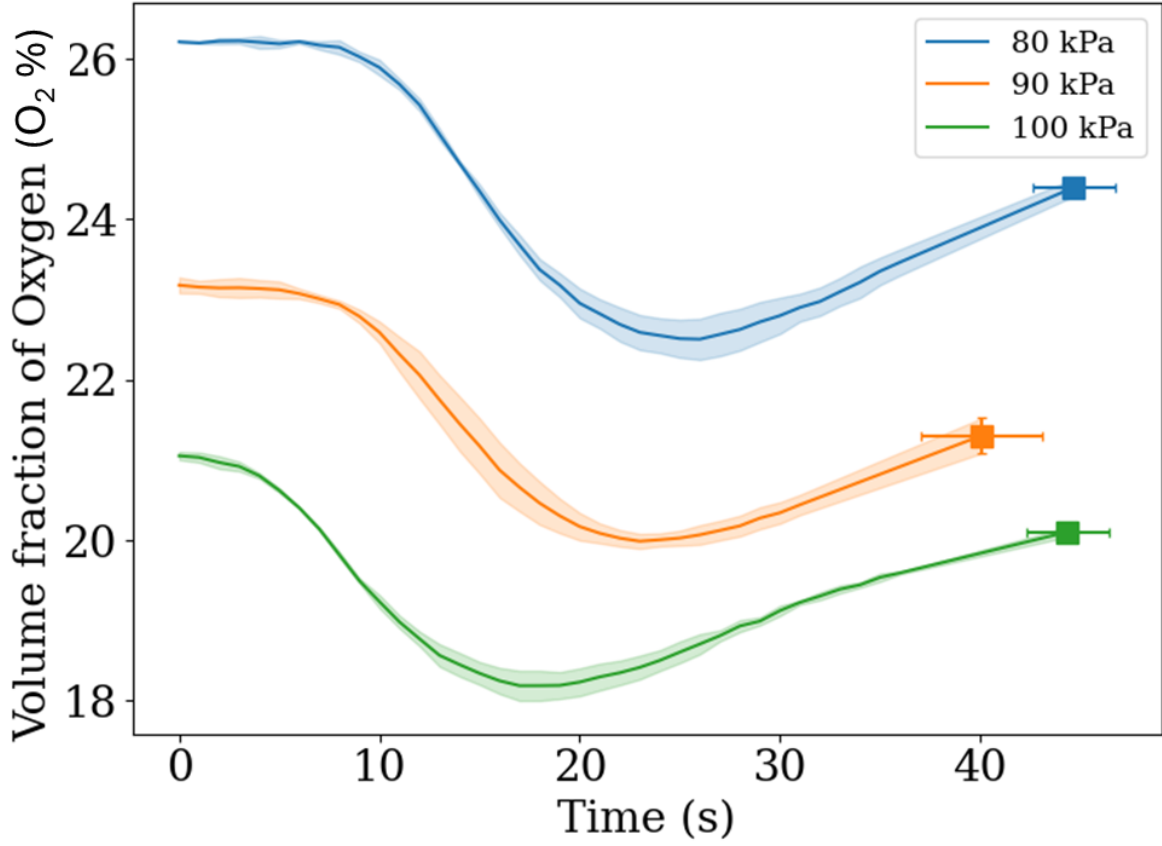


Figure 31: Average of oxygen volume fraction over time. Shaded region shows standard deviation.

PMMA Flame Tip	PMMA Pyrolysis Front	PMMA Burnout Front
$V \approx P^{-0.5}$	$V \approx P^{-1}$	$V \approx P^{-2}$

Table 2: Relationship between flame velocity and ambient pressure over PMMA sheets.

Cotton Flame Tip	Cotton Pyrolysis Front	Cotton Burnout Front
$V \approx P^{-0.5}$	$V \approx P^{-0.75}$	$V \approx P^{-0.75}$

Table 3: Relationship between flame velocity and ambient pressure over cotton sheets.

