Flammability of Combustible Solids in Spacecraft Environments

by

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Abstract

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The flammability of combustible materials inside a spacecraft environment is of importance for fire safety applications because the conditions in this type of environments can greatly differ from those on earth, and a fire could have catastrophic consequences. Moreover, experimental testing in space can be difficult and expensive, and ground-based microgravity facilities such as drop towers or parabolic flights are limited to a few second duration. Additionally, future space missions may require spacecraft cabin environments different than those currently used in the International Space Station, 21% \( O_2 \) by volume and 101.3 kPa, moving to reduced cabin pressure and increased oxygen concentration. These new conditions may result in an increased fire risk of the materials used due to the higher flame temperatures and the reduction in the convective losses from the heated solid surfaces. In particular, the influence of low pressure on material flammability and flame spread behavior is emphasized here because of the similarities existing in between the flow field produced in reduced pressure environments and microgravity.

Chapter 1 presents an introduction to material flammability and flammability testing, focusing particularly on flame spread over solid fuels and previous related research. Chapter 2 presents a description of the experimental setups used for the normal gravity and the microgravity tests presented as part of this work. Chapter 3 is an experimental study covering flammability boundaries for flame spread of fire resistant fabrics exposed to different environmental conditions. In Chapter 4 and 5, an experimental study is presented along with a phenomenological analysis to simulate the burning behavior of thin and thick solids in microgravity conditions by using reduced pressure environments. Then, in Chapter 6 a similar approach is presented to study the flame spread behavior under the effect of external radiant heating, making comparisons with low pressure and microgravity environments.

Flammability; Flame Spread Rate; Solid Fuel; Microgravity; LOC; Reduced Pressure; Environmental Conditions
To my family, friends, and everyone who made this possible.
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Nomenclature

Notation

\( c_p \) specific heat of the gas
\( c_s \) specific heat of the solid
\( \text{Da} \) Damköhler number
\( E \) activation energy
\( \text{Gr} \) Grashof number
\( g \) gravity
\( k \) thermal conductivity
\( h \) heat transfer coefficient
\( l_h \) heated length
\( l_p \) pyrolysis length
\( P \) Ambient pressure
\( \text{Pr} \) Prandtl number
\( \dot{q}'' \) heat flux per unit area
\( \dot{q}' \) external radiant flux
\( \dot{q}_{fc}' \) convective heat flux at the solid surface
\( \dot{q}_{fr}' \) radiant flux from the flame to the solid
\( \dot{q}_{rs}' \) re-radiation from the solid
\( \text{Re} \) Reynolds number
\( s \) solid thickness
\( T \) temperature
\( T_f \) flame temperature
\( T_o \) initial solid temperature
\( T_p \) pyrolysis temperature
\( t \) time
\( t_{\text{chem}} \) chemical time
\( t_{\text{ig}} \) ignition time
\( t_{m} \) mixing time
\( t_{p} \) pyrolysis time
\( U \) flow velocity
\( U_f \) forced flow velocity
\( U_m \) mixed flow velocity
\( V_f \) flame spread rate
\( W_O \) molecular weight of oxygen
\( x \) coordinate parallel to the solid surface
\( Y_{F,s} \) fuel mass fraction
Greek letters

\[ \beta \]  volumetric thermal expansion coefficient
\[ \Delta H_R \]  heat of combustion
\[ \Delta h \]  change in enthalpy
\[ \delta \]  boundary layer thickness
\[ \rho \]  density
\[ \mu_g \]  microgravity

Subscripts

b  buoyant
f  flame
ig  ignition
s  solid
\[ \infty \]  ambient gas

Abbreviations

ASTM  American Society for Testing and Materials
EVA  Extra-Vehicular Activities
HRR  Heat Release Rate
IDT  Ignition Delay Time
ISO  International Organization for Standardization
ISS  International Space Station
LOC  Limiting Oxygen Concentration
LOI  Limiting Oxygen Index
MOC  Maximum Oxygen Concentration
NASA  National Aeronautics and Space Administration
PMMA  polymethyl methacrylate
SEA  Space Exploration Atmospheres
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Chapter 1

Introduction

1.1 Motivation

Understanding the flammability of solid combustible fuels is of utmost importance to the field of fire safety, because it makes possible to assess the fire risk associated to a given material and determine how fire safe it is. In practical applications a material can be exposed to a wide range of ambient conditions and its flammability can change depending on the environment at which it is exposed. Generally, material flammability is determined through the ease of ignition, the rate of flame spread, the rate of burning and heat release, and its toxicity. Ignition and flame spread are important as indicative of the initiation and progress of a fire, while heat release and toxicity are indicative of its consequences. Material flammability is tested under several specific conditions, i.e. a set ambient pressure and oxygen concentration, with or without a forced flow, with or without external radiation, etc. However, these conditions might not represent the real environment in which the material will be used or might not consider unexpected changes at which it may be exposed to. For this reason, considering a wider range of conditions or a more general testing method is important, especially in situations where safety is a critical factor that must be carefully ensured at any time, such as inside the case of commercial planes or on spacecrafts.

The work presented here is developed and motivated by the fact that the National Aeronautics and Space Administration (NASA) has proposed the use of reduced cabin pressure and increased oxygen concentration as part of the design of new space exploration vehicles \footnote{1} \footnote{2}. These conditions are usually referred to as Space Exploration Atmospheres (SEA). The main reason laying behind the changes in the SEA relate not only to a reduction of the preparation time required by the astronauts before they can conduct Extra-Vehicular Activities (EVA), but also to a reduction of the risk of suffering decompression sickness after the astronauts return from EVA \footnote{3} \footnote{4}.

The current fire safety strategy in space exploration relies on selecting and using materials that are not likely to be flammable inside a spacecraft. The selection of this materials is mainly based on a screening flammability test, NASA Standard 6001 \footnote{5}. This test establishes guidelines and
requirements for the evaluation and testing of materials that are considered for use in a spacecraft by exposing them to the worst-case scenario expected. Nevertheless, even if the worst-case scenario is considered, the presence of gravity immediately affects any results that are obtained on earth, making possible that a material that passes the NASA Standard 6001 could still be unsafe inside a spacecraft. In an ideal world, the flammability of materials that are going to be used in a spacecraft, should be tested in space. However, microgravity testing is expensive and there are multiple safety limitations, so this is a very unlikely possibility.

In this context, it is a relevant and attractive idea to develop testing methodologies and conditions that could simulate microgravity environments on earth. The use of drop towers or parabolic flights is a valid option; however, they are expensive, the access to this type of facilities is restricted, and the duration of the microgravity conditions provided is limited to a few seconds. Another alternative is to test material flammability and flame spread at different buoyancy levels to alter the influence of gravity. This can be achieved by changing the orientation of the solid surface where the flame spreads [6–14]. However, there are several problems associated with changing the surface orientation; one is that the thickness of the boundary layer is changed and consequently the heat flux from the flame to the surface is also changed, affecting ultimately the flame spread rate. Another is the stratification of the hot pyrolyzate near the solid surface in a ceiling orientation or away from the surface in a floor orientation that changes the transport of the pyrolyzate and air [7–15]. A more promising approach is to reduce pressure, and consequently density, to reduced gravity effects. Several studies have successfully taken advantage of the changes in buoyancy resulting from reducing pressure to simulate solid burning (ignition, opposed flame spread, extinction) encountered in microgravity [16–21]. The main motivation of this work is to study the flammability, specifically flame spread, behavior of solid materials in different environments by using reduced ambient pressure and to compare with similar tests conducted in microgravity conditions. The materials studied in this work are currently used inside space exploration vehicles and the atmospheres tested relate to current and future possible SEA.

1.2 Background

1.2.1 Material flammability

The flammability of a solid fuel is a material characteristic that relates to its capability of burning, and it is usually associated to the combustibility or the fire hazard that the material can represent. In spite the fact that there isn’t a perfect definition of flammability, a common way of defining this property is by looking at how easy it is to ignite the material, the intensity with which it burns and releases heat when it is burning, the rate at which produces toxic gases or smoke, and the propensity to spread a fire [22, 23].

A material’s ease of ignition is a very fundamental characteristic to assess the flammability of
a material because there is no fire hazard without ignition. Commonly, it is defined as the time required to the onset of the fire under certain heating conditions, and it is usually evaluated by measuring the ignition delay time, which is the time considered from the moment heating begins until ignition occurs [24]. In general, ignition of a combustible material is often classified in two different ways: spontaneous ignition and piloted ignition. The first one, also referred to as autoignition, occurs through the self-heating of the reactants, whereas the second one requires the assistance of an ignition source. From a fire safety point of view, piloted ignition is usually considered a more conservative measurement compared to spontaneous ignition, as well as a more representative depiction of what happens in a real fire scenario, where sparks or embers from already burning objects or electrical shortcuts can act as pilot and cause ignition [25].

In piloted flaming ignition it is not the solid fuel that actually ignites but the gasified solid fuel or pyrolysis gases that are generated when the solid is heated and the material starts decomposing. For ignition to occur, there is a sequence of physical and chemical processes involved that are strongly affected by the environmental conditions such as the amount of heating applied to the surface, ambient pressure and oxygen concentration, and any imposed flow velocity. Usually, there are three main stages: an initial heating period, followed up by thermal decomposition, and the mixing of gases that leads to the onset of the gas-phase chemical reactions [22]. During the heating of the material, the rate at which the temperature of the solid is increased depends strongly on the applied heat flux, but also of the heat losses to the surroundings and the thermal properties of the material. Since thermal decomposition does not occur until the solid temperature is high enough to start the process, for a given material there is a minimum heat flux that is required to overcome the heat losses, generate the pyrolysis of gases, and thus, allow ignition to potentially occur. If the heat flux applied is large enough to overcome such heat losses, a decomposition zone begins to form and propagates in-depth into the solid generating the pyrolysis gases. These pyrolyzates mix with the air and, if a flammable gaseous mixture is generated near the ignition source, the flame is ignited.

There is a large amount of work with detailed descriptions of the fundamentals of solid fuel ignitions including the reviews of Drysdale [6], Kashiwagi [26], Babrauskas [27], Fernandez-Pello [8], and Torero [28], among others.

A material’s heat release rate is an indication of the intensity of the fire, the size, and the potential to cause thermal damage, and it has been indicated as one of the most important variables used to characterize the fire hazard [27]. Heat release rate is directly correlated to the smoke production and the rate of spread of the fire, since it determines the heat feedback from the flames to the solid surface [22]. Additionally, a fire’s heat release rate can be linked to the plume temperatures and flow velocities, and can be used to determine the risk of flashover. Flashover is a rapid event that occurs when surfaces that are exposed to thermal radiation reach their ignition temperature more or less simultaneously, resulting in a sudden growth of the fire [29, 30]. It is considered one of the most dangerous stages of a fire due to the extremely limited time to escape [31].
The heat release rate is usually measured in cone calorimeters that use the oxygen consumption principle to determine it \[32, 33\]. In this type of devices, the heat release rate is determined for small samples of material burning under an imposed radiant heat flux. This technique requires the collection and measurement of the exhaust flow rate and oxygen concentration. With these values, the heat release rate can be estimated based on the assumption that all materials release approximately the same amount of heat per unit mass of oxygen consumed. A more detailed description of the oxygen consumption method and the cone calorimeter can be found in \[32–36\].

The toxicity of a material is another important factor when assessing fire risk. Non-thermal hazards are the main cause of death in fires \[37\], because of the reduced visibility effect from the smoke (that limits the ability to find an exit) and asphyxia caused by inhaling toxic gases from the fire. In the case of building/house fires, as the fire begins to burn it consumes much of the oxygen available that individuals need to breathe, making it even harder to escape. Table 1.1 shows the effect of a reduction in the oxygen level on a person’s health.

Table 1.1: Main symptoms experienced by a person when oxygen concentration is reduced \[38\].

<table>
<thead>
<tr>
<th>When oxygen levels are at...</th>
<th>... a person experiences:</th>
</tr>
</thead>
<tbody>
<tr>
<td>21 % by vol.</td>
<td>Normal outside air</td>
</tr>
<tr>
<td>17 % by vol.</td>
<td>Impaired judgment and coordination</td>
</tr>
<tr>
<td>12 % by vol.</td>
<td>Headache, dizziness, nausea, fatigue</td>
</tr>
<tr>
<td>9 % by vol.</td>
<td>Unconsciousness</td>
</tr>
<tr>
<td>6 % by vol.</td>
<td>Respiratory arrest, cardiac arrest, death</td>
</tr>
</tbody>
</table>

Toxic gases originated from combustion are usually classified in two categories: asphyxiants and respiratory or pulmonary irritants \[39, 40\]. Asphyxiant gases affect the central nervous system and can result in loss of consciousness and ultimately death. Their effects are directly correlated to the concentration and the duration of the exposure, increasing the severity of the effects with increasing dose. Two of the main asphyxiant gases produced by a burning material are carbon monoxide (\(CO\)) and hydrogen cyanide (\(HCN\)). The toxicity of \(CO\) is related to a reduction in the oxygen-carrying capacity of the blood, known as hypoxia. Hypoxia following exposure to carbon monoxide results from the competition between \(O_2\) and \(CO\) for the heme-binding sites of hemoglobin, with the affinity of hemoglobin for \(CO\) being about 250 times greater than that for \(O_2\) \[41\]. The response of an individual to carbon monoxide exposure is directly related to the amount of gas inhaled and his physiological conditions. The action of hydrogen cyanide, on the other hand, is due to cyanide ion, which are formed in the blood and distributed to make contact with cells of tissue and organs. Unlike \(CO\), the inhalation of \(HCN\) do not decrease the availability of oxygen but rather prevents its use by cells, affecting particularly the heart and the brain \[39\]. Another complication associated with the inhalation of hydrogen cyanide is hyperventilation. This causes a more rapid uptake of not only \(HCN\) but also other gases that may be present, such as \(CO\) \[42\]. Thus, it is likely that interactions between these different gases have an additive effect that can lead
to fatality. Irritant gases are characterized for causing irritation to the eyes, respiratory tract and lungs. They can impair the person’s ability to escape a fire and their effects are also related to the concentration of the irritant and the exposure time [39]. Some typical irritant gases originated from combustion are nitrogen oxides ($NO_x$) and halogen acids ($HCl$). There are plenty of papers that cover fire toxicity and the effect of smoke in a fire visibility, such as the ones of Purser [42, 43], Gann and Bryner [39], Hartzell [41], Jin [44], Mulholland [45], among many others.

Finally, a material’s propensity to spread a fire is important because it influences the initial growth of a fire. The capability of a material of sustaining flame spread relates directly to the heat release rate of the fire as it affects the total surface area that is burning. The flame spread process is also closely related to the ease of ignition and sometimes is presented as a continuous sequence of piloted ignitions [8, 24]. During the flame spread process, the flame has a dual function: it serves as the heating source needed to preheat the material, allowing it to pyrolyze after reaching the pyrolysis temperature, and it also acts as the pilot source that ignites the flammable gases once they have mixed. In the same way as ignition, the flame propagation over the solid depends on different physio-chemical process that are strongly affected by variables such as ambient pressure, oxygen concentration, the amount of heating applied, the orientation of the material, the gas flow velocity, among others. Because of its importance in fire safety, several reviews have discussed the fundamentals of flame spread over solids including those of Williams [46], Fernandez-Pello [47], Hirano [48], Quintiere [24], Whichman [49]. Flame spread over a solid combustible is further analyzed in Section 1.2.2.

### Flammability testing

As mentioned before, there are multiple ways to assess a material’s flammability and consequently multiple test methods that can be used for that task. In this section, four standardized test methods, relevant for the present work, are introduced: NASA-STD-6001B [5, 50], the LOI test [51, 52], the LOC method [53, 54], and the Lateral Ignition and Flame Spread Test [55].

NASA-STD-6001B establishes a set of guidelines and requirements for the evaluation and testing of flammability, odor, and off-gassing characteristics of materials, exposing them to the worst-case possible scenario expected. This standard includes different criteria such as burn propagation, generation of debris, spotting capability, dripping and self-extinguish behavior, among others, that are used to determine whether a material is safe to be considered for use in a spacecraft [5]. Particularly relevant for this work is the Test 1, which is also registered with the International Organization for Standardization (ISO) as ISO 14624-1 [56]. In this test, a vertical strip of material of 30 cm long by 5 cm wide is ignited from the bottom end by a chemical igniter, i.e. a flame, resulting in a concurrent upward flame spread configuration. Figure 1.1(a) shows a diagram of the experimental setup used for NASA Test 1. A total of five specimens are tested in ambient conditions that replicate the worst-case environment expected. The test method is essentially a pass/fail test. The material passes the test if the flame spread does not exceed 15 cm from ignition in any of the samples tested and none of the specimens propagates the flame by transferring burning debris
onto a piece of paper placed 20 cm below the burning sample.

A second flammability test is the Limiting Oxygen Index, also known as LOI. The LOI is the minimum oxygen concentration for self-sustained flame spread over a solid material strip. Its detailed characteristics are specified in the standardized test ISO 4589-2 [51] or the ASTM D2863 [52]. This test employs downward flame spread, i.e. opposed flame spread, and requires the flame to spread longer than 50 mm or for at least 180 s to be considered a sustained spread after ignition. The samples sizes are usually between 80 and 150 mm long by 10 mm wide, and ignition is achieved using a propane flame. Figure 1.1(b) shows a diagram of the experimental setup as defined by the ASTM D2863 standard. The advantage of this method relies on its precision determining the limiting conditions. However, downward flame spread is generally not preferred for spacecraft material testing, as it is not as conservative as upward flame spread and the flame spread process is usually slower.

The third flammability index of interest is closely related to the NASA-STD-6001B and the LOI, and it is called Limiting Oxygen Concentration (LOC). The LOC is defined as the smallest concentration of oxygen that can support a self-propagating flame [53]. It is also referred as the Maximum Oxygen Concentration (MOC), meaning the maximum oxygen concentration that consistently results in self-extinguishment of the flame [57, 58]. This flammability index is a more general description and it does not have a defined configuration for burning or sample size, so it can be applied using other standards criteria (like NASA test 1). Unlike the results from NASA-STD-6001B Test 1, that are only applicable to the same conditions as those tested, the LOC or the MOC represent actual flammability boundaries for the material so that a more accurate assessment of the fire risk at a given set of conditions can be made.

With these definitions, several researchers have assessed the flammability of different types of materials such as plastics, fabrics, and other composite materials [57-64]. Hirsch and coworkers [57, 59, 60] studied the flammability of different materials relevant for spacecraft application focusing on the effect of ambient pressure and oxygen concentration. Olson et al. [62] followed a similar line studying material flammability of thin solids in space exploration atmospheres. Additionally, Olson et al. [58] also studied material flammability at different gravity levels comparing with standard testing performed in normal earth gravity. Miyamoto et al. [64] and Osorio et al. [63] focused on the flammability boundaries of electrical wires under the effect of external radiation using an analysis based on the LOC.

Lastly, the Lateral Ignition and Flame Spread Test, also known as LIFT, is a testing method defined in the ASTM Standard E1321 [55]. LIFT is used to determine material properties, i.e. the thermal inertia of the material, its ignition temperature, time to ignition, the velocity of flame spread, and a flame spread parameter, all these properties facilitate the comparisons between materials and are commonly required for numerical models. As described by the name, the LIFT apparatus allows testing of both ignition and flame spread. During the ignition tests, samples are oriented vertically under a constant and uniform heat flux and the time to flame attachment, using
a pilot ignition source, is measured. For this type of tests samples are about 155 mm by 155 mm. During the flame spread test, longer samples (155 mm by 800 mm) are exposed to a decaying heat flux that is about 5 kW/m² higher than the minimum heat flux required for ignition at the hotter end. The samples are preheated to thermal equilibrium, subsequently they are ignited with a pilot, and flame spread is measured along the horizontal length. A schematic of the setup is presented in Figure 1.2.
Fire Resistant and Fire Retarded materials

Fire resistant materials are materials that are inherently non-flammable at standard conditions. They are designed to prevent the spread of fires. The flame resistance characteristic comes from their chemical structure and they do not have any additives [65]. In flame retarded materials, flame retardants are applied to the material, so they induce fire resistance capabilities by affecting the gas phase or the solid phase reactions [66]. Gas phase flame retardants act by slowing down the burning of the material by scavenging reactive free radicals that are fundamental to keep the combustion chemical reactions going. Solid phase flame retardants can influence the release of non-flammable gases, such as $H_2O$ and $CO_2$, which dilute the gaseous fuel and cool the polymer through endothermic decomposition of the flame retardant additive. They can also operate by creating a char layer over the material that prevents the release of gaseous fuel and acts as a layer of thermal insulation.

Fire resistant materials are widely used to comply with fire safety regulations [5, 66, 67]. However, labeling a material as fire resistant does not necessarily mean that it will never burn. It has been shown before that material flammability depends on the environmental conditions. More information on fire resistance can be the reviews of Morgan et al. [65, 66], Weil and Levchik [68], and Chen and Wang [69].
1.2.2 Flame spread phenomena

During the flame spread process, enough heat must be transferred to the unburnt solid ahead of the flame to increase its temperature and allow the pyrolysis of the fuel. These pyrolysis gases are moved away from the surface by convection and diffusion, mixing with the oxidizer and creating a flammable mixture. Then, the flammable mixture is ignited by the flame allowing it to spread over the solid surface. Thus, the rate of spread of the flame is determined by the heat transferred from the flame to the unburnt solid, which in turn is also strongly dependent of the flame shape, thickness of the fuel and environmental variables.

Commonly, flame spread processes are characterized in terms of the direction of the flame propagation with respect to the direction of the oxidizer flow and in terms of the fuel thickness. As mentioned before, the heat transferred from the flame to the solid depends strongly on the shape of the flame, and therefore, the direction of the gas flow. In this matter, when the gas flow, either forced or naturally induced, follows the same direction of the propagation of the flame the process is referred to as a concurrent flame spread. On earth, in a quiescence environment, upward flame spread, is used when the flame spread is in the vertical direction assisted by a buoyant gas flow induced upward by the flame. In concurrent flame spread the flame is pushed forward by the gas flow, resulting in an elongated flame that covers part of the unburned material, as depicted in Figure 1.3(a). The elongated shape of the flame favors the heat transferred from the flame to the solid, making the spread of the flame fast. On the contrary, when the gas flow is in the opposite direction of the flame spread, the process is known as opposed flame spread; if the direction of the surface is vertical, the process can also be called downward flame spread. In this configuration, the heating of the unburned material is dominated by heat conduction in the gas-phase from the flame to the solid ahead of the flame leading edge, as shown in Figure 1.3(b), although forward conduction through the solid may become dominant under certain conditions [8]. Because the heating length is smaller than in concurrent flame spread the process is slower and more stable.