The total average heat release rate (HRR) was derived using two methods. The first utilizes the net mass of PMMA burned during an experiment, using the equation $\dot{q} = \dot{m} * \Delta h_c$. In

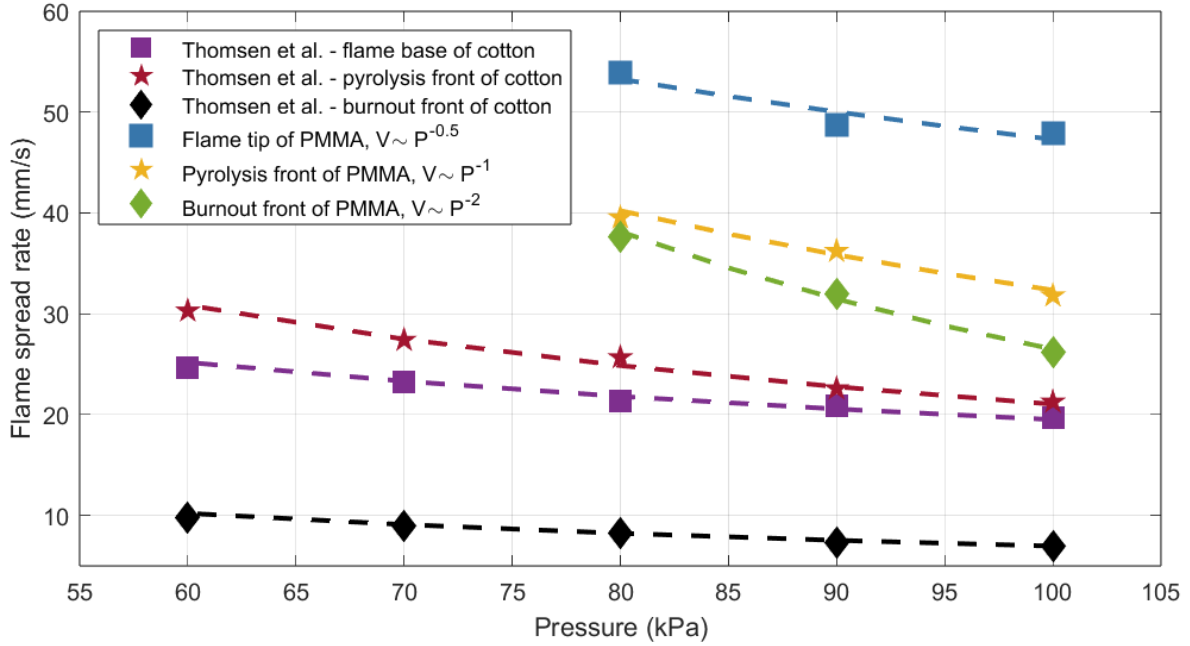


Figure 32: Flame spread rate of PMMA and cotton ([98]) at normoxic conditions. For PMMA, the large markers are experimental data, while the dashed curves follow the correlation of the spread rates on pressure indicated in the legend.

this equation, $\dot{q}$ is the heat release rate of PMMA, $\dot{m}$ is the average mass loss rate of PMMA, and $\Delta h_c = 24.2 \text{ kJ/g}$ is the heat of combustion of PMMA. The second method is through the oxygen consumption, using the equation $\dot{q} = E \dot{m}_a (Y_{O_2}^a - Y_{O_2}^c)$, where $E = 13.1 \text{ kJ/g}$ is the heat release per mass unit of oxygen consumed, $\dot{m}_a$ is the mass flow rate of gases inside the chamber in g/s, and $Y_{O_2}^a$ and $Y_{O_2}^c$ are the mass fractions of oxygen in the combustion air and combustion products respectively [88]. Fig. 33 compares the HRR of PMMA to that of cotton, from experiments conducted by Thomsen et al. [98]. It can be seen that in all cases, the heat release rate is greater as the pressure is reduced and volume fraction of oxygen is increased in normoxic conditions. The increased oxygen concentration leads to a faster mass burning rate due to an increase in the flame temperature. Although the PMMA sheets were only 0.1 mm in thickness, they released approximately 50% more power compared to the cotton samples.

5.4 Discussion

Concurrent spread is driven by a diffusion flame covering the solid surface. This type of flame is not affected significantly by the chemical kinetics, except in cases near limiting conditions such as flame quenching or blow off [31]. Given that all experiments were conducted at

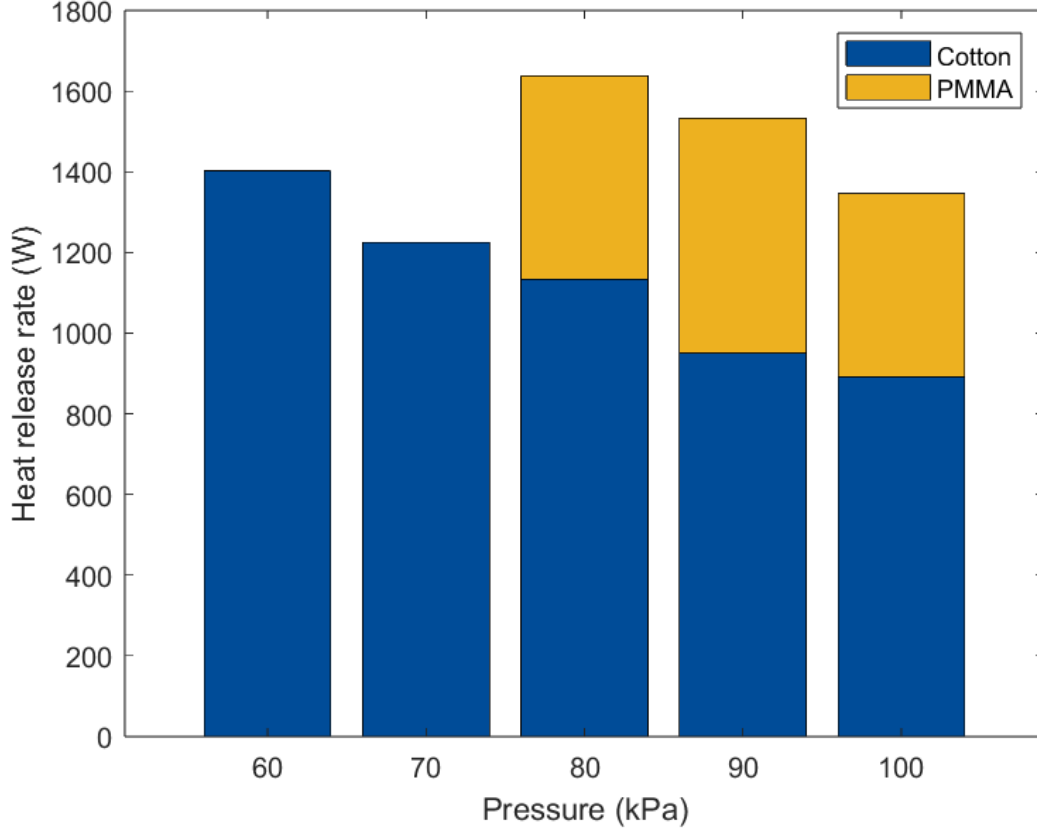


Figure 33: Total average heat release rate of PMMA and cotton at normoxic conditions.

oxygen-rich environments with low velocity flows and fast reaction rates, the pyrolysis front spread rate over a thin solid can be expressed as

$$V_f \sim l_p \left[\frac{\dot{q}_{fc} + \dot{q}_{fr} - \dot{q}_{rs}}{\rho_s c_s s (T_p - T_0)} \right] \quad (28)$$

where l_p is the pyrolysis length, ρ_s and c_s are the solid density and specific heat, s is the solid thickness, and $\dot{q}_{fc}$, $\dot{q}_{fr}$ and $\dot{q}_{rs}$ represent the convective heat flux at the solid surface, the flame radiant flux incident on the fuel surface, and the re-radiation from the solid, respectively. T_p and T_0 denote the pyrolysis and initial temperatures of the solid. The convective heat flux term can be expressed as $\dot{q}_{fc} = h (T_f - T_p)$, where h is the convection coefficient, T_f the flame temperature, and T_p the pyrolysis temperature. The radiant heat flux from the flame to the burning solid surface can be approximated as $\dot{q}_{fr} = \gamma_R Q''_{rr}$, where Q''_{rr} is the heat released by the pyrolyzed fuel burning at the gas phase reaction, and γ_R is the fraction of the heat released that is radiated to the solid surface [99]. Q''_{rr} is given by the product of

the gas phase reaction rate and the heat of combustion, and depends strongly on the flame temperature [100].