The classification in terms of the fuel thickness is based on the importance of the rate of heat transferred by conduction from the surface to the interior of the fuel. Thus, if the solid is very thin and can be treated as if there are no temperature gradients across the fuel thickness, then it can be denoted as a thermally thin solid [6]. Whereas, if the thickness of the solid is larger than the thickness of the heat penetration layer at any particular time, the solid can be considered as a thermally thick solid [8]. Flame spread over a thermally thin solid is generally faster than for a thick solid because it requires less heat to pyrolyze the solid. Usually, the majority of the microgravity experiments that focused on the spread of flames have been conducted on thermally thin solids to take advantage of the high flame spread rates and the low thermal inertia that provides steady state conditions faster than in thermally thick materials. This allows to perform experiments in ground-based microgravity facilities, such as drop towers, that do not provide long microgravity times.

The flame spread over a solid surface has been widely studied [6, 24, 46-49, 70-73] given
Figure 1.3: Schematic diagram of the spread of a flame over the surface of a solid fuel in: (a) concurrent/upward configuration and (b) opposed/downward configuration.

Figure 1.4: (a) Schematic representation of temperature profiles over a thermally thin and a thermally thick solid.
the importance of this process in the development of a fire and its heat release rate. One of the first approaches to flame spread theory over a solid fuel was proposed by De Ris [70] in the late 60’s for opposed flame spread. In his work, De Ris assumes an infinite reaction rate for the gas-phase chemistry (the oxygen and fuel vapor react instantaneously upon coming into contact), with constant gas-phase properties and a uniform velocity flow profile. The model considers main heat and mass transfer mechanisms and provides analytical solutions for thin and thick solids, presented in Equations [1.1] and [1.2] respectively.

\[ V_f = \sqrt{2} \frac{k_s}{\rho_s c_s s} \frac{T_f - T_p}{T_p - T_\infty} \]  
\[ V_f = U_\infty \frac{\rho_g c_{pg} k_g}{\rho_s c_s k_s} \left[ \frac{T_f - T_p}{T_p - T_\infty} \right]^2 \]

where \( V_f \) is the spread rate, \( k, \rho, \) and \( c \) stand for thermal conductivity, density, specific heat. The subscripts \( s \) and \( g \) stand for solid and gas, respectively. \( s \) refers to the solid thickness. \( U_\infty \) is the oxidizer flow speed. \( T_f, T_p, T_\infty \) are the flame, pyrolysis, and ambient temperature.

Later, Williams [46] presented a similar thermal model to describe the spread of flames over solids, liquids, smoldering, and discrete fuel arrays. He defined a fundamental equation of fire spread by considering that the rate of spread is determined by the rate of heat transferred across the surface of the solid. Williams’ fundamental equation is given by

\[ \rho_s V_f \Delta h = \dot{q}' \]

where \( \Delta h \) is the change in enthalpy associated with a unit of mass of fuel increasing its temperature from ambient to ignition temperature, and \( \dot{q}' \) is the rate of heat transfer across the surface.

These initial models succeeded capturing some of the heat transfer aspects of the flame spread process, however they left a gap when considering the inclusion of chemical kinetics effects. Building upon this, research was focused in the development of new models that would better capture the general nature of the flame spread process. Fernandez-Pello and Williams [74] developed a model of opposed flame spread that incorporated gas phase chemical kinetics, although it only was of limited application because only considered forward heat conduction through the solid as the heat transfer mechanism. The works of Fernandez-Pello et al. [75] and Altenkirch et al. [21] explored the inclusion of gas-phase chemical kinetic effects by considering the dependence on the Damköhler number of the problem (\( Da \)), given by the ratio of characteristic flow time to characteristic reaction time. This way, for large Damköhler numbers, i.e. low flow velocities and/or high oxygen concentrations and flame temperatures, the gas-phase reactions proceed very fast and the flame spread is controlled by the heat transfer from the flame to the solid material. On the contrary, for small Damköhler numbers, i.e. high flow velocities and/or low oxygen concentrations and flame temperatures, the flow time is small when compared to the reaction time and therefore the gas-phase kinetics dominate the flame spread process (see Figure [1.7]).
Another approach to model analytically the flame spread problem is to analyze it following the concept that flame spread can be viewed as an ignition problem and calculated as the ratio of a heating length (flame length) to an ignition time \[8, 46, 76, 77\]. Since the time for a solid element to ignite is the same as for the flame to propagate to that solid element position, the rate of flame spread could be determined by the ratio of a solid heated length ahead of the pyrolysis front to an ignition time, i.e. \( V_f = l_h/t_{ig} \). Following this approach, Fernandez-Pello \[8\] developed correlations for the spread of a flame considering two non-dimensional parameters: a non-dimensional flame spread derived from the heat transfer analysis and the Damköhler number to include the gas-phase kinetics.

The ignition time can be considered as a combination of three different processes: the time required to heat the solid fuel to its pyrolysis temperature, also called pyrolysis time \( t_p \), the time required for the fuel pyrolyzates to mix with the oxidizer, or mixing time \( t_m \), and the time required for the onset of the chemical reactions, also referred as chemical time \( t_{chem} \). This way, the ignition time is the result of \( t_{ig} = t_p + t_m + t_{chem} \). The pyrolysis time is normally longer than the mixing or chemical time, being the mayor contribution to the ignition time \[25\]. It is defined by Fernandez-Pello \[8\] as

\[
t_p = \frac{\rho_s c_s s (T_p - T_o)}{(\dot{q}_f^c + \dot{q}_f^r + \dot{q}_e^r - \dot{q}_r^s)} \quad (1.4)
\]

for a thermally thin solid, and

\[
t_p = \frac{\pi k_s \rho_s c_s (T_p - T_o)^2}{4(\dot{q}_f^c + \dot{q}_f^r + \dot{q}_e^r - \dot{q}_r^s)^2} \quad (1.5)
\]

for a thermally thick solid, where \( \dot{q}_f^c \) represents the convective heat flux at the solid surface, \( \dot{q}_f^r \) is the flame radiant flux, \( \dot{q}_e^r \) is the radiant external heat flux, and \( \dot{q}_r^s \) the re-radiation from the solid. \( T_p \) and \( T_o \) represent the pyrolysis and initial temperatures of the solid. Depending on the conditions, the mixing time is usually considered very small when compared to the pyrolysis or chemical time, therefore is usually assumed to be negligible \[8\]. Lastly, the chemical time is usually very fast; however, under certain conditions, i.e. low oxygen concentration or high flow velocity, it can also be a dominant factor. Cordova et al. \[78\] derived an explicit expression for the chemical time, using a one-step Arrhenius global reaction and large activation energy asymptotics, that is given by

\[
t_{chem} = \frac{-C x}{U_\infty} \ln \left( 1 - \frac{\Gamma}{\Lambda_x} \right) \quad (1.6)
\]

where \( C \) is a numerical constant and \( x \) is the coordinate parallel to the fuel surface. \( \Lambda_x \) and \( \Gamma \) are the characteristic Damköhler number and a non-dimensional gas phase parameter, defined by \[8, 78\] as follows
\[ \Lambda_x = \frac{A \Delta H_R \rho_0 W_O E Y_{O,\infty} Y_{F,s} \exp\left(-\frac{E}{RT_f}\right)}{c_p R T_f^2 U_\infty/x} \]  

(1.7)

\[ \Gamma = 4c \left(\frac{E}{RT_\infty}\right) \left[\frac{(2 - \beta)}{\left(e^2(2 - \beta^2)\right)}\right] \]  

(1.8)

with \( \beta = T_\infty c_p / Y_{F,s} \Delta H_R \). Here \( A \) is the pre-exponential factor, \( \Delta H_R \) is the heat of combustion, \( W_O \) is the molecular weight of oxygen, and \( E \) is the activation energy. \( Y_{O,\infty} \) and \( Y_{F,s} \) are the mass fraction of oxidizer and fuel, respectively. \( R \) is the universal gas constant.

Combining Equations 1.4, 1.5, and 1.6 renders the ignition time. Then the flame spread rate can be determined as [8]

\[ V_f = l_h \left[\frac{\rho_s c_s s(T_p - T_o)}{(\dot{q}_{fc} + \dot{q}_{fr} + \dot{q}_e - \dot{q}_{rs})} - \frac{C x}{U_\infty} \ln \left(1 - \frac{\Gamma}{\Lambda_x}\right)\right]^{-1} \]  

(1.9)

for a flame spreading over a thermally thin solid, and

\[ V_f = l_h \left[\frac{\pi k_s \rho_s c_s (T_p - T_o)^2}{4(\dot{q}_{fc} + \dot{q}_{fr} + \dot{q}_e - \dot{q}_{rs})^2} - \frac{C x}{U_\infty} \ln \left(1 - \frac{\Gamma}{\Lambda_x}\right)\right]^{-1} \]  

(1.10)

for a flame spreading over a thermally thick solid. In order to calculate the flame spread velocity, the characteristic heated length is also needed, and its definition depends on the mode of flame spread being considered. For a flame propagating in a opposed flow configuration, the heated length can be assumed to be proportional to the boundary layer thickness [47], i.e. \( l_h \sim \delta \sim Re^{-1/2} \sim (x/U_\infty)^{-1/2} \). On the other hand, for a flame propagating in a concurrent flow configuration, the heated length can be assumed to be proportional to the pyrolysis length [8], i.e. \( l_h \sim c l_p^e \), with \( c \) and \( e \) being material and environmental properties.

The expressions developed by Fernandez-Pello [8] were an important step towards understanding the interaction between thermal and chemical kinetic effects, and they capture the flame spread behavior under different conditions. For a high flow velocity or low oxygen concentration and flame temperature (\( Da << 1 \)), the spread process is controlled by the gas-phase chemical reactions and therefore Equations 1.9 and 1.10 describe the right descending branch of the curves showed in Figures 1.5 and 1.6, respectively. At the same time, for a low flow velocity or high oxygen concentration and high flame temperature (\( Da >> 1 \)), the spread process is controlled by the heat transfer to the unburned solid, and therefore Equations 1.9 and 1.10 describe the left branch of the curves showed in Figures 1.5 and 1.6.

In [79], Quintiere summarizes these concepts by considering that chemical kinetics effects could be included by extending the existing model of opposed flame spread developed by De Ris.
Quintiere suggested that the flame spread rate could be obtained by using Equations 1.1 and 1.2 multiplied by a function of the Damköhler number, as shown in Figure 1.7. His approach worked well for thermally thin solids; however, in the case of thermally thick solid, the flame spread rate obtained depends on the oxidizer flow velocity directly (Equation 1.2), as well as through the Damköhler number, thus, the real flame spread rate may increase or decrease with $U_\infty$ depending on the oxygen concentration.

In Reference [8] Fernandez-Pello also extended the above analysis to concurrent flame spread by considering that in this mode of flame spread the heating length is mainly given by the flame length, and de-emphasizing the chemical kinetic effects because they are less important in this mode of spread. Following this considerations Equations 1.8 and 1.9 turn into

$$V_f = l_f \frac{(\dot{q}_{fc} + \dot{q}_{fr} + \dot{q}_e - \dot{q}_{rs})}{\rho_s c_s s(T_p - T_o)}$$

(1.11)

for a flame spreading in a concurrent flow over a thermally thin solid, and
Figure 1.6: Flame spread rate over thick PMMA sheets as a function of the opposed forced flow velocity for several oxygen mass fractions of the gas flow. computed \[75\].

\[
V_f = l_f \frac{4(\dot{q}_{f_c} + \dot{q}_{f_p} + \dot{q}_{e} - \dot{q}_{rs})^2}{\pi k_s \rho_s c_s(T_p - T_o)^2}
\]  
(1.12)

for a flame spreading in a concurrent flow over a thermally thick solid.

During the spread process, the flame is covering the unburned solid, therefore the heated length is better defined as the distance, on the material surface, between the flame tip and the pyrolysis front. The flame tip or height can be obtained from different methods; it can be calculated by solving the gas phase and determining the position where all the fuel has been consumed, or by calculating the distance above the burning surface that is required for all the excess of pyrolyzates to be consumed. Quintiere et al. [80] presented an expression to obtain flame height as a function of the heat release rate given by
Figure 1.7: Qualitative dependence of opposed flow flame spread rate with Damköhler number, D, [79].

\[ l_f = c \left( \frac{\dot{Q}'}{c_p T_f \rho_f g^{1/2}} \right)^{2/3} \]  \hspace{1cm} (1.13)

where \( \dot{Q}' \) is the heat release rate per unit of width of fuel. This expression agrees with what is presented by Fernandez-Pello [8] since the heat release rate is proportional to the pyrolysis length [8]. In the case of thin fuels, as the material burns, there is also fuel burnout at the upstream edge of the fuel surface, so the flame length is controlled by the pyrolysis length, i.e. the difference between the pyrolysis front and the fuel burnout. Figure 1.8 shows the progress of the flame tip, pyrolysis and burnout front for flames spreading over thin paper in concurrent air flow.

### 1.3 Contribution of present work

The research conducted in the present work has the goal of expanding the current understanding of material flammability of solid fuels in different environmental conditions. An initial task was taken to look into the limiting conditions for flame spread of fire resistant materials that could be applied to different types of environments. The effect of variables such as ambient pressure, oxygen concentration, and external radiation on such limiting conditions was studied, trying to assess the importance and effect of each one of them on the flame spread process over these materials. Later, the focused of this research moved to material flammability primarily in ambient conditions.
relevant for spacecraft application, following NASA’s general plan to transition to new cabin environments that would use reduced cabin pressure and increased oxygen concentration. This was done by looking at the effect of buoyancy, using low pressure environments, on flame spread behavior and flame appearance. Comparisons with microgravity data obtained in a spacecraft during the Saffire flights I, II, and III [82] provided an insight of what is to be expected in spacecraft conditions and the similarities between those conditions and low pressure atmospheres. This work provides an insight into low-pressure flammability testing to simulate microgravity environments by taking advantage of the changes in buoyancy.

The following pages of this dissertation are organized as follows. Chapter 2 covers the experimental setup and background for the experiments performed on earth as well as those performed in microgravity during the Saffire tests. Chapter 3 presents experimental flammability limits for flame...
spread of fire resistant fabrics exposed to different environmental conditions of ambient pressure, oxygen concentration, and an external radiant heat flux. In Chapter 4 and 5, an experimental study is presented along with a phenomenological analysis to simulate the burning behavior of thin and thick solids in microgravity conditions by using low pressure environments. In Chapter 6, a similar approach is presented to study the effect of ambient pressure and oxygen concentration on the concurrent/upward flame spread over a fire resistant fabric exposed to two different sources of heating, making further comparisons between low pressure and microgravity environments. Finally, in Chapter 7 concluding remarks are given.
Chapter 2

Experimental Setup

The experimental task of this work included studying the flammability of different materials exposed to different environmental conditions of ambient pressure, oxygen concentration, and external radiant heat flux. To accomplish this, the work was focused on determining flammability limits for flame spread and measuring flame spread rates along with other main flame characteristics, i.e. pyrolysis length, flame tip. The majority of the experiments reported here were conducted in normal gravity at the Combustion and Fire Processes Laboratory at U. C. Berkeley. A few tests were conducted in microgravity in an unmanned spacecraft. In this chapter the setups of both experiments are presented.

2.1 Normal gravity experiments

The normal gravity experiments were conducted in a modified version of the FIST (Forced Ignition and Flame Spread) apparatus, developed previously at U.C. Berkeley under NASA sponsorship to study flammability of solid combustible materials in environments expected inside of spacecraft [83]. The original version of the FIST apparatus was used to study the effects of uniform heat flux, oxygen concentration, and oxidizer flow velocity on the ignition delay and critical pyrolysite mass flux at piloted ignition for a polypropylene glass-fiber composite (PP/GL) and polymethyl methacrylate (PMMA) [83]. After that work was completed, the apparatus was modified and placed inside a pressure vessel (renamed FIST/ESA) to study the ignition of materials, particularly thick PMMA, in NASA’s proposed new spaced explorations atmospheres, i.e. reduced cabin pressure and increased oxygen (∼60 kPa and ∼34% oxygen concentration by volume) [84–86]. Later on, FIST/ESA was used to study the flammability of fire resistant materials, when burning on one side, by looking at the critical radiant heat flux necessary for the flame to spread over the solid surface [87]. Up to that point, the majority of the tests conducted inside the FIST/ESA apparatus consisted of one-side burning of different solids. In comparison, all the experiments included in this research are performed with both faces of the sample exposed to the forced flow, therefore it was necessary to make some modifications to the FIST/ESA apparatus to conduct the new tests.
The new apparatus consists of a laboratory scale combustion tunnel that is inserted inside the same pressure chamber previously used. A schematic of the combustion tunnel inside of the pressure chamber is shown in Figure 2.1. A photograph of the pressure chamber and the combustion tunnel are presented in Figure 2.2.

The tunnel has a 125 mm by 125 mm square cross section and a 600 mm total length. The first 350 mm section of the duct serves as a flow straightener, where inlet gases pass sequentially through perforated stainless-steel plates, a 30 mm layer of 35 mm borosilicate beads and 40 mm thick, aluminum honeycomb with 6 mm cells before entering the test section. This configuration was tested with hot-wire anemometry, at atmospheric pressure, and found to provide steady flow that was uniform to within ± 3.5% at the duct outlet.

The other 250 mm segment of the duct is used as the test section. The side walls of the test section normal to the plane of the samples are made of clear polycarbonate with low profile pins protruding slightly (∼2-3 mm) into the duct to constrain the samples and keep them straight. The walls parallel to the sample are 0.56 mm thick alkali-aluminosilicate glass to improve the image from video and to permit the transmission of radiant flux from outside the duct. The samples used are located vertically at the midplane of the test section with both sides exposed to the flow. Ignition of the solid material is induced with a 29-gage Kanthal wire, that is energized using a controlled current power supply (BK Precision 1785). The time required to assure ignition, as well
as the current applied to the igniter, changes depending on the environmental conditions tested and the material properties.

Eight K-type thermocouple connections were passed through the walls of the pressure chamber and connected to a data acquisition system to record surface temperature of the solid.

Additionally, four quartz near-infrared halogen lamps (Ushio QIH120500T/S) are used as the source of radiant flux. The lamps are located immediately outside of the alkali-aluminosilicate windows, two on each side of the duct. They are mounted on rails that allow them to be easily removed or repositioned depending on what is needed. Each lamp has a lit length of 127 mm and a total length of 220 mm and are half surrounded and supported by parabolic reflectors (Research Inc. 5236- 05-A). For the experiments presented here, the lamps were set to provide a constant heat flux over the samples. The distribution of heat flux from one side was measured using a Schmidt-Boelter radiometer. Lateral flux uniformity was 5%. A calibration of the radiant heaters is included in Appendix A. Power to the lamps is controlled by a variable transformer (2000 VA / TDGC-2KM) and monitored by measuring both the voltage delivered to and current drawn by the ensemble of lamps.

Compressed house air is supplied through critical nozzles (O’Keefe Controls) while constantly evacuating the pressure chamber to maintain constant its pressure. The chamber pressure is controlled by a high-capacity vacuum generator (Vaccon JS-300) and a mechanical vacuum regulator. After metering the flow, the supply line passed through a bulkhead in the pressure chamber and delivers the gas directly to the inlet of the test duct located in the bottom part of the duct. This process ensures that flow through the duct is continually fresh and maintained at a constant mass flow rate. The correct operation of this configuration is constantly verified by monitoring the pressure inside of the vacuum chamber with an electronic pressure transducer (Omega Engineering, Inc. PX303-015A5V).

As part of the work, different materials were tested to include thin and thicker solid fuels. The characteristics of each materials and the description of sample preparation are presented later in their respective chapters. Independent of the material tested, after the sample was prepared and placed in the holder, it was secured inside of the duct and the pressure chamber was sealed. The vacuum system was initiated and set to the ambient pressure required. After the operational pressure was achieved, the air/nitrogen and oxygen supply were activated and adjusted to provide the corresponding mass flow required to obtain the desired atmospheric conditions. Next, when in use, the heaters were energized, set to the operating voltage and the actual voltage and current provided to the lamps was recorded. Once the heaters were on these conditions were maintained for 90 s before ignition in order to provide a consistent pre-heating for all the samples. Two 9000 lumen LED were used with an operating electronic circuit to act as a strobe light to visualize and measure during the same experiment flame spread rates and the flame appearance. At this point, pressure was checked again to be at the expected values, the video recording was started and the igniter was energized. The ignition and subsequent flame spread were video recorded with a resolution of 1280
Figure 2.2: Photograph of the (a) vacuum chamber and (b) combustion tunnel.

by 720 at 59 frames per second using a Nikon D3200 camera to track the pyrolysis front. A second camera (Sony RX10-III) was used to record videos of visible flame length with a resolution of 1280 by 720 at 59 frames per second. When the radiant heaters were in use, a 532 nm dichroic filter was used to improve visibility by suppressing the substantially long wavelength light of the radiant flux.

2.2 Micro-gravity experiments

The microgravity experiments were conducted in between 2016 and 2017 on board of the Orbital ATK’s Cygnus spacecraft, as part of a NASA project called Spacecraft Fire Safety Experiments (Saffire). The Cygnus vehicle is an autonomous cargo supply to the International Space Station (ISS). Because the vehicle is autonomous it allowed to carry out the experiments, after leaving the ISS and before de-orbiting, without the involvement of any astronaut on board the spacecraft. This not only alleviated the concern of crew safety for a large, unexpected fire, or multiple ones, but it is also an innovative, unique, and novel utilization of an existing microgravity platform. In comparison to previous experiments done on board of the International Space Station, or microgravity experiments performed on earth on parabolic flights or drop towers, the samples used in Saffire had the advantage of allowing a large-scale fire test, or multiple small test, in a long duration microgravity environment without putting at risk the safety of human lives. Figure 2.3 shows a depiction of the flow duct mounted on board the Cygnus spacecraft.
Figure 2.3: The Saffire flow duct (a) was mounted in the Cygnus spacecraft (b). The flow duct was carried by Cygnus spacecraft (c).

The hardware used for the tests consists of a rectangular flow duct measuring 46 cm x 51 cm in cross section with fans at one end to induce a uniform flow of air through the flow duct. Adjacent to the flow duct there is the avionic bay. Figure 2.4 shows a more detailed drawing of the flow duct and avionics bay. The size of the flow duct and samples was designed with the intention of obtaining a given size for the fire. The reason for this was based on two main considerations. On one side, the resulting fire had to be at least one order of magnitude bigger than previous fire experiments to be able to study large scale effects. However, on the other side, it could not be simply made as large as possible because it could compromise the integrity of the spacecraft. Thus, an intermediate fire size was chosen to consider a scenario where the vehicle and crew have a chance to respond.

Two cameras were used to record images of the burning samples at 30 fps, with each camera spanning just over half of the entire sample card. The flow duct was dark to improve flame imaging. However, the fuel samples were illuminated with green LED light periodically (for 0.4 s every 2 s) so that the pyrolysis front could be seen as the material burned. Four radiometers measured front and back side radiation coming from the flame and fuel surface. Each radiometer covered half of the entire sample card, with two of them located on each side to study the symmetry of the flame between the front and back sides. Thermocouples were arrayed to provide temperature measurements at key locations on and near the fuel and throughout the flow duct. Oxygen concentration, carbon dioxide, and pressure were also recorded upstream of the fuel in the flow duct. In addition to the Saffire instrumentation, the vehicle also provided smoke detector data.

The samples to be tested were placed in a holder located in the middle plane of the flow duct, with air flowing on both sides of the sample. A resistively-heated 29-gage Kanthal-wire (0.286 mm) was used to ignite the samples. The igniter configuration, i.e. attachment mode, ignition
time, and ignition power, changed depending on the test and the characteristics of the sample attachment. More details regarding sample configurations, materials tested, igniter settings, etc. can be found in the works of Jomaas et al. [88] and Ferkul et al. [82].

Three Saffire experiments have been conducted on the Cygnus spacecraft so far, with Saffire I, II, and III taking place on CRS OA-6 (Commercial Resupply Services Orbital ATK-6), CRS OA-5, and CRS OA-7, respectively. The main objective of these tests was to study material flammability and flame spread behavior of a larger scale microgravity fire to capture the effect of the complex scale dependent phenomena at relevant length scales. At the same time, these experiments served for validation of different numerical models and screening tests for materials that are consider for use in space. During Saffire I, a large sample of a thin material was burned under similar conditions currently used inside the International Space Station (ISS). Saffire II consisted of a series of 9 different samples burned in different configurations and with different structures. At this point the samples used for Saffire II consisted of thin and thick solids and were significantly smaller than the ones used for Saffire I or III, although they were still larger than commonly tested samples in space. Finally, during Saffire III similar conditions to Saffire I were used but the forced flow velocity was increased to focus on this parameter. Table 2.1 includes a brief description of the tests
showing the main differences between them.

Table 2.1: Spacecraft Fire Safety Experiments (Saffire) characteristics [82, 88].

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Sample size</th>
<th>burning mode</th>
<th>Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saffire I</td>
<td>1 sample. 40.6 cm by 94.0 cm</td>
<td>concurrent/opposed</td>
<td>20 cm/s</td>
</tr>
<tr>
<td>Saffire II</td>
<td>9 samples. 5 cm by 29 cm</td>
<td>8 concurrent/1 opposed</td>
<td>20-25 cm/s</td>
</tr>
<tr>
<td>Saffire III</td>
<td>1 sample. 40.6 cm by 94.0 cm</td>
<td>concurrent/opposed</td>
<td>25 cm/s</td>
</tr>
</tbody>
</table>

Currently, NASA is planning the future Saffire missions (Saffire IV, V, and VI), with new materials and new experimental conditions that could provide a better insight of what is to be expected in future space explorations atmospheres (SEA) during long exposure microgravity conditions.
Chapter 3

Downward Flame Spread Limits of Fire Resistant Fabrics

The selection of fabric materials used in fire safety applications, such as the suits for firefighters, car racers and astronauts, is important when trying to reduce the harm that a fire could cause to the individuals. The fire resistant performance of these materials is generally tested under standard atmospheric conditions. However, their flammability properties can change depending on the ambient conditions at which they are exposed. In certain environments such as high-altitude locations, or inside of aircraft and spacecraft cabins, pressure and oxygen concentrations may be different than in a standard atmosphere. Additionally, external thermal radiation is a common setting when materials are exposed to an adjacent fire, or an overheated adjacent device, so it is also an important variable to consider. In this chapter, experiments are presented to study the influence of environmental variables such as oxygen concentration, ambient pressure and external radiant heat flux on the flame propagation limits and flame spread rates of two different fire resistant fabrics: Nomex HT90-40 and a blend made of Cotton/Nylon/Nomex. In the tests, oxygen concentration is reduced until the limiting conditions for flame propagation (LOC) are found at each ambient pressure and radiant heat flux considered. Among the results, it was found that as ambient pressure is reduced the oxygen concentration required for the flame to propagate must be increased. The external radiant heat flux acts as an additional source of heat and allows propagation of the flame at lower oxygen concentrations. An analysis of the propagation limits in terms of the partial pressure of oxygen suggest that the LOC of a material is not only determined by heat transfer mechanisms but also by chemical kinetic mechanisms. The information provided in this work helps identify increased flammability risk of materials that are tested under standard atmospheric conditions but that can be further considered for applications at non-standard environments.

This chapter is based on research previously published in Fire Safety Journal [17] and presented at the Eighth International Seminar on Fire & Explosion Hazards in Hefei, China [89].
3.1 Background research

It is well known that the flammability of a material does not only depend on its chemical and physical properties, but also on the surrounding conditions at which it is exposed. When a material is exposed to a fire in different environmental conditions its behavior can change dramatically. Therefore, from a fire safety point of view, it is important to understand how these environmental conditions can affect the burning characteristics of a material. Changes in ambient pressure, oxygen concentration, gas flow velocity, an external heat flux, or gravity, are relevant environmental variables studied in this context. Over the years, several researchers have shown interest in the study of the flammability properties of materials and their flame spread behavior under different environmental conditions. McAllister et al. [85] and Fereres et al. [86] studied the effect of pressure and oxygen concentration on ignition delay time and critical mass flux for ignition of thick PMMA samples finding that both parameters decrease as ambient pressure is reduced, suggesting an increase in the flammability risk at low pressures.

Frey and T’ien [90] studied flame spread over thin paper samples in a horizontal and a downward configuration, looking at the effect of reducing oxygen concentration or reducing pressure on the flame spread rate and flame temperature near extinction. From their results, the authors showed that at high enough pressures, flame spread rate was independent of this variable. However, near extinction, the flame spread rate became strongly dependent on ambient pressure.

Kleinhenz [91] studied Nomex III burning in a downward configuration under different environmental conditions and found that the flame spread rate decreased as ambient pressure was reduced. For the same set of experiments Kleinhenz also found the limiting oxygen concentration at one atmosphere to be 28 vol.%. Kleinhenz and T’ien [92] also tested Nomex III burning in an upward configuration under different environmental conditions and found that flame spread was possible at an oxygen concentration of 24 vol.% for pressures as low as 50 kPa.

Harper et al. [93] studied the time required for common spacecraft materials exposed to oxygen to return to reduced flammability after removal from the increased oxygen concentration environment. The authors focused on the use of multiple different material, relevant for spacecraft application such as Nomex HT90-40, cotton, polyethylene foam, among others. They used a two-phase test methodology that included the NASA-STD-6001A flammability test and the ASTM Standard F1927, finding that for porous materials, despite the low risk of oxygen entrapment, care should be taken when considering different configurations and saturation conditions.

Additionally, when microgravity is considered, material flammability can vary even more. Kimzey [94, 95] showed experimentally that in quiescent environments, a less flammable condition was encountered in microgravity when compared to normal gravity. However, when very low air flows are introduced in these microgravity environments, materials that would not burn in normal gravity can sustain a flame [96, 97]. Olson et al. [62] conducted experiments using Nomex HT90-40 and found that the limiting oxygen concentration required for flame spread in micro-
gravity is about 4 vol.% of O\textsubscript{2} lower than the one in normal gravity. Hirsch et al. \cite{57, 60} tested different materials to identify their flammability risk under different oxygen concentrations and ambient pressure. Their results showed that the limiting oxygen concentration that allowed flame spread depended inversely on the total pressure; however, they also noticed an opposite linear trend when considering the partial pressure of oxygen. Nakamura and Aoki \cite{98} studied the flammability of thin samples of cellulosic paper under the effects of sub-atmospheric ambient pressure and different oxygen concentrations. Their results showed a wider flammable range at lower pressures, presenting the same linear trend found in \cite{60}.

The presence of an external radiant heat source has also been of interest in flammability related studies, since it can represent a potential setting when a combustible material is exposed to an adjacent fire or an overheated device. Quintiere et al. \cite{99} measured ignition, downward and lateral flame spread of different materials using a decaying heat flux in an apparatus named “Lateral Ignition and Flame Spread Test” (LIFT). From the study a testing method from the American Society for Testing Materials (ASTM) was established to measure specific parameters useful in the prediction of ignition and fire behavior in combustible materials. Osorio et al. \cite{87} also focused on the effect of an external heat flux and oxygen concentration on the limiting conditions for flame spread of fire resistant fabrics when exposed to a forced flow and burning only on one side. Their results showed that for a given oxygen concentration there is a minimum external heat flux that allows flame spread to occur. Additionally, extensive research has also been done using external heating when studying the flammability of electrical wires and their behavior in different environments \cite{63, 64, 100}.

### 3.2 Experimental conditions and samples

The apparatus used for the experiments presented in this Chapter is the same as the one described in Chapter \cite{2}. The experiments presented were performed in a downward configuration, i.e. the direction of the forced flow was opposed to the direction of the flame spread. Four different ambient pressures that ranged from 40 to 100 kPa were considered. Flow velocity was set at 10 cm/s and oxygen concentration was varied between 14 and 35 % by volume, depending on the material that was being tested. Experiments were performed using different levels of external radiation to evaluate the influence of this variable.

For the experiments two materials were considered: a single layer of Nomex HT90-40 (Stern and Stern Industries Inc., Hornell, NY, USA) and a single layer of a fabric blend made of 29% Cotton, 31% Nylon and 40% Nomex (Magnafabrics, Denton, NC, USA). Nomex is the registered name for a flame resistant and high temperature resistant fabric made by DuPont \cite{101}. It is made from a synthetic aromatic polyamide polymer and its structure is composed by long strong flexible chains that compose the fibers. Given its structural characteristics, Nomex does no melt, drip or sustain combustion in normal air conditions, however when exposed to high temperatures py-
rolyzes and leaves a char residue. Both of these materials, pure Nomex and the fabric blend, are characterized as fire resistant and have been studied previously [87] in the context of understanding the interactions of different oxygen concentrations and the minimum external heat flux at which the flame would propagate in environments similar to those in high altitude locations and aircraft environments. The present work differs from that of Osorio [87] in that flame spreads downward with both sides of the sample exposed to the air flow, and pressure is incorporated as a parameter of the problem to simulate better the SEA environment in future spacecraft. Table 3.1 shows some of the main properties of the materials tested and Figure 3.1 shows a photograph of them.

Table 3.1: Information on the fabrics used in this study.

<table>
<thead>
<tr>
<th></th>
<th>Nomex fabric</th>
<th>Blend fabric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fabric composition</td>
<td>100% Nomex®</td>
<td>29% Cotton</td>
</tr>
<tr>
<td></td>
<td></td>
<td>31% Nylon</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40% Nomex®</td>
</tr>
<tr>
<td>Area Density (mg/cm²)</td>
<td>24.41</td>
<td>20.72</td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td>0.30</td>
<td>0.38</td>
</tr>
<tr>
<td>Weave pattern</td>
<td>HT090</td>
<td>Not available</td>
</tr>
</tbody>
</table>

To place the fabric samples inside the test duct, they were held between two stainless steel support plates of 200 mm by 125 mm and 0.4 mm thick. Each plate had an identical rectangular opening 150 mm in the flame spread direction and 75 mm wide, which was the test sample area (See Figure 3.2). Because the samples were burned in a downward configuration, the igniter wire was woven on the top, downstream side, of the samples. In some cases, char fragments would fall over the unburned material, so two evenly spaced 0.3 mm diameter chromel wires were attached to the outer faces of the support plates in the direction of spread in order to hold the char sample in place and prevent inconsistency between the tests. The presence of these wires produced no visible disruption on the flame or flame spread process and fulfilled the purpose of holding in place the
sample charred. Each sample holder was fitted with electrically insulated posts to connect Kanthal wires for ignition. For each sample, these wires were sewn into the fabric at approximately 5 mm from the top of the opening in the holder.

During the experiments, the procedure followed was the same for all test and was derived from the Oxygen Index tests described in NASA-STD-6001B [5] and the definition of LOC as presented by Fujita [54].

### 3.3 Results

#### 3.3.1 Downward flame spread limits

For the present study, flame propagation was considered to have occurred when the flame propagated distances longer than 10 mm away from the igniter. Based on this flammability criterion, the limiting oxygen concentration (LOC) for flame spread was determined as the environmental condition at which all of the tests resulted in no propagation of the flame, and at least one at the following higher oxygen concentration resulted in full or partial propagation of the flame. For this work, full propagation over the sample refers to the complete burn after the flame propagated over the entire sample. Partial propagation refers to when the flame would propagate more than 10 mm
away from the igniter but self-extinguish before burning the sample entirely. A no propagation test was considered when ignition was achieved but the fabric would only burn around the igniter and no propagation would be observed.

To find the LOC of the fabric as a function of ambient pressure, for a given pressure the oxygen concentration was reduced until the flame no longer propagated. The probability of burning ($P_b$) was evaluated as the ratio between the number of cases that resulted in flame propagation ($N_b$) and the total number of repeating tests ($N_{tot}$), as shown in Equation 3.1. For each of the conditions tested between three and five experiments were done to address the variability of the results.

\[ P_b = \frac{N_b}{N_{tot}} \cdot 100 \] (3.1)

Figure 3.3(a) shows the experimental data collected for the downward flame spread/no flame spread boundary for Nomex HT90-40 using an external radiant heat flux of 5 kW/m$^2$. The circles show the calculated probability of burning and they are colored according on the color-bar at the right-hand side of the figure. Thus, black circles denote conditions were no flame propagation was observed and bright yellow circles denote conditions were all the tests showed flame spread. The plotted probability helps identify the limiting flame spread boundary and this is presented by a dashed line that indicates the limiting oxygen concentration for flame spread, LOC, for each ambient pressure. During the experiments, higher oxygen concentrations were initially tested resulting in a bigger flame that propagated uniformly over the entire fabric sample, leaving behind a char residue. As the oxygen concentration was reduced the flame spread started transitioning to an irregularly shaped pattern and in some cases, extinction occurred before the flame could propagate over the total length of the sample. Figure 3.4 shows an example of a uniform shaped propagation front, a non-uniform propagation front, and a no propagation test. In some of the experiments, when close to the limiting condition, the flame propagation front would spread in a diagonal way that overcame the effect of the flow velocity and prevented its extinction. When the oxygen concentration approached the limiting values for propagation, after ignition was achieved, the fabric would only burn around the igniter and no propagation was observed.

A similar set of experiments was performed using the fabric blend of Cotton/Nylon/Nomex. Figure 3.5 shows the experimental data collected, presenting also the boundary for flame and no flame spread with and without the external radiant heat flux. In this case, the experimental results seem to follow a similar trend as for Nomex, however the lower content of Nomex (fire resistant material [101]) is clearly reflected in a lower oxygen concentration (LOC) required for the flame to propagate at the same ambient pressures.

Overall, the trend is consistent and independent of the fuel that is being considered; as pressure is reduced an increase in the oxygen concentration is required for the flame to propagate over the material. Similar conclusion can be done for the data obtained without the external heat flux, as shown in Figure 3.3(b) and Figure 3.5(b). The results in this case follow the same trend; however, for both types of fabric, the flame spread boundary, and the LOC for each pressure, is higher than
Figure 3.3: Flame spread boundary for Nomex HT90-40 as a function of ambient pressure and oxygen concentration at an external radiant flux of (a) 5 kW/m$^2$ and (b) 0 kW/m$^2$.

Figure 3.4: Example of a uniform propagation test (a), a non-uniform propagation test (b), and a no propagation test (c) for Nomex HT90-40. Experiment conditions are as follow: (a) 60 kPa, 31 vol.% of O$_2$ and 5 kW/m$^2$, (b) 60 kPa, 29 vol.% of O$_2$ and 5 kW/m$^2$, and (c) 60 kPa, 31 vol.% of O$_2$ and 5 kW/m$^2$. 
Figure 3.5: Flame spread boundary for the fabric blend as a function of ambient pressure and oxygen concentration at an external radiant flux of (a) $5 \, kW/m^2$ and (b) $0 \, kW/m^2$.

the boundary obtained using the external radiation. The external heat contributes to the heat provided by the flame to pyrolyze the fuel and compensates for the lower flame temperatures at lower oxygen concentrations, allowing the flame to propagate at these lower oxygen concentrations.

A similar analysis of the limiting conditions for flame spread can also be performed in terms of the ambient pressure and the partial pressure of oxygen. Understanding the flammability of materials in terms of the oxygen partial pressure is of importance because this allows to easily relate the flammability of the material to ambient conditions that are suitable for human living (Normoxic conditions) [102], which are conditions that are strictly required when designing environments for human applications. A normoxic atmosphere is defined by the combination of ambient pressure and oxygen concentration where the oxygen partial pressure is equal to that experienced in air at sea level.

Figure 3.6 shows the boundary for flame and no flame spread plotted in terms of the partial pressure of oxygen for the Nomex and the fabric blend for no radiant flux and a radiant heat flux of $5 \, kW/m^2$. It is seen that when the experimental data is presented in terms of the oxygen partial pressure, the limiting flame spread boundary shows a linear trend. This trend is similar to the data presented in previous works [60, 98, 103]. In the pressure range studied (100 to 40 kPa), the required partial pressure of oxygen for ignition decreased almost linearly as the total pressure decreased. The data from Nakamura and Aoki [98] for cellulose paper and Hirsch et al. [60] for polyethylene and silicone are presented in Figure 3.6 for comparison purposes. It is seen that within that range of pressures tested the data for the three materials follows the same linear trend
as the materials tested in the present work. As it can also be seen in Figure 3.6, at ambient pressures lower than 80 kPa, Nomex becomes flammable in normoxic equivalent environment since the boundary is below the normoxic line. The fabric blend has proven to be flammable in normoxic equivalent environment over the entire range of pressures tested. These results are particularly relevant for determining material flammability in future spacecraft or other environments where both pressure and oxygen concentration are varied to provide a sustainable living environment.

From Figure 3.6, it can also be noted that the limiting oxygen concentration for flame spread is altered somewhat by the external heat flux, although the trend is still linear. Independent of the type of fabric or the ambient conditions, the change in the flame spread boundary limits when an external heat flux is present seems to be proportional to a change in the partial pressure of oxygen.

The linear character of the flame spread boundary when presented in terms of partial oxygen pressure is somewhat puzzling. As it is stated in the discussion section, it is speculated that this behavior is related to the reactivity of the flame at its leading edge. A decrease in ambient pressure will require a proportional change in the partial pressure of oxygen in order for the mixture generated to be reactive.

![Flame spread diagram](image)

Figure 3.6: Flame/No Flame spread boundary for fire resistant fabrics and other materials as a function of O\(_2\) partial pressure and total ambient pressure.
3.3.2 Downward flame spread rate

Flame spread rate was measured under conditions that were similar to those used for determining the flame spread limits. The non-uniform and diagonal flame spread encountered very close to the limiting conditions were not well-defined because flames were no longer propagating in direct opposition to the oxidizer flow. For this reason, those conditions were not considered. Flame spread data was collected from observation of the video recordings of the downward progress of the flame. The location of the pyrolysis front was defined as the point where the fabric was first visibly blackened. Pyrolysis front was then tracked over time with a script written in Python, using OpenCV libraries to aid in the processing of the images. For this process frames were taken in sequence every 5 second intervals.

The observed, averaged flame spread rates are presented in Figures 3.7 and 3.8 for a high (5 kW/m^2) and low (1 kW/m^2) value of external heat flux. The consistent trend across all of tests was that flame spread rate increased with pressure, oxygen concentration and external heat flux, as was observed also from the flammability boundaries. It was observed that the spread rate was most sensitive to oxygen concentration, where a reduction of 2% in the oxygen concentration was found to reduce the flame spread rate as much as a 60% reduction in pressure. In contrast with the limiting behavior, the external radiant flux had a significant impact on spread rate across both materials and a wide range of conditions.

![Figure 3.7: Downward flame spread rate over Nomex as a function of partial pressure of oxygen with (a) 5 kW/m^2 and (b) 1 kW/m^2 external heat flux.](image)

3.4 Discussion on flame spread limits

The flame spread process over a thin solid fuel can be discussed in terms of the effect of the environmental variables studied here. When the flame is spreading over the fuel surface different
Figure 3.8: Downward flame spread rate over the fabric blend as a function of partial pressure of oxygen with (a) 5 kW/m$^2$ and (b) 1 kW/m$^2$ external heat flux.

physical, thermal and chemical mechanisms interact at the same time making the understanding of the flame behavior complicated. Several researchers have developed theoretical models of the flame spread process, starting from different analytical models to more complex numerical simulations. The reader is referred to the works of Williams [46], Wichman [49], Delichatsios [104], Hirano [71], Bhattacharjee [73] or Takahashi [105], for references on the subject. Here, the analysis developed by Fernandez-Pello [8] is used to understand part of the general phenomenology behind the process. That analysis describes flame spread rate as:

$$V_f = l_h \left[ \frac{\rho_s c_s s (T_p - T_o)}{h (T_f - T_p) + \dot{q}_{fr}' + \dot{q}_{e}'' - \dot{q}_{rs}'' - \frac{C x}{U \infty} t_{chem}} \right]^{-1}$$  \hspace{1cm} (3.2)

where $l_h$ is the heated zone of the solid, $h (T_f - T_p)$ represents the heat flux from the flame to the surface through convection, $\dot{q}_{fr}'$, the heat flux provided by the flame by radiation, $\dot{q}_{e}''$ is the external radiant flux, and $\dot{q}_{rs}''$ the re-radiation from the solid. $U \infty$ the gas flow velocity, $x$ is the coordinate parallel to the surface, $t_{chem}$ the chemical time, $\rho_s$ and $c_s$ are the solid density and specific heat, and $s$ is the solid thickness. $T_f$, $T_p$ and $T_o$ represent the flame, pyrolysis and initial temperatures of the solid respectively.

From Equation (3.2) it can be noted that the addition of an external heat flux will have an impact in the heating process of the solid increasing the flame spread rate. Oxygen concentration will influence the heat provided by the flame to pyrolyze the fuel as it affects the flame temperature, allowing the flame to propagate faster at higher oxygen concentrations. As oxygen concentration is decreased the external radiant flux must supply the additional heat required for the flame to propagate. These effects will remain the same independent of the fuel considered.

For downward flame spread over a thin fabric sample, the main heat transfer mechanism to the
solid is given by the gas-phase heat conduction ahead of the flame. In this type of configuration the flame is located at a small distance from the solid acting as the main source of heat to pyrolyze the fuel. As the ambient pressure is reduced the heat transfer from the flame to the solid is affected because the thickness of the boundary layer, $\delta$, is increased and the flame moves away from the solid. In mixed/forced flows, this stand-off distance described by the boundary layer thickness is proportional to a combined Reynolds number ($Re$) and Grashof number ($Gr$) as

$$\delta \propto l_p \left(Re^4 + Gr^2\right)^{-1/8} Pr^{-1/3}$$

(3.3)

At the same time, when pressure is reduced the convective heat losses from the surface to the surroundings are also affected because the heat transfer coefficient is reduced. Both, convective heat transfer from the flame to the solid and the heat loss from the surface are proportional to the convective heat transfer coefficient, which can be scaled by the same non-dimensional numbers ($Re$, $Gr$), so

$$h \propto \frac{k}{l_p} \left(Re^4 + Gr^2\right)^{1/8} Pr^{1/3}$$

(3.4)

Then their relation to changes in ambient pressure can be determined from the definitions of the Reynolds and the Grashof numbers:

$$Re = \frac{\rho U_\infty l_p}{\mu} \Rightarrow Re \propto P$$

(3.5)

$$Gr = \frac{\rho^2 \beta g l_p^3 P}{\mu^2 \Delta T} \Rightarrow Gr \propto P^2$$

(3.6)

where $\rho$, $\beta$, $\mu$, $g$, $l_p$, $P$ and $\Delta T$ are the flow density, volumetric thermal expansion coefficient, viscosity, gravity, pyrolysis length, pressure and the temperature difference between the solid and the surroundings. The interaction between the heat input and the heat losses suggests that the heat provided by the flame to pyrolyze the fuel is partially compensated by a simultaneous reduction in the heat losses from the surface, making the total effect of pressure less significant when compared to other variables. When oxygen concentration and ambient pressure are simultaneously changed, if the ambient pressure is significantly reduced an increase in the oxygen concentration is required in order to sustain pyrolysis and avoid extinction of the flame. An external radiant source also compensates from a reduction of oxygen concentration and pressure.