With F_{12} being the view factor, ϵ the emissivity, and σ the Stefan Boltzmann constant, the surface re-radiation is $\dot{q}_{rs} = F_{12}\epsilon\sigma (T_p^4 - T_0^4)$, and can be neglected in concurrent flame spread away from the extinction limit. The flame temperature can be approximated as $T_f = T_0 + \Delta H_c X_0 s / c_p \approx C X_0$ where ΔH_c is the heat of combustion, X_0 is the mole fraction of oxygen, and s is the stoichiometric fuel to oxygen ratio [100]. Therefore, the flame spread rate depends strongly on the flame temperature and consequently on the oxygen volume fraction (O_2 mole fraction).

The convective heat transfer coefficient, is related to density and pressure through the Reynolds number $Re = \rho U_f l_p / \mu$ and Grashof number $Gr = g\beta \Delta T l_p^3 \rho^2 / \mu^2$:

$$h = C \frac{k}{l_p} [Re^4 + Gr^2]^{1/8} Pr^{1/3} \quad (29)$$

with C being a generic constant related to the flow and pyrolysis length, U_f the forced flow velocity, μ the dynamic viscosity, and Pr the Prandtl number. The pyrolysis length, i.e. the difference between the flame base and flame tip, can be assumed as approximately constant for thin fuels. Combining the Reynolds and Grashof numbers into Eq. 29,

$$h = C \frac{k}{l_p} \left[\rho U_f l_p / \mu^4 + (g\beta (T_f - T_p) l_p^3 \rho^2 / \mu^2)^2 \right]^{1/8} Pr^{1/3}. \quad (30)$$

It is worthwhile to consider in the flame spread rate analysis a pure forced flow convection heat transfer coefficient that is of the same magnitude as the mixed flow in this experimental setup. This is achieved by setting the mixed flow heat transfer coefficient of Eq. 30 to be equal to that of a pure forced flow (Eq. 30 with $g = 0$). With P_0 being the ambient pressure at standard temperature and pressure (STP), the mixed convection velocity is [98]:

$$U_m = U_f \left(\frac{P}{P_0} \right) \left[1 + \frac{g^2 \beta^2 (T_f - T_p)^2 l_p^2}{U_f^4} \right]^{1/4}. \quad (31)$$

Therefore, when natural convection is negligible, such as at large forced flow velocities or in the absence of gravity, the flow velocity becomes $U_m = U_f \left(\frac{P}{P_0} \right)$. On the other hand, in cases of no forced velocity or increased gravity levels, the mixed flow velocity becomes $U_m = \left(\frac{P}{P_0} \right) [g\beta(T_f - T_p)l_p]^{1/2}$. Putting these terms back into Eq. 28,

$$V_f = \frac{Ck \left(\frac{U_m Pl_p}{\mu} \right)^{1/2} Pr^{1/3} (T_f - T_p) + \gamma_R Q_{rr}''}{\rho_s c_s s (T_p - T_0)} \quad (32)$$

The dependence of the concurrent flame spread rate of the pyrolysis front on pressure and oxygen volume fraction can be obtained with Eq. 32, although some of the parameters in the equation are not known here. However, the predictions agree qualitatively with the results presented in Fig. 32, particularly the result that the effect of oxygen concentration is stronger on the flame spread rate than that of pressure.

5.5 Conclusion

This paper examines the flame spread process over thermally thin PMMA sheets in normoxic conditions, which include sub-atmospheric pressures and elevated volume fractions of oxygen. The objective of the project is to study the flammability of materials in environments similar to those found in spacecraft facilities or other low pressure locations such as aircraft and at high altitudes. The experiments have shown that as the pressure is decreased and the volume fraction of oxygen is increased, the flame spread rate over the thin PMMA sheets increases as well, demonstrating that the increased oxygen concentration has a larger effect than the decreased pressure. At lower ambient pressures, the thermal boundary layer thickens due to the reduction in gas density. At the same time, high oxygen concentrations result in elevated flame temperatures, which lead to the increased heating of the solid and a larger gas phase reaction rate.

Additionally, the heat release rate of the flame is calculated for each normoxic condition tested, and it is found that the heat release rate is highest at low pressure and high oxygen environments. Future work conducted in microgravity or with thermally thick samples could give us further insights for fire safety in low pressure environments.

5.6 Acknowledgments

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6 Conclusion

The work discussed here is an investigation of flame behavior in microgravity versus Earth gravity, with a focus on the effects of pressure and heat flux on the flame propagation along a solid fuel and extinction. It was found that the oxygen concentration needed to sustain combustion is significantly lower in microgravity as opposed to normal gravity, implying that fire is more dangerous in a spacecraft. This is because there is no flame induced buoyant convective flow in the absence of gravity, so the oxidizer residence time in the pyrolysis region is increased. As a result, the combustion process can progress even at oxygen-lean environments, and the gasified fuel pyrolyzes fully, characterized by a clean blue flame. This process can be explained mathematically through the elevated Damkohler numbers in microgravity compared to normal gravity. Besides burning to lower oxygen concentrations, combustion in microgravity also lasted for a longer time than on Earth. The flame spreading phase in particular lasted twice as long on the ISS compared to the UC Berkeley Fire Lab.

Furthermore, microgravity flames were found to spread with a similar flow velocity as on Earth when they were under the same ambient pressures. However, the environmental pressure does have a strong effect on the flame velocity and limiting oxygen concentration. For all gravity levels, a decrease in the ambient pressure correlated with a reduction in the rate of conductive heat transfer from the flame to the solid fuel, which in turn resulted in a slowed flame spread rate and an increase in the limiting oxygen concentration. An external radiant heat flux was found to also affect the flame propagation and the LOC significantly. The larger the added heat flux is, the more the sample is preheated ahead of the flame front, which then serves to increase the flame spread rate and decrease the LOC. This implies that if there are overheating equipment near a fire, the energy exchanged between the two could possibly make the fire spread faster and last to lower oxygen concentrations.

This work is not without limitations. In particular, all the analyses presented here used the same fuel. It would be worthwhile to explore the behavior of other fuels, especially those used frequently aboard spacecraft, such as structural materials and astronaut clothing fabrics, to assess if the findings of this report can be applied more generally. With the possible plans to build a Lunar base, it would be valuable to conduct similar tests at other gravity levels - especially Lunar and Martian gravities and using sample geometries more complex than cylinders or sheets.

In addition, the data collected as part of these investigations could be analyzed through a machine learning model or genetic algorithm to propose an equation that can predict the flame spread rate and limiting oxygen concentration given the inputs of gravity level, ambient pressure, and external radiant heat flux. An attempt at such a correlation was made in Chapter 2 using varying pressures and heat fluxes, and it would be beneficial to extend it to

include the force of gravity, as well.

Hopefully, this dissertation, which in itself is a continuation of the research conducted by everyone who came before, serves as a launch pad for questioning the validity of current microgravity fire safety measures such as the pre-flight flammability tests, and sparks more interest into the mysteries of combustion in the absence of buoyancy. As humans' desire to explore the limits of engineering continues to increase, microgravity fire safety will be evermore relevant.