Equation [3.2] also shows that the environmental variables also influence the chemical kinetics in the gas phase. This helps explaining the observed linear relationship of the effect of pressure on the LOC when described in terms of the partial pressure of oxygen. Osorio [103] discussed the effect on the flame propagation limits by the rate of chemical reactions in the gas phase. Starting from a two-component global reaction, he demonstrates that a critical characteristic chemical time, $t_{chem}$ can be maintained by an approximately linear relationship between pressure and oxygen partial pressure. This very fundamental analysis begins to explain the experimental observations, but
only provides a limited agreement with the experimental observations. Most notably, linear fits to the observed limits require a non-zero y-intercept. A conceptually similar, but more accurate approach to the analysis in [103] is to use a detailed chemical mechanism to describe the gas-phase reactions. To this end 0-D simulations of ethane/oxidizer mixtures were conducted using Cantera [106], with the AramcoMech 1.3 [107] chemical kinetic mechanism. Ethane was selected as fuel because it has somewhat similar characteristics to pyrolyzed PMMA (MMA), a more realistic solid combustible material. Stoichiometric ethane-oxidizer mixtures initially at 1500 K were allowed to react and ignition delay time, IDT, was determined as the point at which fuel concentration reached 90 vol.% of its initial value. Total pressure and oxidizer oxygen concentration were varied to span the conditions used in the experiments. Taking IDT as the primary measure of reactivity (an analogue of \( t_{chem} \)) lines of constant IDT were graphed in terms of P and \( P_{O_2} \) in Figure 3.9. As with the flame spread boundaries, isolines of IDT are linear in terms of these variables but do not exhibit the problematic zero y-intercepts mentioned earlier. This agreement strongly supports the premise that limiting behavior is controlled by the chemical time, i.e. the downward flame spread LOC is not only determined by heat transfer mechanisms but also by chemical kinetic mechanisms.
3.5 Conclusion

Experimental data regarding the flame spread limits and spread rated of two thin solid materials was provided under different environmental conditions. A single layer of Nomex HT90-40 and a fabric blend of Cotton/Nylon/Nomex are used as different types of fuel.

The relations between the flame spread process over the sample and the different variables of interest are presented in terms of their influence on the different heat transfer and chemical mechanisms. As ambient pressure is reduced a consequent increase in the oxygen concentration is required in order for the flame to be able to provide enough heat to pyrolyze the fuel and avoid extinction. The addition of an external heat source will provide the additional heat that is required to compensate the reduction in pressure, allowing the flame to propagate at lower oxygen concentrations.

The analysis used in this work supports an understanding of how some of the characteristics of the fire change in response to variations in environmental conditions. The data presented, together with these relations provides a clearer picture of flammability of materials and what is to be expected under untested conditions.
Chapter 4

The Effect of Buoyancy on Concurrent Flame Spread over a Thin Solid

The flammability of combustible materials in spacecraft environments is of importance for fire safety applications because the environmental conditions can greatly differ from those on earth, and a fire inside a spacecraft could have catastrophic consequences. Among their characteristic conditions, spacecraft environments include microgravity, low velocity flows induced by the ventilation system, and potentially low pressure ($\sim 60$ kPa) and elevated oxygen concentration ($\sim 34\%$). However, because in a gravity field there is a flame-induced buoyancy, it is very difficult to reproduce on earth the environmental conditions of a spacecraft, particularly the low velocity flows. The spacecraft ventilation system induces flows with velocities that are of the order 10 cm/s, while in earth gravity the buoyant flows induced by a propagating flame have velocities of the order of 30 cm/s to 60 cm/s. Thus, fire testing of materials to be used in spacecraft requires either a reduced gravity facility, or alternative approaches to reduce buoyancy. Experimental testing in spacecraft environments can be difficult and expensive, so using ground-based tests to inform microgravity tests is vital. Reducing buoyancy effects by decreasing ambient pressure is a possible approach to simulate a spacecraft environment on earth.

The objective of this work is to study the effect of pressure on material flammability, and by comparison with microgravity data, determine up to which point reducing pressure can be used to simulate reduced gravity. Specifically, this work studies the effect of pressure and microgravity on upward/concurrent flame spread rates and flame appearance of a burning thin solid. The material used in this work is a thin composite fabric made of 75% cotton and 25% fiberglass usually referred as Sibal. Experiments in normal gravity were conducted using pressures ranging between 100 and 30 kPa and a forced flow of air of 20 cm/s. Microgravity experiments were conducted during NASA’s Spacecraft Fire Experiment (Saffire), on board of the Orbital Corporation Cygnus spacecraft at 100 kPa and an air flow velocity of 20 cm/s. Results show that reductions of ambient pressure slow the flame spread over the fabric. As pressure is reduced, flame intensity is also reduced. Comparisons with the concurrent flame spread rates in microgravity show that similar flame spread rates are obtained at around 30 kPa. The normal gravity and microgravity data is correlated
in terms of a mixed convection non-dimensional parameter that describes the heat transferred from
the flame to the solid surface. The correlation provides information about the similitudes of the
flame spread process in variable pressure and reduced gravity environments, providing guidance
for potential on-earth testing of thin solids for fire safety design in spacecraft and space habitats.

This chapter is based on research previously published in the Proceedings of the thirty-seventh
Combustion Symposium [108] and presented at the forty-eighth International Conference on En-
vironmental Systems in Albuquerque, New Mexico [109].

4.1 Background research

4.1.1 Experimental background

In 1973, Markstein and De Ris [110] were one of the first ones to study upward flame spread over
thin solids using large cotton samples, about 0.9 m wide by 1.5 m long. Through their experiments,
the authors showed that the spread process was accelerating initially, and that the acceleration could
be characterized by a power-law relationship between pyrolysis spread rate and pyrolysis length.
However, as the flame progressed, and the material burn out at its bottom edge the flame length
and the flame spread rate approached a constant value. Another early study was performed by
Quintiere et al. [99] who also performed large-scale upward flame spread tests under the influence
of external radiation, using different types of solid materials (foams and polymers, among others).
The authors did not measure directly flame spread rates but looked into flame heights and their
correlations to energy release rate.

More recently, Johnston et al. [111] conducted experiments using Sibal, the same thin com-
posite fabric used in this work. The experiments were set to burn on both sides in an upward
configuration, looking at the effect of various widths using long samples (∼1.5 m). They noticed
that for thinner samples, widths about 5 cm or less, instabilities at the base of the flame would
lead to blow off on one side of the sample. The remaining flame on the other side would continue
spreading along the sample but it would quickly shrink in size. The authors suggested that flame
blow off was the result of an increase buoyancy induced air velocity at the flame base as a result of
the increasing flame length.

Over the years, researchers have also investigated the differences between flame spread in nor-
mal gravity (1g) and microgravity (µg) by looking at the effects of different variables such as
geometry, low flow velocities, type of fuel, etc. [63, 73, 97, 112–117]. The tests conducted using
ground-based facilities such as drop towers [97, 118] and airplanes flying parabolic trajectories
[119, 120] are limited by the short microgravity test duration, while past space experiments were
limited to small samples due to safety considerations on the International Space Station (ISS). For
example, in the recent BASS (burning and suppression of solids) experiment [121], experiments
were conducted aboard the International Space Station, in a small flow duct within the Micrograv-
ity Science Glovebox. The experiments looked into studying flame growth, spread, and quenching extinction over Sibal sheets of 2.1 cm by 10 cm burning in low speed concurrent forced flow in microgravity. They also looked at the effect of oxygen concentration and flow speed on flame spread rate and flame quenching, finding limiting conditions for flame spread. Feier et al. [122] also studied flames spreading in an upward configuration in partial gravity environments by doing experiments inside an aircraft flying parabolic trajectories with samples of 1 and 2 cm width. Feier et al. [122] noticed that the spread rate and the flame length were constant when using narrow samples and reduced pressure environments. Furthermore, the upward flame spread rates, the length and the pyrolysis length increased linearly with increasing the gravity level.

Olson and Miller [113] experimentally investigated a flame spread in concurrent forced flow in microgravity using Kimwipes samples as thin fuel. Among the variables changed in their study, they controlled variations in the forced flow velocity, oxygen concentration, and ambient pressure. Olson and Miller [113] found that, in typical spacecraft ventilation flows, opposed flow flames spread faster than concurrent flow flames under otherwise similar conditions of pressure and oxygen concentration because of the incoming fresh air and vitiation of the atmosphere generated near the downstream solid by the same flame. Later on, Olson et al. [123] conducted experiments in normal gravity using a narrow channel apparatus (NCA) to simulate flame spread in microgravity conditions. The narrow channel reduces the effects of buoyancy by limiting the height of the channel gap to a value where the vertical flow is small compared to the horizontal forced flow. The researchers found that for low flow speeds, like those encountered inside spacecrafts, the flame would transition from a uniform front to multiple separate flamelets, allowing the flame to continue propagating at conditions below the standard flammability limits.

One of the main findings of solid burning in microgravity environments is the importance of gaseous and surface radiation in low-intensity flames typical of those near extinction [54, 124, 125]. In previous normal gravity work, radiation in fires was considered an important mechanism for flame development only when the flame size became greater than about 40 cm, at which point these large flames yielded substantial soot radiation [126]. In microgravity, radiation becomes more important, not because the radiative flux increases, but because of the absence of natural convection. When the convective velocity decreases, the flame standoff distance increases, and the fuel burning rate decreases. As a result, the combustion heat generated decreases, resulting in a less intense flame. The rate of radiative loss, however, is decreased much slower than that of the heat generation. Consequently by comparison, the ratio of radiative loss rate to the heat generation rate increases, so the flame temperature decreases [125].

In the concurrent configuration, the solid preheating and pyrolysis rate are dominated by convection, and the external flow velocity will therefore influence the heat flux from the flame to the solid surface and the flame length [8, 117, 127, 128]. Following this line, there are clear differences in the velocity profiles between a purely forced flow or a buoyancy induced flow, therefore it is expected to observe differences in the flame spread process. Since the pyrolysis rate and consequently the flame length increases with flow velocity, an incipient flame spread may continually
grow from the point of ignition, as found in References \[129, 131\].

Given the importance of the gas flow velocity field, some researchers have tried taking advantage of reduced pressure environments to reduce gravity effects \[17–20\]. As pressure (and density) is reduced, the boundary layer thickens, and the flame moves further from the surface, reducing heat transfer to the solid \[47\]. Consequently, the rate of flame spread is reduced, both because the reduced heat flux on the surface and a reduction in the flame length \[132\]. Nakamura et al. \[18\] studied flame spread over electric wires in low pressure environments and found that the flame shape in low pressure is similar to that observed in microgravity. Fereres et al. \[20\] studied numerically solid fuel pilot ignition similarities between microgravity and low pressure environments. They found that at low flow velocities ignition in microgravity, as well as flame geometry and appearance, could be approximated by reducing ambient pressure below 50 kPa. Research conducted by other investigators showed that an upward-burning flame over thin narrow paper samples in reduced pressure could reach a steady rate and with a constant (limiting) flame length \[122, 127, 133\]. This means that the sample burnout rate was equal to the pyrolysis advance rate at the flame front. It should be noted that as pressure is reduced the buoyant flow velocity is also reduced, thus reducing the buoyant effects on the flame spread rate. Interestingly, in an experiment of flow-assisted horizontal spread with paper samples in a wind tunnel in normal gravity \[81\] it was also found that pyrolysis front spread rate became constant once the pyrolysis length reached a steady value. In this case, the horizontal configuration would also have reduced the buoyant effects on the flame spread rate.

A similar approach was taken by Kleinhenz et al. \[19\], who focused on using pressure-gravity correlations to simulate upward flame spread and burning rates of vertical solids burning in partial gravity environments. The researchers based their analysis using a theoretical factor derived from a Grashof number and correlated microgravity data for both thin and thick solids at different gravity levels. Following a similar analysis, Olson et al. \[134\] conducted experiments inside a large sealed chamber to observe the flame spread process inside large enclosures using larger samples (\(~1\) m length) and different ambient pressures. The researchers also noticed that the flame spread rate was scaled as \(~P^2\), in agreement with the findings of \[19\]. Olson et al. \[134\] noticed that a steady burning could only be obtained for the low pressure environments (about 45 kPa).

### 4.1.2 Numerical studies

The development of detailed numerical models for flame spread over thin solids has also received significant attention over the years. Ferkul and T’ien \[132\] formulated and solved a two-dimensional steady state model for concurrent flow flame spread. The authors solved full Navier-Stokes equations using different solutions for the upstream and downstream parts of the flame. They used a one-step, second-order finite-rate Arrhenius reaction to model the gas phase. The solid is assumed to be thermally thin with surface radiative losses and a surface pyrolysis relation (zeroth-order pyrolysis model). The formulation of this model allowed the investigators to analyze...
extinction limits, both quenching and blow-off. They noticed that as flow velocity or oxygen concentration is reduced, the flame spread rate, the pyrolysis length, and the flame length decreased. They also noticed that, at low flow velocities, surface radiative losses are significant, leading to lower flame temperatures, and ultimately, a quenching extinction. A few years later, Jiang et al. [135] used a similar model, also based in the Navier-Stokes equations, introducing also gas phase radiation (from CO$_2$ and H$_2$O) into the model, this modified the quantitative results but did not alter the essential features. The authors focused on the effect of gravity level, finding that flame length and spread rate increase approximately linearly with gravity level. The model developed also allowed them to predict a low-gravity flame quenching limit.

In 2001, Shih and T’ien [136] upgraded the previously developed model to move to a three-dimensional flame spread model that solves a steady form of the compressible Navier-Stokes equations with chemical reactions. The model provides insight of flame structure and details of the product exhaust, aiding in the design of future microgravity experiments. Later, the authors used their model to simulate a thermally thin, non-charring cellulosic sheet burning in a concurrent flow configuration [137]. The model included gas-phase reactions represented by a one-step, second-order, finite-rate Arrhenius kinetics and the solid pyrolysis is approximated by a one-step, zeroth-order decomposition obeying an Arrhenius law. They focused on the effect of changing the solid widths and the flow velocity, by looking at wall heat losses and oxygen side diffusion. They found that at low flow velocities, the flames are short and closer to the quenching limit, with oxygen diffusion becoming the dominant mechanism and flame spread rate increasing with narrower samples. At higher flow velocities, heat transfer to the side walls in the downstream part of the flame becomes the dominant mechanism, and therefore the flame spread rate increased with wider samples. Application of the same two-dimensional model to upward spread over thin cellulosic sample suggested that steady spread is only possible for wide samples in very small gravitational field of less than 0.1 g [138]. A transient computation showed that in addition to the magnitude of the incoming velocity, the entrance length to the flame base influenced flame length [139]. Since the flame was located inside the boundary layer, fuller velocity profiles produced a longer flame, consistent with earlier work [140, 141].

Liao and T’ien [142] used an unsteady three-dimensional model to simulate the ignition and flame development over a composite fabric made out of cotton and fiberglass. Ignition of the sample is accomplished by a localized heating by a radiant beam. The authors noticed the existence of two types of ignition modes, with reaction kernel initiated on the solid surface or in the gas phase depending on the intensity of the beam. The authors also looked at changing sample thickness, ignition heat source spatial shape factor, and gravity level.
4.2 Experimental conditions and sample

The apparatus used for the experiments presented in this chapter is the same as the one described in Chapter 2 and will not be repeated here. The experiments presented here were performed in an upward/concurrent flame spread configuration, i.e. the forced flow and the flame spread were in the same direction. Four different ambient pressures were tested, from 100 to 30 kPa. The experiments were performed using a forced flow of air set to 20 cm/s. Oxygen concentration was kept constant throughout all the test.

A thin solid material was used for the experiments presented in this chapter. The sample was selected to match one of the materials tested in the Saffire I and II microgravity experiments [82]. The material used, Sibal, was a thin sheet made of 75% by mass of cotton and 25% of fiberglass and has an overall area density is 18.0 mg/cm$^2$. The selection of this sample is based on the fact that the noncombustible fiberglass in the matrix of the fabric provides structural integrity and prevents the fabric from curling or cracking while burning, preventing the generation of debris that could disturb the flame spread. Figure 4.1 shows a closeup of the material before and after burned, showing that after burned the fiberglass mesh remains there keeping what is left of the material together. Furthermore, the physical properties of cotton are well known, which facilitates the validation of numerical models of flame spread in microgravity [121, 137, 143].

![Figure 4.1: Solid material, Sibal, (a) before and (b) after burned.](image)

The Sibal samples tested were 150 mm long by 50 mm wide, smaller than the ones used during the Saffire I and II tests, because of limitations of the pressure vessel size. The sample was held in between two identical stainless-steel frames of 200 mm by 125 mm and 0.4 mm thick. Each frame had an identical rectangular opening the size of the sample to serve as the test area. Eight K-type thermocouples were attached to the surface of the material to record the surface temperature. To assure that the thermocouples would stay as close to the sample surface as possible while the material was burning, the thermocouples were sewn into the thin sheet and then kept tight when installing the material in the holder. The recording of the thermocouples was started soon after the
system was initiated but well before ignition was achieved.

Two electrically insulated posts were fitted near the upstream edge of the holder to connect the igniter wires. Additionally, two covered channels were attached on the sides of the holder frame to protect the wires from the heat provided by the flame during the tests. For each sample, igniter wires were sewn into the fabric at approximately 5 mm from the bottom edge of the opening in the holder. Figure 4.2 shows a picture of the sample holder used during the test.

![Sample holder](image)

Figure 4.2: Sample holder used during the upward flame spread tests for thin solids. Stars labeled with T indicate the positions of the thermocouples.

The microgravity experiments presented in this chapter were conducted aboard the Orbital Corporation Cygnus spacecraft (Saffire I and II) [82] and in the Microgravity Science Glove-box aboard the ISS [121]. More details about the characteristics of the samples used in those experiments can be found in their respective publications [82, 121].
4.3 Results

The normal gravity concurrent flame spread was investigated under different ambient pressures. The primary data collected were burnout front and pyrolysis front positions (see Figure 4.3). Figure 4.4 shows two representative frames of the flame spreading over the sample. Figure 4.4(a) displays the sample with the strobe light on and shows the pyrolysis front. Figure 4.4(b) shows the same sample but this time with the strobe light off and shows the flame burnout front and flame tip. Here, the position of the pyrolysis front was defined as the point where the fabric is first visibly blackened. The burnout front position was defined as the upstream edge of the flame, which coincides with where the flame begins receding. During each test, after ignition is achieved, the flame spreads uniformly along the surface of the sample. The pyrolysis front had an inverted “U” shape in all tests. The flame tip had a flickering inverted “V” shape. The flame flickering appears to decrease as the pressure is decreased. Usually, after ignition of the sample, a short initial period of laminar flame spread was observed, followed by the flame transitioning to a turbulent flame. As the flame spreads over the fabric it consumes most of the cotton, leaving behind the fiberglass mesh and some smoldering cotton residue (bottom of Figure 4.4(b)).

To measure burnout front and pyrolysis front, an image processing tool developed in python was used. The program corrects the videos from any distortion given by the positioning of the cameras and allows the user to track the corresponding position by opening sequence of frames every 0.5 seconds. Additional to the data obtained from the videos, temperature profiles over time were recorded at 8 different positions along the surface of the thin solid. Although care was taken to ensure that the thermocouple bead was well attached and in contact with the surface of the solid, these measurements were used as an approximation and should not be considered as the absolute surface temperature value due to movement of the thermocouple when the material burns. Figure 4.5 shows an example of the temperature profiles recorded during one of the experiments. In order to validate the data extracted from the videos using the image processing tool, thermocouple measurements were used to track the evolution of the pyrolysis front over time. This was done by considering a reference pyrolysis temperature of 350 °C [121]. Figure 4.6 shows together the evolution of the pyrolysis front extracted from the videos as well as the tracking of the pyrolysis front using the data recorded by the thermocouples during the same experiment. The results presented in this figure show the good agreement existing in between both methods and serves as a validation of the image processing tool.

A characteristic result of the time evolution of the pyrolysis and burnout fronts is presented in Figure 4.7 for an ambient pressure of 40 kPa. Also included is the evolution of the pyrolysis length, which is obtained as the difference between the pyrolysis front and the burnout front. For validation purposes the data of Olson et al. [134] is also presented in Figure 4.7. Note that although the length of the samples in Ref. [134] are larger than in the present tests (1 m vs 0.15 m), both tests show very similar data during the initial part of the spread of the flame, with the flame spread rate increasing with time initially and then eventually reaching steady state for the larger samples. The results show that the samples used in the present experiments were not long enough for the flame
spread to reach steady state, although the pyrolysis front approaches steady spread faster than the burnout front.

Similar data was extracted from the images recorded with the burning samples used during the Saffire experiments. Figure 4.8 shows the evolution of the pyrolysis front and the flame burnout front over time for the Sibal sample burned during Saffire II \([82]\). The figure also includes the evolution of the pyrolysis length. From the figure it can be seen that soon after ignition, there is a short growing period (~20 s) after which the flame is stabilized with both the pyrolysis front and the burnout rate propagating at similar rates.

Figure 4.9 shows the progress of the pyrolysis front and burnout front for pressures ranging from 100 to 30 kPa. Looking at the slope of the plots, it is seen that as pressure is reduced the spread of the flame is slower. During most of the tests, the flame is still accelerating as it spreads over the solid. However, as pressure is reduced, the pyrolysis front and flame burnout front begin to stabilize faster. Similar results were also reported by Olson et al. \([134]\) with longer samples.
Figure 4.4: Front view showing two representative frames with the (a) pyrolysis front, and (b) flame tip and burnout front.

Figure 4.5: Temperature profiles over the surface of the Sibal sheet while burning under normal air and 40 kPa of ambient pressure.
Figure 4.6: Comparison of tracking methods used to record the pyrolysis front evolution over time. Test presented is for the Sibal sheet burning under normal air and 40 kPa of ambient pressure.