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A Supplementary Results

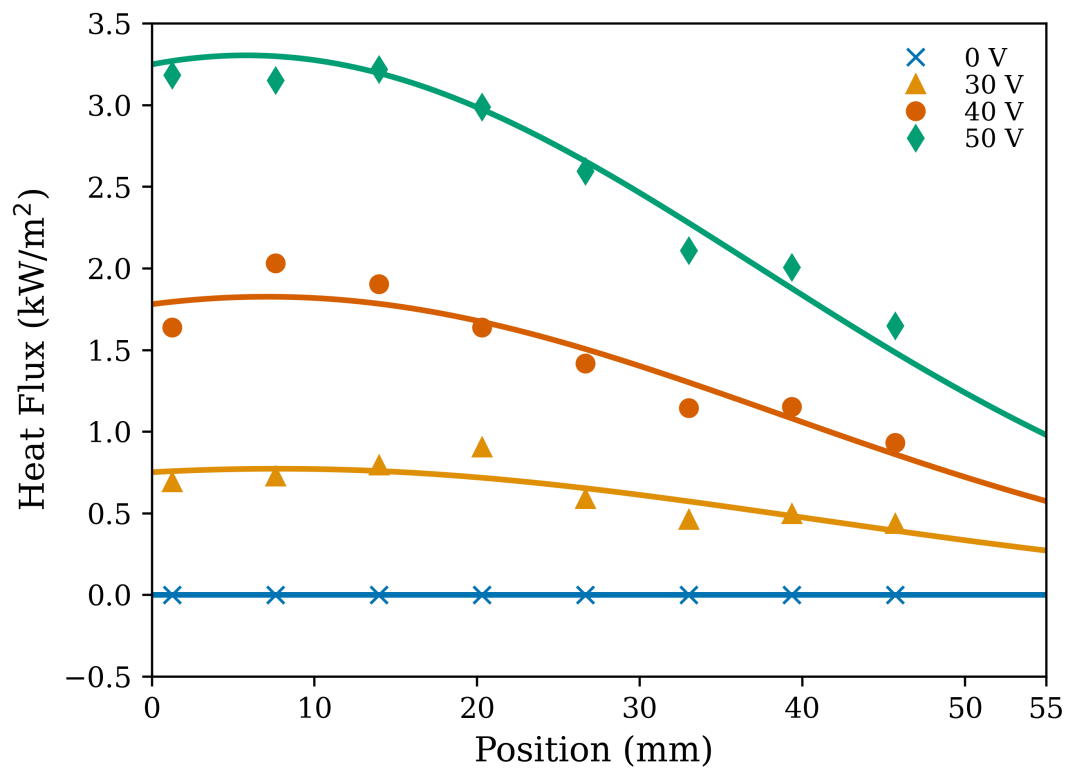


Figure A.1: Heater calibration curve along the length of the sample and with various voltages applied to the heaters.



Figure A.2: “Astronaut Mike Barratt replaces fuel bottles inside the Combustion Integrated Rack”. Image by NASA.