Figure 4.7: Location of the pyrolysis front and burnout front position, as well as the pyrolysis length, as a function of time for an ambient pressure of 40 kPa.
Figure 4.8: Location of the pyrolysis front and burnout front position, as well as the pyrolysis length, as a function of time for the microgravity test Saffire II [82].

It is seen that the average total burn time for the 100 kPa initial pressure was 13.2 s, significantly smaller when compared to the average 43.7 s obtained at about 30 kPa. For comparison purposes, the evolution of the pyrolysis and burnout fronts from the Saffire II experiments [82] are included in Figure 4.9, keeping in mind that that test was performed in microgravity at 100 kPa ambient pressure. It is seen that as the ambient pressure is reduced, the pyrolysis and burnout front data approaches the microgravity data.

The flame brightness is also affected by pressure changes, becoming weaker as pressure is reduced. In these conditions, the flame changes from a bright yellow/orange to a faint purple/orange color, as shown Figure 4.10. Visible flame height is also reduced, although for the lower pressures the flame tip becomes very diffuse and hard to define. Also, as the pressure is reduced, the flame appearance became similar to what was observed during the Saffire microgravity experiments. The photographs of the Saffire tests could not be include in Figure 4.10 to compare with the normal gravity ones because they are too dark and difficult to reproduce here.

The progress of the pyrolysis front is often used to determine the flame spread rate. Figure 4.11(a) shows the average flame spread rate as a function of ambient pressure as obtained from the pyrolysis front data of Figure 4.9. Because of the size of the samples, and the accelerative characteristics of the flame, an averaged spread rate over the last 50 mm of the sample is presented so that the data are closer to the steady state value and transient effects are minimized. For comparison, the flame spread rate data of Saffire I and II [82] and the microgravity data of Zhao et al. [121] are also included. It is seen that in normal gravity the flame spread rate decreases from 41.8 to 5.4
mm/s as the ambient pressure decreased from 100 to 30 kPa, at which point the flame spread rate was similar to the microgravity value in the Saffire II test of 2.03 mm/s.

An important parameter for concurrent flame spread is the pyrolysis length because it determines the amount of fuel being pyrolyzed, and consequently the flame length, and in turn the heat transferred from the flame to the solid. The variation of the pyrolysis length with pressure is included in Figure 4.11(b). The pyrolysis length is obtained toward the end of the test when it approaches steady state. It is seen that in normal gravity the pyrolysis length decreases with decreasing ambient pressure. As pressure is reduced to 30 kPa, the pyrolysis length in normal gravity approaches that in microgravity. Both results are an indication that concurrent flame spread in low pressure and normal gravity, may have similar characteristics as that in reduced gravity. It should be kept in mind however, that the total pressure reduction necessary to see these similarities will vary depending of the material and environmental conditions used.

4.4 Discussion

To understand the observed dependence of the flame spread rate on pressure it is helpful to use a simplified analysis of flame spread as that developed by Fernandez-Pello [8]. The analysis provides an analytical equation for the concurrent flame spread rate as:

\[
V_f = l_{st} \left( \frac{\rho_s c_{ss}}{q_{fe} + q_{fr} - q_{rs}} \frac{T_p - T_o}{C_x} + \frac{C_x}{U_m t_{chem}} \right)^{-1}
\]  

(4.1)
where $l_h$ is the heated length, $\dot{q}_{fc}''$ represents the convective heat flux at the solid surface, $\dot{q}_{fr}''$ is the flame radiant flux, $\dot{q}_{rs}'$ the re-radiation from the solid, $U_m$ the mixed flow (forced and free) velocity, $t_{chem}$ the chemical time, $\rho_s$ and $c_s$ are the solid density and specific heat and $s$ is the solid thickness. $T_p$ and $T_o$ represent the pyrolysis and initial temperatures of the solid. The first term in Equation 4.1 describes the heat transfer mechanisms controlling the flame spread process and the second term the gas phase chemical kinetic. The contribution of the chemical kinetics term is small until the pressure becomes of the order of 30 kPa \[85\]. Assuming that the radiant flux from the flame approximately balances the surface re-radiation, then the flame spread rate is primarily determined by the product of the flame heated length, $l_h$, and the convective heat flux, $\dot{q}_{fc}'' = h(T_f - T_p)$, with $h$ representing the convective heat transfer coefficient and $T_f$ the flame temperature. Flame temperature is not strongly dependent on ambient pressure until the chemical time starts to become larger than the physical time, thus it is considered constant in the range of the present experiments. The heating length is related to the pyrolysis length as $l_h \sim C l_p$ \[8\]. Under these conditions the flame spread rate becomes

$$V_f \approx l_p \left[ \frac{h(T_f - T_p)}{\rho_s c_s s(T_p - T_o)} \right]$$

(4.2)
Figure 4.11: Measured (a) average flame spread rate and (b) pyrolysis length as a function of ambient pressure.
From Equation 4.2 it is seen that the flame spread rate is proportional to the convective heat transfer coefficient at the solid surface, which is a function of the problem parameters. For a mixed flow, forced and free, as that of the normal gravity experiments the average convective heat transfer coefficient can be expressed in terms of the Reynolds number and the Grashof number as \[ h = C_k \frac{\ell_p}{l_p} (Re^4 + Gr^2)^{1/8} Pr^{1/3} \] (4.3)

\[ = C_k \frac{\ell_p}{l_p} Re^{1/2} \left( 1 + \frac{1}{Fr^2} \right)^{1/8} Pr^{1/3} \] (4.4)

where \( Re = \rho U_f \ell_p / \mu \), \( Gr = g \beta \Delta T l_p^3 \rho^2 / \mu^2 \), and \( Fr = Re^2 / Gr = U_f^2 / g \ell_p \). Here \( l_p \) is the pyrolysis length which is taken as the solid surface characteristic length in the flow direction, \( U_f \) is the forced gas velocity, \( \mu \) is the dynamic viscosity, \( \rho \) is gas phase density, \( \beta \) is the coefficient of thermal expansion and \( g \) is gravity level. Substituting Equation 4.4 into Equation 4.2, and taking into consideration the definition of each of the non-dimensional numbers, a relation is obtained between the flame spread rate and the problem parameters as shown in Equation 4.5

\[ V_f \propto P^{1/2} l_p^{1/2} U_f^{1/2} \left( 1 + \frac{g^2 l_p^2}{U_f^4} \right)^{1/8} \] (4.5)

The above relation shows that at low forced flow velocities, like in the 1g experiments, the heat transfer from the flame to the surface is dominated by natural convection \( (h \propto Gr^{1/4} \propto g^{1/4} P^{1/2} l_p^{3/4}) \) so \( V_f \propto g^{1/4} P^{1/2} l_p^{3/4} \) as in upward flame spread over a thermally thin fuel [8]. At large flow velocities or low gravity, like in the \( \mu g \) tests, the process is dominated by forced flow convection \( (h \propto Re^{1/2} \propto P^{1/2} l_p^{1/2} U_f^{1/2}) \) so \( V_f \propto P^{1/2} l_p^{1/2} U_f^{1/2} \) as in purely forced flow flame spread over a thermally thin fuel [8]. It should be noted that the predicted dependence of the concurrent flame spread on pressure of Equation 4.5 is the same as that obtained by Olson et al. [62] in their correlation of available data on concurrent flame spread over thin fuels. The predicted dependence of the flame spread rate on the forced flow velocity is not linear as found by Olson et al. [62], although the product \( l_p^{1/2} U_f^{1/2} \) is approximately linear.

Equation 4.5 can be used to plot the normal gravity, low pressure data and the microgravity, normal pressure data along a common variable. Plotting the flame spread rate data of Figure 4.11 in terms of Equation 4.5 as in Figure 4.12(a), it is seen that as the pressure is reduced the flame spread rate decreases and approaches that obtained in microgravity. Also, flame spread rate as a function of pressure and gravity, agrees well with what is expected from a scaling analysis using Grashof number as reported by [19]. The pyrolysis length can also be correlated using the above approach, as shown in Figure 4.12(b). It is seen that a similar trend is observed for the pyrolysis length, and that the normal gravity data aligns well with that obtained in microgravity, at least for
Figure 4.12: Measured (a) average flame spread rate and (b) pyrolysis length as a function of the relation to P and g.
the Saffire data.

It should be noted that a similar alternative approach to correlate the flame spread data in terms of the problem parameters can be made by defining a mixed flow gas velocity that when applied in a forced flow boundary layer analysis will produce a boundary layer of the same thickness to that of the mixed flow. This approach is logical since the heat transfer coefficient is directly related to the boundary layer thickness, $\delta$, through $h = k/\delta$, and the boundary layer thickness is directly related to the gas flow velocity (see Figure 4.13). Following this approach, the mixed convective flow velocity can be obtained by equating the boundary layer thickness for a forced flow ($\delta_f = \frac{1}{2} \frac{P_r - 1}{P_r - 1/3}$) with that for a mixed convective flow ($\delta_m = \frac{1}{8} \frac{P_r - 1/3}{1} (Re^4 + Gr^2)^{-1} R_l^4$), which gives

$$U_m = \frac{P}{P_0} U_f \left( 1 + \frac{g^2 l_p^2}{U_f^4} \right)^{1/4} \quad (4.6)$$

Substituting this equivalent forced flow velocity, $U_m$, of Equation 4.6 for the forced flow velocity, $U_f$, in Equation 4.5 and setting $g = 0$, the resulting flame spread rate would be that of a forced flow with a velocity equal to that of the mixed flow. The correlation of the data of Figure 4.11 in terms of the mixed flow velocity as obtained with Equation 4.6 is given in Fig. 4.14. It is seen that the microgravity data can also be correlated well using this approach. It is also seen that the flame spread is linearly proportional to the mixed flow velocity, in agreement with theoretical predictions [8] and with experimental measurements of concurrent flame spread over paper [11].

The results of Figures 4.12 and 4.14 are relevant because they indicate that the concurrent flame spread over Sibal in a microgravity environment can be approximately simulated by reducing the ambient pressure to levels of the order of 30 kPa. However, at those low-pressure environments, chemical kinetic effects start to become important in the flame spread process and may give inaccurate predictions for other fuels and environmental conditions, particularly when changing oxygen concentration. It is also relevant that different gravity levels, such as in the Moon or Mars, can be also simulated with this flame spread formulation. At those gravity levels the simulation pressure would be higher, and consequently the chemical kinetic effects would be reduced.

### 4.5 Conclusion

The concurrent flame spread rate and flame appearance of a thin composite fabric (Sibal) burning in different environments have been studied under reduced ambient pressure. It has been found that as pressure is reduced, the flame spread rate over a thin fabric is also reduced. Flame intensity is also weakened resulting in dimmer blue-purple flames. As ambient pressure is reduced to around 30 kPa the flame spread rate approaches that observed in microgravity. The correlation of the flame spread rate data in terms of a mixed flow parameter that includes gravity and pressure
Figure 4.13: Schematic diagram of boundary layer profiles.
Figure 4.14: Measured (a) average flame spread rate and (b) pyrolysis length as a function of the mixed flow velocity from Equation 4.6.
suggests that reduced pressure can be used to simulate untested levels of gravity conditions.

It should be kept in mind, however, that variations in ambient pressure will affect flame chemistry. For a constant oxygen concentration, as total ambient pressure is reduced there is a subsequent reduction in the partial pressure of oxygen and flame temperature \[144\]. Additionally, lower pressure environments result in an increase in the mean free path between molecules \((\lambda \propto 1/P)\), therefore reducing the number of collisions in the reaction zone and thickening the flame sheet \[145\]. The combined effect of reduced partial pressure of oxygen and a larger mean free path between molecules, slows down the chemical reactions in the gas phase, affecting the heat provided by the flame to the unburned solid and therefore reducing the flame spread rate. Thus, care should be taken interpreting and applying these results, particularly because eventually low pressure will affect the chemical kinetics of the process.
Chapter 5

The Effect of Buoyancy on Concurrent Flame Spread over a Thick Solid

As described in the previous chapter, the understanding of material flammability of combustibles solids inside spacecraft environments is of utmost importance because if a fire occurs its consequences could be catastrophic. Additionally, the difference in the environmental conditions present inside these vehicles are very different to what is encountered on earth, i.e. microgravity, low flow velocities induced by the ventilation systems (∼ 10 cm/s), reduced ambient pressure (∼ 60 kPa), and increased oxygen concentration (∼ 34% O_2 by vol.). Thus, there is a current need to define new testing methodologies that allow simulating on-earth the burning behavior inside spacecraft environments.

Following the same line of the previous chapter, the main objective of this work is to study the effect of pressure on the flammability of thick solids and determine, by comparison with microgravity data, if reduced ambient pressure environments can be used to replicate flame characteristics and flame behavior observed inside of spacecrafts. Specifically, this chapter focuses on the effect of pressure and microgravity on upward/concurrent flame spread rates over thick polymethyl methacrylate (PMMA) slabs. Experiments in normal gravity were conducted over pressures ranging between 100 and 40 kPa and a forced flow velocity of 20 cm/s. Microgravity experiments were conducted during NASA’s Spacecraft Fire Experiment (Saffire II), on board the Cygnus spacecraft at 100 kPa with an air flow velocity of 20 cm/s. Results show that reductions of pressure slow down the flame spread over the PMMA surface. As pressure is reduced, flame intensity is also reduced. Comparison with the microgravity data shows that as the pressure is reduced, the normal gravity flame spread rate approaches that in microgravity, and that similar spread rates could be obtained a around 20 kPa. The data presented is correlated in terms of a mixed convection non-dimensional number that describes the convective heat transferred from the flame to the solid, and that also describes the primary mechanism controlling the spread of the flame. The correlation provides information about the similitudes of the flame spread process in variable pressure, flow velocity and gravity environments, providing guidance for potential ground-based testing for fire safety design in spacecraft and space habitats.
This chapter is based on research currently submitted to the journal Combustion and Flame.

5.1 Background research

Concurrent, or flow assisted, flame spread is particularly relevant in fire safety because it is generally fast and consequently hazardous. Several studies have been focused on the characteristics of this process when using thick fuels. However only some of them are mentioned in here, focusing particularly in the burning of thick polymethyl methacrylate, PMMA, in a concurrent/upward configuration. This material has been extensively used in research because of its repeatability when doing experiments and the wide knowledge available in terms of thermo-physio-chemical properties, which makes it a good laboratory material to validate numerical models.

In terms of microgravity data, the majority of experiments performed have not considered the concurrent spread of flames over thick solids burning under microgravity conditions mainly because the size constrains, the time required to burn this type of samples, and the complexity associated with this configuration. Despite of this, there are some works available where research is focused on the burning of relatively thick solids in microgravity under certain specific conditions. West et al. [146] studied thick PMMA burning in quiescent environments. The samples used were 25.4 mm long by 6.35 mm wide by 3.18 mm thick, and were burned in atmospheres of 50% \( O_2 \) in \( N_2 \) at 1 atm, 50% \( O_2 \) in \( N_2 \) at 2 atm, and 70% \( O_2 \) in \( N_2 \) at 1 atm. The experiments showed that the flame spread rate slowly decreases with time. Given the absence of a flow of air (forced or buoyant) the heated layer in the solid is not well developed and the process remains unsteady. A model of the experiments further revealed that eventually the flame extinguishes because the diffusion length increased more rapidly than the rate of spread of the flame, and therefore the rate of oxygen diffusion to the flame decreased. Additionally, the West et al. [146] noticed the existence of a critical thickness below which steady spreading is obtained in microgravity. Below this thickness the fuel is heated fast enough that the flame spreads faster and the oxygen diffusion is not a problem. A couple years later, a second set of similar experiments were performed by Alterkirch et al.[147]. This time the samples used were twice as long and the purpose of the tests was to experimentally validate the findings of the previous model developed and confirm the ultimate fate of the flames. During the tests, altenkirch et al. observed that after 540 s the flames extinguished, showing a similar behavior as predicted by the model.

In the experiments of Tarifa [148], he studied ignition and flame spread over hollow PMMA cylinders in oxygen/nitrogen atmospheres. Tarifa detected that at very low flow velocities flames would either extinguish or become “invisible” in the optical range, this would happen for thick fuels or relatively low oxygen concentrations. Olson et al. [149] conducted experiments over thermally thick PMMA to further study the effect of low-velocity flows, oxidizer concentration, and weak radiant heat flux on flame spread. The experiments were conducted during four ~ 6 min microgravity flights on board of a sounding rocket. The authors found that flames would propagate steadily in opposed flows down to 1 cm/s, even though previous research with similar samples had
shown that quiescent conditions do not support steady flame spread. The authors also found that, in
general, flame spread was more sensitive to changes in oxygen concentration than flow or external
flux. Other sounding rocket experiments were also performed by Vietoris et al. [150] to test flat
plates of PMMA burning in atmospheres of 40% oxygen and 60% nitrogen using an opposed flow
that ranged in velocities from 15, 10 and 5 cm/s to look at uniform propagation, transitional regime
and extinction. The authors concluded that as the flow was reduced, the net heat flux to the surface
was also reduced, causing the flame to slow down and eventually stop.

Concurrent/upward flame spread in normal gravity has also been widely studied before [10–
12, 14, 117, 129, 151, 152]. As the flame spreads over the solid the hot gases generated during
combustion move ahead of the pyrolysis front enhancing the heat transferred to the unburnt solid
and consequently affecting the flame spread. This preheating process is dominated by convective
heat transfer and the external flow velocity, whether purely forced or induced by buoyancy, plays a
over thick PMMA slabs using a forced flow with varied oxygen concentration. Among their results
they notice that the flame spread rate had a linear dependence on the flow velocity and a square
power dependence on the oxygen concentration. Also, for the conditions tested, the process was
mainly controlled by the heat transfer from the flame to the solid and finite rate chemical effects
had very little influence.

Given the challenges associated to microgravity testing, research has been dedicated to finding
alternative testing methods that could minimize gravity effects, and therefore facilitate testing on
earth. Depending on the environmental conditions at which the material is exposed or the configu-
ration at which is being burned, buoyancy is going to play an important role as it will influence the
development of the boundary layer and the positioning of the flame regarding the solid surface. A
possible approach to test flame spread under different buoyancy levels is to vary the orientation of
the solid surface where the flame spreads [7, 9, 10, 12–14]. Zhou and Fernandez-Pello [10] noticed
that buoyancy has two main effect when burning solids in the ceiling configuration: on one hand it
enhances the heat transfer to the solid surface because the flame is kept closer to it, on the other it
results in incomplete combustion caused by larger heat losses to the wall and boundary layer strat-
ification. Drysdale and Macmillan [12] tested flame spread over thick flat plates of PMMA using
different angles of inclination, from horizontal to vertical positioning. The researchers noted clear
differences in the spread of flames after the inclination angle became greater than 20 °C, increasing
the average flame spread rate as the angle was increased. Gollner et al. [14] followed a similar
approach, but looked into the relations between the spread of the flame and the rate of mass loss.
They found that the maximum flame spread rate, which occurs near the vertical position, does not
correspond with the maximum mass-loss rate of fuel, which occurs closer to a horizontal position,
because of the effect of buoyancy-induced flows that modified the heat-flux provided by the flame
to the burning surface of the fuel.

Another approach to simulate microgravity conditions is by using what is usually referred as a
narrow channel apparatus (NCA) [123, 153, 155]. The NCA is a technique used to simulate mi-
microgravity conditions by reducing the characteristic height of the flow duct. This reduction in the duct height affects buoyancy forces as they scale to the cube of the length. Zhu et al. [153] studied flammability of PMMA in very low flow velocities, like those encountered inside of spacecrafts, using a narrow channel apparatus and looking at flammability limits and flame spread rates. They found that in the low velocities regime, the opposed flame spread faster than the concurrent flame at a given flow velocity. They noticed that concurrent spread had a wider flammable range than opposed case, i.e. LOC of 14% for the concurrent case compared to an 18.5% for the opposed spread.

A third possible approach to affect buoyancy effects is by modifying ambient pressure. As ambient pressure is reduced, the buoyant flow velocity is also reduced, thus reducing the buoyant effects on the flame spread rate. Thus, the effect of reducing the ambient pressure on the flame characteristics and the spread rate is similar to that of reducing the flow velocity. Nakamura et al. [18] studied flame spread over electric wires in low pressure environments and found that the flame shape in low pressure is similar to that observed in microgravity. Fereres et al. [20] studied the similarities between microgravity and reduced pressure environments by using a numerical model. The researchers noticed that, at low velocity flows, solid fuel ignition and flame geometry could be approximated by reducing ambient pressure below 50 kPa. Gong et al. [156] also looked at the influence of low pressure environments on material flammability and found that the burning rate was proportional to $P^{1.8}$. At reduced pressures, Gong et al. found that the flames would go quenching below a critical Damköhler number, which is caused by chemical kinetic change and reduction of total heat feedback from flame to solid fuel.

Given the complexity of the problem, and to complement the experimental work, theoretical and numerical models to predict flame spread rate have been developed to improve the understanding of the process and different mechanisms involved. Fernandez-Pello [47, 128, 131] developed a theoretical model for the propagation of flames over a solid fuel in a laminar forced flow moving in the direction of the spread. The model uses boundary layer approximations and solves the gas-phased separately from the solid-phase, given analytical expressions for the rate of spread of the pyrolysis front and flame tip, and using experimental data to validate his predictions. Lautenberger et al. [157] used a CFD code called Fire Dynamics Simulator (FDS) [158], developed by the National Institute of Standards and Technology (NIST), coupled with their own pyrolysis model to account for subsurface pyrolysate generation and two-dimensional heat conduction. In this work, Lautenberger et al. [157] studied the opposed flow flame spread over thick samples of PMMA focusing in changes in flow velocity and gravity level. The researchers found good agreement between the model and experimental results for the normal pressure experiments, however flame spread rate at different oxygen concentrations or microgravity was not very well predicted. Pizzo et al. [159] developed a model, based on a modified mass transfer number, to simulate transient pyrolysis of vertically oriented PMMA slabs. The model shows good agreement with data obtained from experiments for flames spreading in upward configuration as well as for data using different inclination angles.
5.2 Experimental conditions and sample

The apparatus used for the experiments presented in this Chapter is the same as the one described in Chapter 2. The experiments presented here were performed in an upward/concurrent flame spread configuration, i.e. the forced flow and the flame spread were in the same direction. Four different ambient pressures were considered, going down from 100 to 40 kPa. The experiments were performed using a forced flow of air set to 20 cm/s. Oxygen concentration was kept constant throughout all the test.

A thick solid material was used for the experiments presented in this chapter. The sample was selected to match one of the materials tested in the Saffire II microgravity experiment [82]. The material used was cast polymethyl methacrylate (PMMA), commonly known as acrylic. PMMA is a transparent thermoplastic with high impact strength, is lightweight, shatter-resistant, and exhibits favorable processing conditions [160]. At the same time, the material has also very good optical properties, and it can be machined in different forms using diverse types of methods. The selection of this sample is based on the fact that this material has good experimental repeatability and it is also a very well characterized material with most of its properties available in the literature, so the data obtained from the experiments can also be used to validate numerical models of flame spread and material flammability [13, 20, 157]. Furthermore, PMMA will also be included as part of the interior panes of Orion spacecraft windows [161].