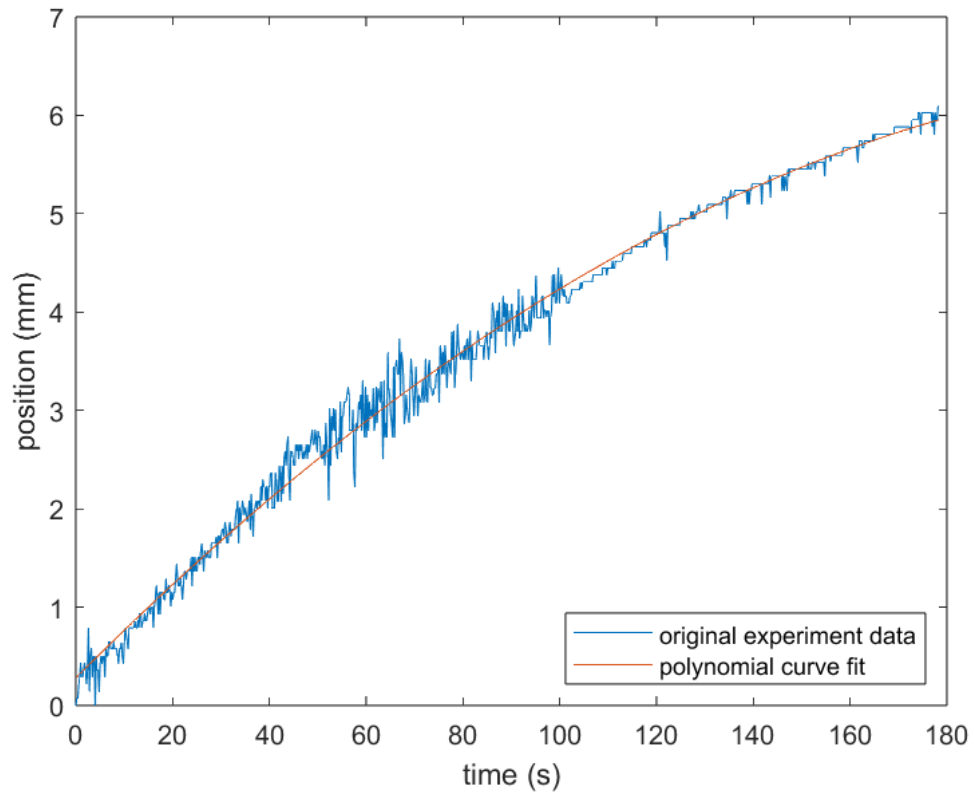


Figure A.3: Position versus time plot of an experiment at 100 kPa in normal gravity. In blue is the experimental data and in orange is the second order polynomial fit of the data; $R^2 = 0.992$.

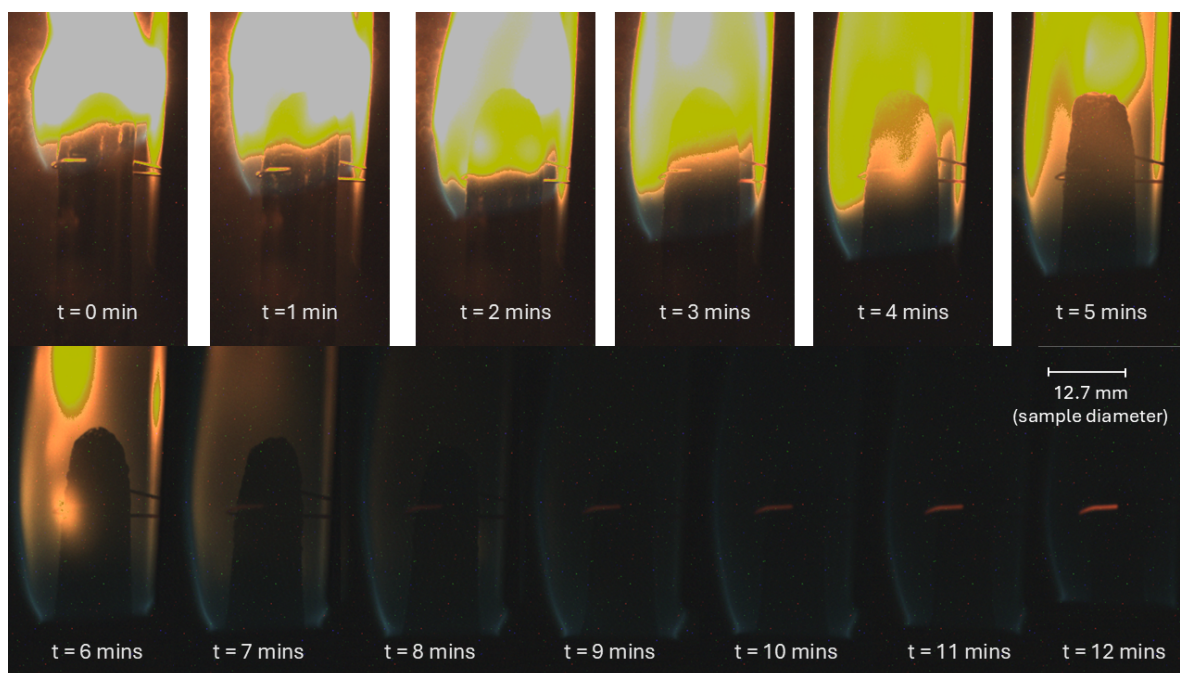


Figure A.4: Collage of the flame propagation over time at 100 kPa in microgravity, and under a depleting oxygen concentration. The colors are enhanced to improve visualization of the flame.