The material used to make the samples was obtained from McMaster-carr. The PMMA slabs were 150 mm long by 50 mm wide, with a thickness of 10 mm, as shown in Figure 5.1. The sample length was the maximum that could be tested in the experimental apparatus, although they were still smaller in length than the ones used during the Saffire II test. The samples had one small groove on each side that was used to slide them into a stainless-steel frame to hold them in position during the test. The holder had sidewalls 25 mm wide to prevent air entrainment from the sides to the burning solid. During the tests, the sample holder was placed vertically at the midplane of the test section with both sides exposed to the flow but only one side burning. Ignition of the PMMA slab is induced with a 29-gage Kanthal wire, that is threaded along the upstream edge of the sample through 14 equally spaced holes on a tapered end of the sample about 5 mm long (see Figure 5.1). Two electrically insulated posts were fitted near the upstream edge of the holder to connect the igniter wires. A ceramic block was used to cover the igniter on the non-burning side of the sample, this block prevented the ignition of the material without blocking/disrupting the air flow. The igniter is energized using a constant current power supply set to 68 W, the time required to assure ignition changed depending on the ambient pressure tested. Figure 5.2 shows a picture of the sample holder used during the test.

As part of the data collected, eight K-type thermocouples were attached to the surface of one of the faces of the material to record the surface temperature. To assure that the thermocouples would stay as close to the sample surface as possible while the material was burning, the thermocouples were buried into the melted plastic using a soldering station, the thermocouple wires were also
buried at at least three points more on the downstream direction at each side to assure they will stay in the desired position. The recording of the thermocouples was started soon after the system was initiated but well before ignition was achieved.

The microgravity experiments presented in this chapter were conducted aboard the Orbital Corporation Cygnus spacecraft (Saffire II) [82].

5.3 Results

The primary data collected were pyrolysis front and flame tip positions (see Figure 5.3) as a function of time, and through them, the concurrent flame spread rate was extracted as the first derivative of the positions over time (i.e. the slope of the data). All the videos recorded during the tests were post-processed to extract these changes in positions over time using the a program written in python. The program corrects distortions originated by the positioning of the cameras and generated frames equally spaced in time (\(\sim 4 - 8\) s) to allow the user to do the tracking. Figure 5.4
shows representative frames from videos of the flame spreading over the PMMA in normal gravity at normal pressure and at 40 kPa. Photograph 5.4(a) displays the burning samples with the strobe light off and shows the visible flame used to determine the flame tip. The location of the flame tip was approximately determined from dark frames with the visible flame when the pixel intensity dropped past a threshold of 75% compared to the intensity of flame pixels. Photograph 5.4(b) shows the burning sample with the strobe light on and shows the pyrolysis front. Here, the position of the pyrolysis front was defined as the point where the PMMA is first visibly pyrolyzing (bubbling). During the tests, after ignition is achieved, the flame spreads along the surface of the sample until it reaches its end. The pyrolysis front had an inverted “U” shape in all the tests. The flame tip also had a flickering flatter inverted “U” shape. The flame flickering appears to decrease as the pressure is decreased. This agrees with previous studies of flame flickering in buoyant pool fires [162–164]. Usually, after ignition of the sample, an initial period of laminar flame spread was observed, followed by the flame transitioning to a turbulent flame [110, 165]. During the tests significant soot streamed out of the tip of the flame and deposited along the length of the material. Vapor jetting of bubbles of PMMA bursting at the surface caused distortions in the flame that got worse as the test progressed [166].

Additional to the data obtained from the videos, temperature profiles over time were recorded at 8 different positions along the centerline of the solid surface. Although care was taken to ensure that the thermocouple bead was well attached and in contact with the surface of the solid, as
the material started burning the thermocouples would detach from the surface and move around. Furthermore, the measurement of the thermocouple is also influenced by the depth at which it was buried in the solid, so differences could arise between them. For all these reasons, these measurements were used as an approximation and are not taken as absolute surface temperature values. Figure 5.5 shows an example of the temperature profiles recorded during one of the experiments. In order to validate the data extracted from the videos using the image processing tool, thermocouple measurements were used to track the evolution of the pyrolysis front over time. This was done by considering a reference pyrolysis temperature of 300 °C [86]. Figure 5.6 shows together the evolution of the pyrolysis front extracted from the videos as well as the tracking of the pyrolysis front using the data recorded by the thermocouples during the same experiment. The results presented in this figure show the good agreement existing in between both methods and serves as a validation of the image processing tool.

Figure 5.7(a) shows the progress of the pyrolysis front along the sample surface for the pressures tested in normal gravity. The shaded areas represent the scatter in the measurements between the different tests. It was not possible to track pyrolysis front from the Saffire II images because the flame covered the pyrolysis region and its luminosity prevented its visualization. The data from Figure 5.7(a) is used to obtain the dependence of the pyrolysis length on pressure at different times.
Figure 5.4: Front view of two representative frames at 100 and 40 kPa with (a) the light off showing the flame tip, and with (b) the light on showing the pyrolysis front. All frames are taken 100 s after ignition.

It is seen that within the length of the sample, time dependence of the pyrolysis front is fairly linear for all pressures tested indicating an approximately constant flame spread rate. The progress of the flame tip along the sample surface for the different pressures tested is shown in Figure 5.8. For comparison purposes, the flame tip progress during the Saffire II test is also included in the figure. It is difficult to determine the location of the flame tip because the flame fluctuates, consequently the data is only approximate. In the initial 10 to 50 seconds the flame length is affected by the igniter, but after the igniter is turned off the time dependence of the flame tip is also approximately linear, until close to the end of the sample where end effects affect the spread of the flame. Above the end of the sample (150 mm) the flame is a plume flame rather than a wall flame; thus, its length would be somewhat different than with a longer sample. While upward flame spread is typically an acceleratory process in normal gravity [131, 151], the change in spread rate over the relatively small distances measured here, and the weak dependence of spread rate on distance [151] is not sufficient to capture the transient characteristics of the flame spread process in these tests. From Figure 5.7 it is seen that as pressure is reduced the flame spread rate obtained from the pyrolysis front is also reduced. At an ambient pressure of 100 kPa, the pyrolysis front takes about 150 s to progress over the entire length of the sample (∼ 140 mm), which is significantly faster when compared to the average 450 s obtained at about 40 kPa. Similar
Figure 5.5: Temperature profiles over the surface of the thick PMMA sample while burning under normal air and 100 kPa of ambient pressure.

Figure 5.6: Comparison of tracking methods used to record the pyrolysis front evolution over time. Test presented is for the thick PMMA slab burning under normal air and 100 kPa of ambient pressure.
results are obtained when looking at the variation of the flame tip with pressure, shown in Figure 5.8. From the results of Figure 5.8 it can be inferred that as the ambient pressure is reduced the flame tip progress approaches the microgravity data from the Saffire II experiments.

Figure 5.7: Time evolution of the (a) pyrolysis front position and (b) variation of the pyrolysis length with pressure at different times in normal gravity.

The data in Figures 5.7 and 5.8 can be used to approximately obtain the variation of the length of the PMMA heated region downstream from the pyrolysis front (heated length) as the flame
progresses along the sample. As shown below the heated length is an important parameter in the spread of the flame. This length is calculated here by subtracting the flame length from the pyrolysis length. Although the results are only approximate because it is difficult to determine the flame tip accurately and the flame changes character after it passes the end of the sample, they help interpreting the experimental results. Figures 5.9(a) and 5.9(b) show the variation with time of the measured pyrolysis and flame lengths, and of the calculated heated length for 100 kPa and 60 kPa. The heated length is calculated only until the point that the flame tip reaches the end of the sample, since after then the flame is a plume flame rather than a wall flame. It is seen that the heated length does not vary much along the fuel sample, but varies significantly with pressure, decreasing as the pressure is decreased. This is shown in Figure 5.10 where the dependence of the averaged heated length with pressure is presented.

The flame brightness is also reduced with pressure, becoming weaker as pressure is reduced. In these conditions, the flame changes from a bright yellow/orange to a faint blue color, as it can be seen in Figure 5.11. This indicates that ambient pressure, and consequently buoyancy affects both the soot generation and the flame temperature, and in turn the radiation from the flame to the solid. Visible flame height is also reduced as the pressure is decreased, although for the lower pressures the flame tip becomes very diffuse and hard to define. These observations seem to agree with those of Ref. [167, 168], where it is shown that soot production in diffusion flames in microgravity is significantly affected by the oxidizing stream conditions. From Figure 5.11 it is also seen that as the pressure is reduced, the flame size decreases toward what was observed during the
Figure 5.9: Variation with time of the pyrolysis, flame tip and heated lengths for (a) 100 kPa and (b) 60 kPa.
Figure 5.10: Averaged heated length for different ambient pressures in normal gravity.

Saffire microgravity experiment, although the color is different. This last observation indicates that reducing pressure may not be able to reproduce well the soot formation and flame temperature in microgravity.

The progress of the pyrolysis front is often used to determine the flame spread rate because it can be measured more accurately than the progress of the flame tip, which fluctuates and is more difficult to determine. Figure 5.12 shows the average flame spread rate as a function of ambient pressure as obtained from the pyrolysis front data of Figure 5.7. Also included in Figure 5.12 is the flame spread rate calculated from the flame tip data of Figure 5.8. The error bars show the standard deviation of the data from the different tests conducted at each condition. It is seen that the flame tip method gives higher spread rates particularly at ambient pressure, although the error from the flame tip data gives more confidence in the flame spread rate values obtained from the pyrolysis front data. For comparison, the flame spread rate data of Saffire II obtained from the flame tip progress shown in Figure 5.8 is also included. It is seen that the microgravity flame spread rate is significantly lower than in normal gravity at the same ambient pressure, indicating that the buoyantly induced flow velocity plays an important role in normal gravity concurrent flame spread. However, as the pressure is decreased in normal gravity the flame spread rate also decreases, approaching that in microgravity conditions.
Figure 5.11: Effect of ambient pressure on flame appearance.

Figure 5.12: Average flame spread rate over PMMA as a function of ambient pressure obtained from the pyrolysis front and flame tip.
5.4 Simplified Analysis and Data Correlation

To understand the observed dependence of the flame spread rate on pressure it is helpful to use a simplified analysis of concurrent flame spread as that developed in Refs [8, 47]. The analysis, which is based on the concept that flame spread can be viewed as a series of ignition steps where the flame act as the heating and the ignition source [8, 46, 76, 77] provides an analytical equation for the concurrent flame spread rate from the ratio of the heating length and the ignition time. For a thermally thick solid it gives [8]:

\[ V_f = l_h \left( \frac{\pi k_s \rho_s c_s (T_p - T_o)^2}{4 (\dot{q}''_{fc} + \dot{q}''_{fr} - \dot{q}''_{rs})^2 + \frac{C_x}{U_m} \varphi (t_{chem})} \right)^{-1} \]  

(5.1)

where \( l_h \) is the heated length of the slid ahead of the pyrolysis front, \( \dot{q}''_{fc} \) represents the convective heat flux at the solid surface, \( \dot{q}''_{fr} \) is the flame radiant flux to the solid surface, \( \dot{q}''_{rs} \) the re-radiation from the solid, \( U_m \) the mixed flow velocity, \( t_{chem} \) the chemical time, \( k_s, \rho_s \) and \( c_s \) are the solid conductivity, density and specific heat. \( T_p \) and \( T_o \) represent the pyrolysis and initial temperatures of the solid. The first term in Equation 5.1 describes the heat transfer mechanisms of the flame spread process and the second term the gas phase chemical kinetic mechanisms.

The chemical kinetics term affects the spread rate at conditions that reduce the Damköhler number and make the term comparable with the heat transfer term. This may occur at low oxygen concentration, low pressure, and at large flow velocity (blow off) [8], or very low flow velocity in microgravity (diffusive transport and radiation losses) [169-171]. As indicated in the discussion section the present experiments are conducted away from these limiting conditions, thus, the spread rate is given primarily by the heat transfer term in Equation 5.1.

There are some other simplifications that can be made in Equation 5.1 and that are justified in more detail in the discussion section below. The radiant flux from the flame to the solid surface is difficult to calculate because the ambient pressure and buoyant flow may affect the soot formation and the flame temperature, and consequently the radiant flux from the flame to the solid [8, 167]. Given the approximate nature of this analysis, it is assumed that the radiant flux from the flame to the solid is approximately balanced by the surface re-radiation. This is a significant simplification that allows to obtain an analytical expression for the flame spread rate. Then the heat flux to the solid is primarily the convective heat flux from the flame to the solid surface, \( \dot{q}''_{fc} = h(T_f - T_p) \), with \( h \) representing the convective heat transfer coefficient, \( T_f \) the flame temperature and \( T_p \) the PMMA pyrolysis temperature. The flame temperature is directly proportional to the ambient oxygen concentration but is not strongly dependent on ambient pressure until the pressure is relatively low and the chemical time starts to become larger than the physical time. Because the oxygen concentration is that of air for all the experiments, the flame temperature is assumed constant in the range of pressures of the present experiments. This is another simplification in the analysis that should be reasonable for not too low ambient pressures, as discussed below in the discussion.
Under these conditions the flame spread rate becomes

\[ V_f \approx \frac{4(h(T_f - T_p))^2}{\pi k_s \rho_s c_s (T_p - T_o)^2} \]  \hspace{1cm} (5.2)

From Equation 5.2 it is seen that the flame spread rate is proportional to the heating length and the square of the convective heat transfer coefficient at the solid surface, with the other parameters, or properties, considered constant.

The heat transfer coefficient is directly related to the boundary layer thickness through \( h = \frac{k}{\delta} \). The boundary layer thickness is related to the problem parameters either through the Reynolds number in pure forced flow, or through the Grashof number in pure natural convection (free) flow. For a mixed flow, forced and free, as that of the current normal gravity experiments the boundary layer thickness can be expressed in terms of the Reynolds Number and the Grashof number as [7]

\[ \delta_m = Cl_p \left[ Re^4 + Gr^2 \right]^{-\frac{1}{8}} Pr^{-\frac{1}{3}} \]  \hspace{1cm} (5.3)

For a forced flow dominated mixed flow Equation 5.3 is better expressed as

\[ \delta_m = Cl_p Re^{-\frac{1}{2}} \left[ 1 + \frac{1}{Fr^2} \right]^{-\frac{1}{8}} Pr^{-\frac{1}{3}} \]  \hspace{1cm} (5.3a)

and for a natural convection dominated mixed flow as

\[ \delta_m = Cl_p Gr^{-\frac{1}{2}} \left[ Fr^2 + 1 \right]^{-\frac{1}{8}} Pr^{-\frac{1}{3}} \]  \hspace{1cm} (5.3b)

where \( C \) is a generic constant related to the type of flow and the pyrolysis length, \( l_p \), has been selected as the characteristic length of the problem, which gives \( Re = \rho U_f l_p / \mu \), \( Gr = g \beta (T_f - T_o) l_p^3 \rho^2 / \mu^2 \), and \( Fr = Re^2 / Gr = U_f^2 / gl_p \). \( U_f \) represents the forced flow velocity component of the mixed flow, \( \mu \) is the dynamic viscosity, \( \rho \) is gas phase density, \( \beta \) is the coefficient of thermal expansion and \( g \) is gravity level. Equation 5.3 shows a general expression for the boundary layer thickness in a mixed flow. Equation 5.3a is more representative of a forced flow dominated flow, and for \( Fr \sim \infty \), is the boundary layer thickness for a pure forced flow. Equation 5.3b is more representative of a natural convection dominated flow, and for \( Fr = 0 \), is the boundary layer thickness for a pure natural convection flow. It is seen that similar boundary layer thickness can be obtained by varying accordingly the Reynolds, \( Re \), and Grashof, \( Gr \), numbers.

As the flame spreads along the solid surface the pyrolysis length increases with time and consequently the boundary layer thickness and the heat flux on the surface also vary with time and
pressure. In keeping with the simplified character of the analysis the pyrolysis length in Equation 5.3 is taken as constant and equal to half the sample length. This results in an average boundary layer thickness and heat flux from the flame to the solid, as discussed in the discussion section below. Using \( h = k/\delta \) together with Equation 5.3 and the definitions of the non-dimensional numbers, the mixed flow average convective heat transfer coefficient is given by

\[
h = C \frac{k}{l_p^2} P^2 U_f \left[ \frac{g^2 l_p^2}{U_f^2} + 1 \right]^{\frac{3}{2}} Pr^{\frac{3}{2}}
\]

Substituting Equation 5.4 in Equation 5.2 the following expression is obtained for the concurrent flame spread rate in terms of the problem parameters

\[
V_f \approx \frac{l_h}{l_p} \left[ \frac{4 \left( C k P^2 U_f \left[ \frac{g^2 l_p^2}{U_f^2} + 1 \right]^{\frac{3}{2}} Pr^{\frac{3}{2}} \right)^2 (T_f - T_p)^2}{\pi k_s \rho_s c_s (T_p - T_o)^2} \right]
\]

The heating length, \( l_h \), is the difference between the flame length and pyrolysis length, and increases somewhat with time, although weakly as stated above. In a previous application of Equation 5.1 it was considered that \( l_h \sim C_1 l_p^2 \). Since here \( l_p \) is taken as constant, we will assume that \( l_h \) is also constant and proportional to \( l_p \), thus their ratio is also constant. The constant of proportionality between both heating lengths is embedded in the constant \( C_1 \). This approximation is also discussed in the discussion section below. Then the spread rate will be given by Equation 5.6.

\[
V_f \approx \frac{4C_1 k^2 P U_f \left[ \frac{g^2 l_p^2}{U_f^2} + 1 \right]^{1/4}}{\pi k_s \rho_s c_s (T_p - T_o)^2} Pr^{2/3} (T_f - T_p)^2
\]

Equation 5.6 describes natural convection upward flame spread for \( U_f = 0 \), and forced flow concurrent flame spread for \( g = 0 \).

Equation 5.6 can be used to plot the data obtained in normal gravity and low-pressure conditions with that obtained in microgravity and normal pressure, in common coordinates. Figure 5.13 shows the flame spread data of Figure 5.12 as a function of the squared heat convection problem parameter (Equations 5.3 and 5.6). It is seen that the flame spread rate as given by Equation 5.6 successfully correlates the dependence of the spread rate on pressure and gravity, and agrees well with what is expected from a scaling analysis using Grashof number as reported in Ref. [19]. Particularly relevant is that normal gravity experimental data at varied ambient pressures can be used to approximately predict the concurrent flame spread rate in microgravity.
Incorporating mixed flow conditions in analytical flame spread models is complicated and for this reason most models consider only forced flow conditions, and give the flame spread rate as a function of the forced flow velocity. Thus, another, maybe more useful, approach to obtain the dependence of the concurrent flame spread rate on the problem parameters is to define a mixed flow gas velocity that would be representative of the actual mixed flow boundary layer at a given ambient pressure and flow velocity, but that if applied in a pure forced flow, would produce a boundary layer of the same thickness as the one in the mixed flow. Although the mixed flow and forced flow boundary layers would have different velocity profiles, this approach is still applicable to determine the flame spread rate because, by definition, the heat transfer coefficient is directly related to the boundary layer thickness through \( h = k/\delta \), and the boundary layer thickness, \( \delta \) is directly related to the gas flow velocity through correlations as those of Equation 5.3. Following this approach, the mixed convective flow velocity can be obtained by equating the boundary layer thickness for a mixed convective flow as in Equation 5.3 with the boundary layer thickness for a pure forced flow given by Equation 5.3a with \( g = 0 \). Solving for the flow velocity in the forced flow boundary layer the following mixed convection velocity, \( U_m \), is obtained in terms of pressure, forced flow velocity in the mixed flow, and gravity.

\[
U_m = U_f \left( \frac{P}{P_0} \right) \left[ \frac{g^2 l^2}{U_f^4} + 1 \right]^{1/4} \tag{5.7}
\]

where \( P_0 \) is a reference ambient pressure (standard Earth ambient pressure) and \( U_f \) is the forced
flow velocity at this reference pressure $P_0$. From Equation 5.7 it is seen that for zero gravity or large flow velocity the mixed flow velocity is that of a pure forced flow at a given test pressure, $U_m = \frac{P}{P_0} U_f$. For elevated gravity and/or zero forced velocity, the mixed flow velocity becomes that of natural convection at a given test pressure, $U_m = \frac{P}{P_0} (g l_p)^{1/2}$. The mixed convection velocity of Equation 5.7 would produce an equivalent forced flow boundary layer of similar thickness as that of the mixed convective flow, and consequently an approximately similar convective heat transfer coefficient on the fuel surface. From Equation 5.2 it can also be inferred that different flow conditions that would provide similar boundary layer thickness and convective heat transfer coefficient would have similar flame spread rates. Thus, it would be possible to approximately predict the flame spread rate in a pure forced flow, as that experienced in microgravity, with a normal gravity test that has a similar mixed convection boundary layer as that of the forced flow, or conversely. In this case, the convective heat transfer coefficient for the forced flow, based on the mixed flow velocity, would be

$$h = C \frac{k}{l_p} \left( \frac{U_m P l_p}{\mu} \right)^{1/2} P r^{1/3}$$

and the flame spread would be given by

$$V_f \approx \frac{l_h}{l_p} \left[ 4 \left( C k \frac{(U_m P)^{1/2}}{\mu} P r^{1/3} \right)^2 \left( T_f - T_p \right)^2 \frac{\phi k_s \rho_s c_s (T_p - T_o)^2}{\pi k_s \rho_s c_s (T_p - T_o)^2} \right] \approx \frac{4C_1 k^2 \frac{(U_m P)^{1/2}}{\mu} P r^{2/3} (T_f - T_p)^2}{\pi k_s \rho_s c_s (T_p - T_o)^2}$$

As in Equation 5.5 the average pyrolysis length is assumed constant and heated length proportional to the pyrolysis length, thus their ratio is constant and included in the constant $C_1$. It should be noted that Equation 5.8 is similar to the expressions obtained for opposed flame spread rate over a thermally thick solid [8, 46, 70, 76, 77], with the value of $l_h$ as the primary difference. In opposed flame spread $l_h$ is the solid heated length upstream of the flame front, or pyrolysis front, while here is approximately the length of the flame from the pyrolysis front. This is understandable since the primary controlling mechanisms of opposed and concurrent flame spread are the same.

The flame spread data of Figure 5.12 can be correlated in terms of the mixed convective flow velocity, $U_m$, given by Equation 5.7 and using Equation 5.9, as shown in Figure 5.14. It is seen that Equation 5.9 correlates well the variation of the flame spread rate with pressure, and that the extrapolation to lower flow velocities (pressures) approximately predicts the data in microgravity. As the pressure is reduced the resulting mixed flow velocity is also reduced, correspondingly the flame spread rate decreases and approaches that obtained in microgravity in the Saffire II experiments which had a lower flow velocity than the mixed flow velocity.
The correlation of the experimental flame spread rate data of Figures 5.13 and 5.14 suggests that reduced pressure can be used to approximately replicate similar flame behavior of untested gravity conditions for the spread of flames over thick combustible solids. It should be kept in mind however that variations in ambient pressure will affect flame chemistry and other parameters affecting the spread of the flame. This is important since it would be necessary to reduce the pressure to values of the order of 20 kPa (Figure 5.12) to simulate microgravity conditions and some of the simplifications used in the analysis may not be applicable to these environments. This problem could be reduced if the microgravity tests were conducted at higher flow velocities, since the spread rate could then be simulated at higher pressures, thus reducing the flame chemistry effects.

### 5.5 Discussion

The good correlation of the flame spread data as a function of ambient pressure, or buoyancy, and the apparent capability to predict at least approximately the concurrent flame spread in microgravity, is an indication that the flame spread description given by the present analysis has merit. This is somewhat surprising given the simplifications used in the analysis, but it indicates that the physico-chemical concepts underlined in the model and the assumptions used are reasonable at least for the correlation of present experiments in terms of pressure. In this section the implications of these simplifications and the limitations of the analysis are discussed.
The assumption that chemical kinetics effects can be neglected is an important simplification. Gas phase chemical kinetics affects the spread rate at conditions that reduce the Damköhler number and make the term in Equation 5.1 comparable with the heat transfer term. There are two limiting conditions where chemical kinetic effects are important. One is at large flow velocities where the chemical time is larger than the physical time and the flame spread rate decreases with the flow velocity until it is blown-off (blow off limit) [8, 47, 169]. The flow velocities in these experiments are too small for chemical kinetics to affect the flame spread in the blow-off limit, at least at elevated pressures. Although as the pressure is reduced the reaction rate decreases and the chemical time increases, also does the physical time since the buoyant velocity also decreases. So, it is unlikely that the blow off limit is reached in the present experiments. Also, the experimental results of Ref. [85] indicate that chemical kinetics affects the ignition of PMMA in air for pressures smaller than 30 kPa, thus it is reasonable to assume that at least up to this pressure the present analysis is valid.

Another condition where chemical kinetics may have a considerable influence is at very low velocity flows. In microgravity and very low velocity flows the transport of oxidizer to the flame is reduced which causes the flame to move outward seeking oxygen and the flame temperature and soot generation to decrease. This reduces the radiant flux from the flame to the surface to the point that surface re-radiation becomes important, causing the spread rate to decrease and eventual extinction of the flame (diffusion/radiation limit) [169–171]. In the present case the gas flow velocity is large enough that this potential effect is not important, although if the pressure is too low it may become more significant.

The analysis also assumes that the convective heat flux from the flame to the solid is the controlling mechanism of concurrent flame spread, at least away from the above limiting conditions of flow velocity, oxygen concentration or pressure. It should be noted that the correlation of the data of Figures 5.13 and 5.14 is basically based on the convective heat transfer from the flame to the solid surface. This is somewhat surprising because one would expect that radiation from the flame to the solid would have a more important role in concurrent flame spread. Regarding this issue, from the apparent visual differences in the flame characteristics as pressure is reduced (Figure 5.11), it is inferred that the soot concentration and temperature of the flame, and consequently the flame radiation, are affected by pressure. The work of Refs. [167, 168] on the soot concentration in diffusion flames in microgravity seems to confirm this observation. Thus, the radiant heat flux from the flame to the surface would vary with pressure and this should be reflected in the correlation of the data. However, to reduce the potential impact of radiation heat transfer, in the analysis it is assumed that the radiant flux from the flame to the solid surface is counteracted by the re-radiation from solid surface to the surrounding. The good correlation of the data suggests that in these experiments the resulting radiant flux balance between flame radiation and surface re-radiation, is small in comparison with the convective heat flux, and that the variations in radiant flux with pressure are not strong enough to be reflected in the data. One potential reason for this result is the small scale of the samples. As shown in Ref. [126] as the sample size increases and the flames become more turbulent the radiant flux becomes more important eventually dominating
the heat transfer from the flame to the solid. The size of the sample would also affect the characteristics of the flame and the convective heat flux from flame to solid. As the size of the sample increases and the flames become turbulent not only the radiative characteristics of the flame would change, but also the corresponding turbulent flow convective heat transfer correlations. Thus, the small size of the samples may be the reason for the results and justifies the radiant flux assumption at least for the present experiments.

Regarding the flame temperature, in the correlation of the experiments it is assumed that it is constant and independent of pressure. This appears reasonable at least for not too low pressures since the oxygen concentration of the gas flow is constant (air). Thermodynamically, the adiabatic flame temperature is directly proportional to the oxygen concentration and is basically independent of pressure if the air and post-combustion gases behave as ideal gases. Kinetically, the flame temperature is not strongly dependent on ambient pressure until the pressure is very low. As the pressure is reduced the reaction rate and consequently the heat release rate decrease [144] but also does the gas density. Since they counteract each other the flame temperature is not strongly affected by pressure. At very low-pressure environments there is an increase in the mean free path between molecules \((\lambda \propto 1/P)\) therefore reducing the number of collisions in the reaction zone and thickening the flame sheet [145]. This slows down the chemical reactions in the gas phase, affecting the flame temperature and the heat provided by the flame to the unburned solid. However, this effect is not too important until the ambient pressure is reduced significantly. The experiments of Ref. [85] on the effect of pressure on the ignition time of PMMA show that chemical kinetic effects are relevant for pressures lower than 30 kPa. Thus, since flame spread is related to the solid ignition, and these experiments are conducted at pressures above 30 kPa it is justifiable to assume that chemical effects do not affect the flame spread rate through the flame temperature and that consequently it can be assumed constant in the range of pressures of the present experiments. This is a reasonable assumption particularly considering the simplified character of the analysis. The good correlation of the experimental data also supports the assumption.

Another important simplification is the assumption of a constant average value for the pyrolysis length. The pyrolysis length increases as the flame spreads along the sample surface and since \(V_f = dl_p/dt\), it is seen that Equation 5.5 predicts an acceleratory flame spread rate for mixed flow, which will depend on the relative values of the gravity, forced flow and sample size. It also predicts an acceleratory flame spread for natural convection upward flame spread as observed experimentally [110, 129, 151]. This is due to the boundary layer growing at a slower rate than the flame heating length in mixed flow and upward flame spread. It should be taken into account that the above theoretical models assume laminar flow and the experiments were conducted with small samples. It is possible that if the sample is long enough the flame spread rate may become constant, this could be because the growth of the boundary layer becomes small with distance and the flame becomes turbulent and probably of almost constant length. Thus, the total heat flux from the flame to the surface may also become constant and consequently the flame spread rate. For pure forced flow Equation 5.5 predicts a constant flame spread rate, in agreement with boundary layer type theoretical models of concurrent flame spread [128]. In forced flow, the growth of the
boundary layer and the consequent decrease in the heat flux on the surface as the flame spreads is compensated by a growth of the flame heated length. Both effects compensate each other resulting in a constant flame spread rate \[7\]. This seems to be confirmed, at least approximately, with the Saffire data of Figure 5.8 once the influence of the igniter subsides. This aspect of the concurrent flame spread could not be verified until the Saffire II microgravity experiments.

Predicting the time dependence of the concurrent flame spread involves the solution of the transient conservation equations that govern the problem, which is beyond the scope of the present simple analysis whose primary objective is to predict the dependence of the spread rate on buoyancy through pressure. To meet this objective, it is reasonable to use averages of the parameters that control the spread of the flame and that are time dependent. The most important simplification is the selection of an average pyrolysis length, which is taken as half the sample length in this work. It implies an average boundary layer thickness, an average flame stand-off distance, an average flame tip length, an average solid heated length and an average convective heat flux from the flame to the solid surface. Given that the basic development of Equation 5.1 considers a uniform heat flux from the flame to the solid surface along the solid heated length \[8, 46, 76, 77\], some of these approximations are within the simplified character of the analysis. Theoretically boundary layer and flame stand-off increase along the fuel sample as a power of the distance from the upstream leading edge \[128\], but the variation is gentle (between \(1/2\) in forced flow and \(3/4\) power in natural convection). Consequently, the convective heat flux along the sample decreases also gently. Selecting a characteristic pyrolysis length of half of the sample length results in a heat flux at the solid surface that would correspond to that in the middle of the sample which is a small varying zone of its value, thus the impact of the approximation is relatively small. Furthermore, averaging the heat transfer coefficient along a solid surface is not uncommon in heat transfer \[172\]. The selection of a constant averaged pyrolysis front length implies that the flame tip length is also selected as constant since the latter is proportional to the former \[8, 173, 174\]. Since the heated length is the difference between the flame tip length and the pyrolysis front length, its value is also constant. The experimental measurements of the heated length shown in Figure 5.9 indicate that this assumption is reasonable at least for the present experimental conditions. Finally, it should be noted that in both expressions for the flame spread rate (Equation 5.5 and Equation 5.9), the ratio of the heated length and pyrolysis length, \(l_h/l_p\), appears as a multiplier of the other terms. Thus, even if the assumption that the two lengths are proportional is not accurate, the impact of the assumption on the predicted spread rate would be reduced by their lengths appearing as a ratio.

The above discussion applies to a given sample length. As the sample length is increased the average pyrolysis length will also increase, which is particularly relevant in a gravity field \((g \neq 0)\) because buoyancy depends on the length of the sample, and the buoyant velocity and flame spread rate will increase with the sample length. This issue is approximately captured in the model (Equation 5.6 or 5.9) through the Froud Number. The equations predict that the effect of sample length is less important as the forced flow velocity is increased, and the pressure or gravity are reduced. In \(g = 0\), the spread rate is theoretically constant along the sample length, and consequently is independent of the sample length. Thus, the sample length would be reflected in Figures 5.13 and
5.14 with different lines of flame spread versus mixed flow velocity, or heat convection coefficient, with the major separation at 100 kPa (the larger the sample the larger the difference) and that would all converge to the microgravity value. The separation of the lines would be reduced as the sample length is decreased, the forced flow velocity is increased, or the gravity level is reduced.

5.6 Conclusion

The concurrent flame spread rate and flame appearance over a thick slab of PMMA have been studied under reduced ambient pressure to determine if it is possible to simulate the characteristics of the concurrent flame spread in reduced gravity environments by reducing the ambient pressure. It has been found that as pressure is reduced, the concurrent flame spread rate over the surface of a thick solid is also reduced. Flame intensity is also weakened, resulting in dimmer blue flames for the lowest pressures. As ambient pressure is progressively reduced, the flame spread characteristics get closer to what is observed in microgravity. The correlation of the flame spread rate data in terms of a mixed flow heat convection parameter, or a mixed flow velocity, as those of Figures 5.13 and 5.14 that includes gravity and pressure suggests that reduced pressure can be used to approximately replicate similar flame behavior of untested gravity conditions for the burning of thick solids. It should be kept in mind however that variations in ambient pressure will affect flame chemistry and other parameters affecting the spread of the flame. Thus, caution should be taken in implementing test methods that would use only ambient pressure reduction to predict flame spread at different gravity levels. This is important since it would be necessary to reduce the pressure to values of the order of 20 kPa to simulate microgravity conditions and some of the simplifications used in the analysis may not be applicable to these environments.

Also, worth noting is that at different gravity levels, such as on the Moon or Mars, the concurrent flame spread can be simulated for thick solids with a flame spread formulation as in Equation 5.9 by reducing the pressure so that the mixed flow gas velocity remains the same than that at reduced gravity. At those intermediate gravity levels, the simulation pressure would be higher, and the chemical kinetic effects consequently reduced, thus the proposed analysis should have better applicability. The analysis should also able to predict flame spread in environments with different oxygen concentrations through the dependence of the flame temperature on the oxygen concentration of the gas flow.
Chapter 6

Concurrent Flame Spread over Externally Heated Nomex under Mixed Convection Flow

Fire-resistant materials are used in multiple applications (clothing, curtains, tents, etc.) where protection from fire is needed. Their fire-resistant capacity is often tested under specific conditions that might not represent the situation in an actual fire. Particularly relevant for this work is the application for astronaut spacesuit, since a spacecraft environment may be different than earth atmospheres. There, a material is exposed to low velocity flows, microgravity, reduced pressure, and enriched oxygen concentration. Under these conditions, material flammability can be altered. In addition, flammability tests are based primarily on the exposure of the material to an external radiant flux to simulate an adjacent fire, but not a real flame. In this work, an experimental study was performed to investigate the effect of ambient pressure and oxygen concentration on the concurrent/upward flame spread over a fire-resistant fabric (Nomex HT90-40) exposed to two different external heat sources. One is the radiation from infrared lamps, and the other is the flame from a burning polymethyl methacrylate (PMMA) sheet placed below the fabric. The experimental results show that an external heat flux extends the limiting oxygen concentration (24% LOC) of Nomex. This effect is more pronounced when the PMMA flame provides the heat flux (17% LOC). For oxygen concentrations larger than the Nomex LOC, the flame spread rate decreases as the ambient pressure is decreased, indicating that reducing buoyancy reduces the flame spread rate. A simple analysis of concurrent flame spread that incorporates mixed flow heat transfer correlates well with the experimental data. This suggests that flame spread in microgravity can be predicted in terms of a mixed flow velocity that includes the Reynolds and Grashof numbers. The results of this work provide further information about the effect of the type of external heating on material flammability. They may also guide future fire safety design in space exploration.

This chapter is based on research previously published in the Proceedings of the thirty-seventh Combustion Symposium [175] and presented at the forty-seventh International Conference on Environmental Systems in Charleston, South Carolina [109].
6.1 Background research

The ignition and propagation of fire under the influence of an external heat source have been the subject of several studies evaluating material flammability [24] because an external heat source simulates conditions often encountered in a fire, i.e., the preheating of a material by an adjacent fire. External heat sources have been often used to simulate the heating of a material by a real fire while having a controllable heat source [24]. An example is ASTM E-1321 [55], used to determine the material flammability parameters related to piloted ignition and flame spread. Flammability tests are normally conducted at standard atmospheric conditions; however fires may occur in different environments, such as those in spacecraft, aircraft, high-altitude locations, etc. Specifically, a spacecraft fire may occur in environments where the oxygen concentration, ambient pressure, flow velocity or gravity are different than in standard atmospheres [54]. Although some work has been conducted on aspects of the effect of external radiation on material flammability in different environments, such as piloted ignition [85, 176, 177], Limiting Oxygen Concentration (LOC) [17, 57, 87], and flame spread [113, 178], there is still a need for further understanding of this process particularly because a fire may occur in conditions where the oxygen concentration, the pressure, flow velocity or gravity may be different than in standard atmospheres, such as inside of a spacecraft [54]. These environmental variations become extremely relevant in applications where fire safety is a critical factor as in spacecraft application, where the entire atmospheric condition needs to be carefully controlled to support human habitation while minimizing the launch weight and all other risks involved [1].

Several researchers have studied the flammability properties of materials in different atmospheres. Hirsch et al. [57, 60] studied the fire risk of different materials under a wide range of oxygen concentrations and ambient pressures. Their work showed that the maximum oxygen concentration (MOC) resulting in the flame self-extinguishment decreased with the total pressure; however, the limiting partial pressure of oxygen increased linearly with the increased in total pressure. Kleinhenz and Tien [92] studied the burning of Nomex III in an upward configuration under different combinations of oxygen concentration and ambient pressure. Their results showed that the limiting oxygen concentration for flame spread (LOC) at 1 atm was 24% and its value increased with decreasing pressure. Nakamura and Aoki [98] found that the flammability of thin cellulosic paper had a wider flammable range at lower pressures, presenting the same linear trend for oxygen partial pressure and total pressure found in Hirsch et al. [60].

Furthermore, when considering the possible fire scenarios in spacecraft applications, it is necessary to evaluate the effect of microgravity on the material flammability. A limited number of past studies have been focused on comparing the effect of microgravity (µg) versus normal gravity (1g) on flame structure and flame spread behavior for different fuels and configurations [62, 63, 97, 112, 113, 179-181]. Results from these works have shown that in µg a flame may
spread in a low-speed airflow, similar to the spacecraft ventilation flow, while it cannot spread in normal gravity. Olson and coworkers [62, 97, 112, 113] found that in microgravity the LOC required for concurrent flame spread over Nomex HT90-40 is about 3% lower than the one in normal gravity, and for flow velocities between 0.06 and 0.10 m/s both concurrent and opposed flame spread over thin cellulosic fuels is faster than in normal gravity. Similar flame behavior was also observed for polymethyl methacrylate (PMMA) rods in the recent BASS-II μg experiment [181].

External radiation also plays an important role in the flammability of materials [17, 55, 64, 76, 87, 99]. An aspect of the problem that also needs consideration is the type of heating source that is used to characterize the flammability of materials. In a real fire scenario, there may be different heat sources acting on a material, such as radiation from an adjacent fire or hot smoke ceiling layer, or convection/radiation from a flame in contact with the material. These different heat sources could change the material fire behavior as well as its flammability, because the thermochemical mechanisms controlling the burning may change. For example, Osorio et al. [87] studied the forced-flow flame spread behavior and the LOC for Nomex HT90-40 under external radiation, and showed that for given oxygen concentration there is a minimum external heat flux that allows flame spread to occur. Thomsen et al. [17] studied the effect of external radiation on the LOC for Nomex HT90-40 under different ambient pressures, showing that as the amount of external heating is increased a decreased in the LOC was observed. However, the question that arises is whether an external radiant flux from a radiant heater, as in the ASTM test, has the same effect on the flammability characteristics of the material as an actual fire near its surface. This is important since the current tests methods used to determine material flammability may be used to screen materials used in different applications and may not describe properly the fire hazard that the material may represent. Exploring these issues is the objective of the present work.

6.2 Experiment conditions and sample

The experiments presented here were performed inside the apparatus presented in Chapter 2. During the experiments samples were set to burn in an upward/concurrent flame spread configuration, i.e. the forced flow and the flame spread were in the same direction. Four different ambient pressures were considered, ranging between 100 and 40 kPa. The experiments were performed using a forced flow of air set to 20 cm/s. Oxygen concentration was changed between 34% and 18% oxygen by volume. Additional external radiant heat fluxes of 10 and 5 kW/m² were also considered.

The experiments were conducted with a single layer of Nomex HT90-40 (Stern and Stern Industries Inc.) placed vertically at the midplane of the duct with both sides exposed to the flow. Nomex is the registered name for a flame-resistant fabric made by DuPont [101]. Unlike other flame-retardant materials, Nomex is made from a synthetic aromatic polyamide polymer composed by long strong flexible fiber chains without any additives. Given its structural characteristics, Nomex does not melt, drip or sustain a flame in normal air conditions. Its LOC is 24% (see
Chapter 3. The area density of Nomex HT90-40 is 244.1 g/m$^2$. In these experiments, a 0.33 mm thick Nomex sample was cut into pieces of 140 mm by 76 mm. All the samples were held in between two identical stainless-steel frames of 200 mm by 125 mm and 0.4 mm thick, as seen in Figure 6.1.

To study the effect of external radiation, two different heat sources were considered: one is the flame from a burning sheet of PMMA placed underneath the Nomex fabric, and the other is a radiant flux from halogen lamps. For this, two different sample configurations were used.

The first set of experiments was conducted with a composite sample consisting of a 0.74 mm thick clear cast PMMA sheet (13 mm long and 76 mm wide) placed below the Nomex sample, as shown in Figure 6.2(a). The sheet of PMMA was in direct contact with the fabric with no gap
in between them. Ignition of the PMMA was achieved using a nichrome wire passed through 10 equally spaced holes in the plastic. Once ignited, the PMMA flame provided a source of both heating of the Nomex fabric and ignition of the pyrolyzed Nomex. This sample configuration matches that of one of the tests in the microgravity experiment of Saffire II [82].

A second set of experiments was conducted using only the Nomex fabric (Figure 6.2(b)) but with an external radiant heat source provided by the four quartz near-infrared halogen lamps, located two in each side of the duct (as described in Chapter 2). Three constant radiation levels, 0, 5, and 10 kW/m\(^2\) were chosen, lower than the critical value to pyrolyze the Nomex. About 20% lamp radiation is transmitted through the thin Nomex sample without absorption. The external radiation was applied starting 120 s before ignition. The same nichrome wire was braided near the upstream edge of the sample for ignition, as shown in Figure 6.2. The igniter was energized using a controlled current power supply (BK Precision 1785) set to 40 W for 10 s for all tests.

The experimental procedure used during the tests followed the Oxygen Index tests described
in NASA-STD-6001B [5]. Once the sample was in position, the chamber was sealed to adjust the ambient pressure and oxygen concentration. After the desired conditions were achieved, the heaters were turned on. Then, the igniter was activated. The ignition and subsequent concurrent (upward) flame spread were video-recorded. In addition to video recordings, the mass of the sample was recorded before and after each test using a Sartorius scale (CPA225D) with 10 g resolution.

6.3 Experimental results

6.3.1 PMMA flame as external heat source

Concurrent flame spread over Nomex under the heating effect of the PMMA flame was investigated first. Figure 6.3 shows images of upward flame spread over Nomex when burning with the PMMA sheet for different oxygen concentrations. After the PMMA was ignited, the PMMA flame ignited the Nomex and assisted the flame spread over the Nomex. From the images, it can be noticed that the presence of the PMMA flame under the fabric allowed the burning of the material at oxygen concentrations below the LOC. In ambient air and pressure, Nomex would only burn when assisted by the PMMA flame and the flame would immediately extinguish after the PMMA burned out. As oxygen concentration was increased, the propagation distance of the flame increased, until it eventually spread over the entire sample.

The position of the Nomex pyrolysis front as a function of time is presented in Figure 6.4. It can be observed that the spread of the pyrolysis front is influenced by the heat from the PMMA burning, decaying as the heat flux decreases. Two stages of spread were identified: (I) while the PMMA was burning, the flame spread over the Nomex surface at an increasing rate, and (II) after the PMMA burned out, the flame spread rate slowed down. A notable result was that the PMMA flame helped the spread over the Nomex for oxygen concentrations below 24% (Nomex’s LOC), and extended the LOC to 17% oxygen concentration, although the total propagation distance is relatively short. The total heat flux to the surface from the PMMA flame (about 30 kW/m² [14] for a similar configuration) was high enough to pyrolyze the Nomex while the PMMA flame also acted as a pilot igniting the Nomex pyrolysate. Although the PMMA pyrolysate was the major fuel component in the flame, the flame was stronger due to the contribution from the Nomex pyrolysate. Above the Nomex’s LOC, the pyrolysis was sustained by the Nomex flame, although enhanced by the addition of the PMMA pyrolysate.

Flame front position was tracked from the video recordings to extract flame spread rates. The averaged concurrent/ upward flame spread rate over Nomex (averaged throughout the entire burn duration) as a function of oxygen concentration at two different ambient pressures is shown in Figure 6.5. The mean value of 3-5 repeated tests is reported, and error bars show the standard deviation. As expected, the flame spread rate increases with oxygen concentration, primarily because of the increasing flame temperature. Also, a higher flame spread rate was found for higher
pressures, although the pressure effect is weaker than the oxygen effect \cite{17}. For reference, the result obtained from Saffire II \cite{82} for a similar sample configuration is also included in Figure \ref{fig:6.5}, although no flame spread over the Nomex surface was observed at the test conditions (oxygen concentration of 21% by vol., 100 kPa ambient pressure, and $\mu g$).

Figure \ref{fig:6.6} presents the average flame spread over the Nomex as a function of ambient pressure in air. The flame spread rate decreases as the ambient pressure is reduced. At a pressure of 40 kPa or below, no flame spread was observed.

### 6.3.2 Radiant heaters as external heat source

The concurrent/upward flame spread over the Nomex fabric with thermal radiation from the halogen lamps was also investigated. Figure \ref{fig:6.7} shows a flame spreading upward over the Nomex fabric at different oxygen concentration environments. For oxygen concentrations below the LOC no propagation was observed, and the flame would only burn because of the extra heat of the ig-
Figure 6.4: Position of the pyrolysis front in Nomex assisted by the PMMA flame as a function of time and oxygen concentration at 100 kPa.

Figure 6.5: Average flame spread rate as a function of oxygen concentration under the effect of the PMMA flame.
niter wire. When the oxygen concentration approached the limiting values for propagation, the flame spread becomes weak and non-uniform, sometimes burning only partially the sample. As the oxygen concentration exceeded the LOC the propagation distance of the flame was greater, as well as the damage experienced by the sample.

Average flame spread rates were determined by tracking the pyrolysis front over the fabric. Figure 6.8 shows the position of the pyrolysis front in Nomex as a function of time without any external heating at an ambient pressure of 100 kPa and different oxygen concentrations. The flame spread clearly becomes faster as the oxygen concentration increases. As the oxygen concentration gets higher than the LOC, the pyrolysis of fabric can keep sustaining the flame spread on its own, and therefore propagate over the entire 140 mm sample where the propagation was accelerating at the beginning and then kept constant.

The results of the average flame spread rate as a function of the ambient oxygen concentration are presented in Figure 6.9 for ambient pressures of 100 and 60 kPa. For comparison, the data with PMMA as the source of heating are also presented. Without external radiation no propagation was observed at oxygen concentrations below the LOC of Nomex (24%). As the oxygen concentration was increased above the LOC, the propagation distance of the flame was greater. Under external radiation, the LOC decreased from 24% to 22% as the heat flux increased from 0 to 10 kW/m². It is seen that compared to the PMMA results, the flame spread rate follows similar trends with oxygen and pressure, but the PMMA flame heating extends the LOC of Nomex to lower values
Figure 6.7: Sample configuration used for the experiments: (a) Nomex with PMMA below and (b) Nomex only.

(17%). This is probably due to a higher heat flux from the PMMA flame than that achievable with the halogen lamps in the present experimental set up. The contribution of the PMMA flame to the ignition of Nomex pyrolysate seems to help extend the LOC of Nomex.

6.3.3 Mass Loss

To provide further information about the effect of the different heating sources, the mass loss of the sample ($\Delta Y_b$) was measured as

$$\Delta Y_b = \frac{m_b}{m_o} = \frac{m_o - m_r}{m_o} \cdot 100\%$$  \hspace{1cm} (6.1)$$

where $m_o$, $m_b$, and $m_r$ are the initial mass of the sample (before the test), the mass burned, and residual mass of the sample (after the test), respectively. Figure [6.10] shows mass loss normalized by the initial mass as a function of oxygen concentration and pressure. The mass loss fraction of Nomex with a PMMA flame and with the external radiant heater follows a trend like the flame
Figure 6.8: Position of the pyrolysis front in Nomex assisted by the radiant heating from the lamps as a function time and oxygen concentration at 100 kPa.

Figure 6.9: Average flame spread rate over Nomex under an external radiant flux ($\dot{q}_e''$) and a PMMA flame as a function of oxygen concentration: (a) 100 kPa and (b) 60 kPa. Hatched line shows the LOC for each heating source.
Figure 6.10: Mass loss fraction of Nomex under an external radiant flux ($\dot{q}_e''$) and a PMMA flame as a function of oxygen concentration for: (a) 100 kPa and (b) 60 kPa. Hollow points represent the no-spread cases.

spread rate in Figure 6.9, although the two heat sources have different effects on the overall mass loss.

When the Nomex is heated with the radiant lamps, there are two different regions separated by the LOC. Below the LOC, the mass loss fraction is small, but above the LOC the mass loss fraction has a step increase followed by a linear increase with the oxygen concentration, due to the heat flux from the Nomex flame. When heated by the PMMA flame, the mass loss continuously increases with the oxygen concentration. Above the LOC, the mass loss for all radiant heating is larger than that under the PMMA flame, indicating that the external radiation adds up to the heat flux from the Nomex flame enhancing the Nomex pyrolysis. Notice that even under the highest oxygen concentration of 34%, the total mass loss fraction is less than 35%, which shows the fire resistance characteristics of the Nomex fabric.

6.4 Discussion

When the flame is spreading over a thin fuel, the environmental variables can change the physicochemical processes and the flame behavior. Here, the effect of pressure, oxygen concentration, and gravity on the flame spread rate are discussed using an approximate analysis of flame spread previously developed in [7]. The flame spread rate may be expressed as

$$V_f = l_h \left( \frac{\rho_s c_s s (T_p - T_o)}{\dot{q}_{fc}'' + \dot{q}_{fr}'' + \dot{q}_{e}'' - \dot{q}_{rs}''} + \frac{C x [F]}{U_m \frac{F}{r}} \right)^{-1}$$

(6.2)
where $l_h$ is the heated length of the solid ahead of the pyrolysis front, $\dot{q}_{fc}'', \dot{q}_{fr}'', \dot{q}_e''$, and $\dot{q}_{rs}''$ represent the convective heat flux at the solid surface, the flame radiant flux, the external heat flux, and the re-radiation from the solid. $\dot{U}_m$ is the mixed flow (forced and free) velocity, $[F]$ is the fuel concentration in the gas and $\hat{r}$ is the reaction rate. $\rho_s$, $c_s$, and $s$ are the solid density, specific heat, and thickness, respectively. $T_p$ and $T_o$ represent the pyrolysis and initial temperatures of the solid, and $C$ is a numerical constant. Equation 6.2 includes two important flame spread mechanisms: the left term inside the bracket represents the heat transfer to the unburnt solid, and the right term represents the chemical kinetics in the gas phase. Above the LOC, the gas-phase reaction rate ($\hat{r}$) is large, so the right term has a negligible effect on the flame spread. While the heat transfer to the unburnt solid plays the dominant role. Below the LOC, the small gas-phase reaction rate could prevent the occurrence of flame spread, even under strong external heating.

Assuming that the heat transfer from the flame to the surface is primarily by convection, then the flame spread rate is primarily determined by the convective heat flux from the flame plus the external heat flux. As ambient pressure is reduced, changes in gas phase density affect this convective heat flux by changing the boundary layer thickness and influencing the heat transfer coefficient. For a mixed (forced and free) flow as that of the normal gravity experiments, the heat transfer coefficient can be expressed as a function of two non-dimensional numbers: the Grashof (Gr) and Reynolds number (Re) as

$$h = Ck \frac{Re^4 + Gr^2}{l_p} Pr^{1/3}$$

(6.3)

where $Re = \rho U_f l_p / \mu$, $Gr = g \beta \Delta T_p l_p^3 \rho^2 / \mu^2$, and $Pr = \alpha / \nu$. $U_f$ represents the forced flow velocity component of the mixed flow, $\mu$ is the dynamic viscosity, $\rho$ is gas phase density, $\beta$ is the coefficient of thermal expansion and $g$ is gravity. By looking at Equation 6.3 together with the definitions of the non-dimensional numbers, it can be noted that $h$ decreases with the decreasing ambient pressure ($P$). Therefore, as the pressure decreases, the decrease in the effective flame heating slows down the flame spread, as confirmed in Figure 6.9. On the other hand, as the pressure decreases to sub-atmospheric, the flame sheet (reaction zone) may become thicker and the flame temperature decreases [144], which could also contribute to the decrease in the flame spread rate. The global gas-phase reaction rate may be expressed by as

$$\hat{r} = A \exp \left( - \frac{E_a}{RT} \right) [F][O]$$

(6.4)

where $A$ is the pre-exponential coefficient, $E_a$ is the activation energy, and $R$ is the universal gas constant. As the flame temperature decreases, a higher oxygen concentration is required to sustain the minimum flame chemistry. Therefore, a higher LOC is found under a lower ambient pressure. Notice that the decrease in the pressure reduces the buoyancy effect by increasing the flame standoff distance, which is equivalent to the decrease in the gravity. Given Equation 6.2, increasing the external radiant heat flux ($\dot{q}_e''$) accelerates the flame spread above LOC, as confirmed...
by in the experiments. Moreover, part of the radiant heat flux from lamps could also be absorbed by the pyrolysis gas from the Nomex [182]. The preheated gaseous fuel could lead to a higher flame temperature, thus compensating for small reductions in oxygen concentration. Similar reduction in LOC under external radiation was also observed for electrical wires [64].

As per the effect of the ambient oxygen concentration, for the PMMA assisted flame spread, above the LOC of PMMA (17%) but below the LOC of Nomex (24%), the pyrolysate from PMMA is the major fuel component of the flame. Thus, the flame could be viewed as a PMMA flame assisted by the pyrolysate from Nomex, that is, a direct increase in $\dot{q}_f''$, rather than adding $\dot{q}_e''$ like the radiant lamp. Although both heat fluxes have the same influence in Equation 6.2, the PMMA flame acts as an ignition source of the Nomex pyrolysate at oxygen concentrations below the LOC. However, above the Nomex LOC, the PMMA flame may reduce the amount of oxygen that reaches the Nomex pyrolysate, explaining the observed lower flame spread rates and mass loss for the PMMA assisted tests than the lamp radiation assisted tests. Similarly, above the LOC of Nomex, the flame could be viewed as a Nomex flame enhanced by the pyrolysate from PMMA. Notice that the heat of combustion of PMMA (25.4 MJ/kg [24]) is similar to that of Nomex (28.1 MJ/kg [101]), so mixing both pyrolysates may not result in appreciable change in the flame heating. In fact, as shown in Figure 6.9 such enhancement was found to be below 5 kW/m², under both normal and reduced pressures.

Additionally, as ambient pressure is reduced, changes in gas phase density affect this convective heat flux by changing the boundary layer thickness ($h = k/\delta$). Using the same approach used for the heat transfer coefficient [7], for a mixed (forced and free) flow the boundary layer thickness can be expressed as

$$\delta = l_p \left( Re^4 + Gr^2 \right)^{-1/8}$$  \hspace{1cm} (6.5)

$$= l_p Gr^{-1/4} \left( Fr^2 + 1 \right)^{-1/8}$$  \hspace{1cm} (6.6)

$$= l_p Re^{-1/2} \left( 1 + \frac{1}{Fr^2} \right)^{-1/8}$$  \hspace{1cm} (6.7)

with $Fr = Re^2/Gr = U_f^2/g l_p$. At low forced flow velocities and normal gravity, the heat transfer process is controlled by natural convection and the boundary layer thickness is better expressed as Equation 6.6. At large flow velocities or low gravity, the process is dominated by forced flow convection and the boundary layer thickness is better expressed as Equation 6.7. By equating the thickness of the boundary layers for a pure forced flow, as in microgravity, and the mixed convection flow, as in normal gravity conditions, it is possible to obtain a mixed flow velocity ($U_m$) that if applied in a pure forced flow, would produce a boundary layer of the same thickness as the one in the mixed flow.
Figure 6.11: Dependence of the PMMA assisted flame spread rate over the Nomex surface on the mixed convection flow velocity, $U_m$, of Equation 6.8. Normal gravity at various pressures, 21% $O_2$.

\[
U_m = \frac{P}{P_o} U_f \left(1 + \frac{g^2 \rho_p l_r}{U_f^4}\right)^{1/4}
\]  

(6.8)

where $P_o$ is a reference pressure. From Equation 6.8 it is seen that in normal gravity, as the pressure is reduced, the contribution from buoyancy is reduced and in turn the mixed flow velocity is also reduced. Thus, from Equation 6.2 it is obtained that flame spread rate also decreases.

The flame spread data from Figure 6.6 can be plotted in terms of the mixed flow velocity of Equation 6.8 as shown in Figure 6.11. The data point from the Saffire [82] experiment is also included for comparison purposes. It is seen, that as predicted by Equation 6.2, the flame spread rate decreases as the mixed flow velocity, $U_m$, decreases. This dependence agrees with the experimental data for thin paper [81]. It is also seen that the correlation predicts that the Saffire test would not result in flame spread because the forced flow velocity, $U_f = 20$, cm/s is smaller than the minimum flow velocity for the flame to spread $U_f = U_m = 23$ cm/s. Although the spread rate at low pressures can be influenced by the flame chemistry and the decrease in flame temperature [144], it can be inferred that if the forced flow velocity was larger than 25 cm/s, the Saffire test of Nomex supported by the PMMA flame [82] would have resulted in flame spread along the Nomex surface.
Figure 6.12: Dependence of the mass loss of the PMMA assisted flame spread over Nomex on the mixed convection flow velocity, $U_m$, of Equation 6.8. Normal gravity at various pressures, 21% O$_2$.

The mass burning rate is also a function of the heat flux to the surface [8] and consequently of the flow velocity. Thus, it is expected that the mass loss data should correlate with the mixed flow velocity in the same fashion as the flame spread rate as shown in Figure 6.12. It can be seen that as the ambient pressure is reduced the mass loss decreases following a similar trend as the flame spread rate, even though both process have different controlling mechanisms [8].

6.5 Conclusion

The present experiments show that decreases in oxygen concentration and ambient pressure decrease the rate of flame spread and mass burning. The correlation of the flame spread rate data in terms of a mixed flow velocity that includes gravity and pressure suggests that reducing ambient pressure can be used to simulate different levels of gravity. Specifically, the correlation predicts that the microgravity Saffire PMMA/Nomex test [82] would not result in flame spread because the forced flow velocity, $U_f = 20$ cm/s, was smaller than the minimum flow velocity for the flame to spread ($U_f = U_m \sim 23$ cm/s), as was observed in the Saffire experiment. Also, it can be inferred that if the forced flow velocity in the Saffire test was larger than 25 cm/s, the test would have resulted in flame spread. It should be noted that variations in pressure will affect flame chemistry. For a constant oxygen concentration, as total pressure is reduced, there is a subsequent reduction
in the partial pressure of oxygen and flame temperature [144]. The combined effect of reduced oxygen partial pressure and ambient pressure slows the reactions in the gas phase, limiting the heat provided by the flame to the solid and thus, reducing the flame spread rate. Thus, the predictions of the correlation may become worse at lower pressures. While, the approach developed here offers novel possibilities, care should be taken in implementing test methods that would use ambient pressure reduction to predict flame spread at different gravity levels.

The observation that different external heat sources resulted in different flame spread behaviors is important because most test methods only use an external radiant flux to simulate an adjacent fire. The results show that a PMMA flame lowers the LOC of Nomex below the LOC with a radiant heat source. There is a need for more detailed modeling to fully understand the implications of different heat sources on material flammability, beyond the phenomenological explanation presented here.
Chapter 7

Conclusions and Future Work

7.1 Conclusions

The flammability of a solid material can be defined in terms of four different characteristics that can be measured or quantified: how easily it will ignite, how easily will allow the propagation of flames, its heat release rate, and the rate at which produces toxic gases. In order to be able to prevent fires, or minimize their effects once started, we need to better understand material flammability, particularly the effect of the surrounding environmental conditions at which the material is exposed. Following this, this research attempts to help provide information on how environmental conditions can affect material flammability, particularly focusing on the spread of flames in spacecraft environments. This is particularly important when considering NASAs proposed plan for future space exploration vehicles, where they are designing cabin environments to work with reduced cabin pressure and an increased oxygen concentration atmosphere. Additionally, spacecraft cabins have very low flow velocities that are generated by the ventilation system (HVAC), and that are not easily replicated on-earth. These changes in the current cabin environments have led to the evaluation of how these new conditions will affect material flammability and flame behavior, and how to improve current testing methodologies to make testing easier.

The effect of environmental conditions on downward flame spread over two fire resistant materials relevant for NASA is examined on Chapter 5. Among the environmental variables considered are changes in ambient pressure, oxygen concentration and the presence of external radiation. Material flammability was measured by generating flammability limits, i.e. boundary conditions that allow or not allow flames to spread, and by measuring flame spread rates when observed. It was found that as ambient pressure is reduced, the oxygen concentration required for the flame to propagate was also increased. The external radiant heat flux acts as an additional source of heat and allows propagation of the flame at lower oxygen concentrations. It was shown that as ambient conditions change, they influence different processes, heat transfer and chemical kinetic, that affect the spread of the flame. As the flame spreads over the solid, the process is controlled mainly by heat transferred from the flame to the solid. However, an analysis of the boundary conditions
in terms of the partial pressure of oxygen suggest that, as we approach conditions less favorable for the spread, i.e. limiting conditions, the material flammability is not only determined by heat transfer mechanisms but also by chemical kinetic mechanisms that become more important.

Because of the clear differences between current spacecrafts environment and normal-earth environments, the emphasis of Chapter 4, 5, and 6 was set on the study of flame spread in both conditions, working on the development of an analysis that would provide the means to compare experimental data obtained in either conditions. For this, the approach followed focused on using reduced ambient pressure environments to reduce buoyancy effects in normal gravity, allowing this way the comparisons of flame spread between reduced pressure and microgravity conditions. Experiments were conducted in normal gravity using a forced flow of air and different ambient pressures, decreasing from 100 kPa to 30 kPa. Microgravity experiments were conducted on board of the re-supply vehicle Cygnus during a set of experiments that were part of the Spacecraft Fire Experiment (Saffire) Project. These tests were performed using a low air flow velocity representative of the ventilation system of a spacecraft, and normal ambient pressure. Although a similar general approach is presented in Chapter 4, 5, and 6, they differ in the type of sample configurations and materials used. Chapter 4 and 5 were focused on studying the effects of buoyancy when flames spread over a thermally thin and a thermally thick combustible solid, respectively. In both cases, the sample configuration selected was chosen to match the materials/samples used during the Saffire experiments. The data collected during the normal gravity tests was compared with the microgravity tests performed during Saffire. In general, independently of the sample configuration selected, the average flame spread rate decreased with decreasing ambient pressure. Results show that reductions of pressure slow down the flame spread over the material surface. As pressure is reduced, flame intensity is also reduced, with the flame changing from a bright yellow color to a dimmer purple-blue color. Comparison with the microgravity data shows that as the pressure is reduced, the normal gravity flame spread rate approaches that in microgravity, and that similar spread rates could be obtained at around ∼25 kPa. The data presented is correlated in terms of a mixed convection non-dimensional number that describes the convective heat transferred from the flame to the solid, and that also describes the primary mechanism controlling the spread of the flame.

A similar approach is also followed in Chapter 6 trying to reduce buoyancy effects to compare flame spread behavior with microgravity data obtained during Saffire. Additionally, Chapter 6 ventures into the study of the heating source that is used to characterize material flammability, making comparisons between the heating provided by a real adjacent flame and the heat flux provided by radiant heaters. The results obtained as part of this work suggest that different external heat sources resulted in different flame spread behaviors affecting material flammability in different ways. The results showed that the presence of a flame near the material surface allowed flame spread at lower oxygen concentrations than with a purely radiant heat source. However, the presence of the flame acts both as the heating element and ignition source and might alter locally the burning conditions, so there is a need for more detailed modeling to fully understand the implications of different heat sources on material flammability, beyond the phenomenological explanation.
The correlations and analysis presented in this work provide information about the similitudes of the flame spread process in variable pressure, flow velocity and gravity environments. These relations give a better understanding of what is to be expected when burning solid combustible fuels in microgravity and could potentially be extended to environments of untested gravity levels or flow conditions. The work presented here provides guidance for potential ground-based testing for fire safety design in spacecraft and space habitats.

### 7.2 Future Work

The research presented here represents a first step towards developing more accurate testing methodologies that could be used on earth to predict flame spread behavior inside spacecrafts with different environmental conditions, i.e. ambient pressure, oxygen concentration, partial gravity or low flow velocities. The phenomenological relations presented describe the controlling physical mechanisms responsible for the spread of flames over solid fuels. The main physical processes involved are depicted and the results show a good agreement between the data obtained during microgravity tests and the normal gravity reduced pressure tests when correlated using the analysis developed. These correlations provide information about the similitudes of the flame spread process in variable pressure, flow velocity and gravity environments, providing guidance for potential ground-based testing for fire safety design in spacecraft and space habitats. However, the analysis presented is based on several simplifications that need to be addressed to further improve and extend the work presented.

First, the analysis presented in this work considers mainly that the flame spread process is controlled by convective heat transfer from the flame to the solid assuming that chemical kinetic effects are negligible and that radiation from the flame balances out with that of the solid. However, the modification of the radiative features of the flame with different environmental conditions and the fact that, under low flow conditions in microgravity, radiative heat transfer can be the dominant mechanism controlling the heat transfer process (sometimes leading to extinction) requires further research to investigate on the radiative behaviors of flame spreading in different gravity levels.

Additionally, the analysis presented here is performed focusing mainly in the differences generated in buoyancy by using different ambient pressure environments with flames burning in air. However, future space exploration vehicles will also include variations in the oxygen concentrations. As the oxygen concentration is changed, this will impact the flame temperature and, in normal gravity, further influencing the changes in buoyancy generated by the flame. Therefore, the analysis developed needs to be updated to consider these effects. Further understanding in this area could help quantify the behavior of flames where the combination of low pressure and high oxygen represent an increased fire risk.
Finally, it would be interesting to use the current analysis to predict flame spread behavior in different conditions of flow velocity, sample geometry, or partial gravity, i.e. like those of Mars or the Moon, to verify if the same analysis is capable of capturing flame spread behavior in other configurations or possible scenarios. This would require further testing in order to get the experimental data at those particular conditions and be able to make the comparisons with the materials already tested. However, it is also possible to use some of the data already available for some other materials, like that provided by Kleinhenz et al. [19] for thin cellulosic tissue (Kimwipes EX-L) at different gravity levels. Or that obtained during the BASS-II tests for PMMA cylinders in low flow velocity flows in microgravity obtained inside the Microgravity Science Glovebox (MSG) facility aboard the International Space Station (ISS) [183].
Appendix A

External Radiant Heaters Calibrations
Figure A.1: Heat flux measured along the filament of the lamps. Voltage set to 40 V. The radiometer was positioned at 7.62 cm from the lamp’s filament. Measurements were taken considering duct window.
Figure A.2: Heat flux measured across the filament of the lamps. Voltage set to 40 V. The radiometer was positioned at 7.62 cm from the lamp’s filament. Measurements were taken considering duct window.
Figure A.3: Heat flux measured along the entire surface of the sample. Voltage set to 40 V. The radiometer was positioned at 7.62 cm from the lamp’s filament. Measurements were taken considering duct window.
Bibliography


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