EXPERIMENTAL STUDY OF THE EFFECT OF FUEL THICKNESS ON
OPPOSED FLOW FLAME SPREAD OVER PMMA

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DEDICATION

This work is dedicated to my family who’s never ending patience has allowed me to complete this program. My wife who put up with countless hours of school all while helping me care for my two beautiful children and being the best wife a man could ask for. My children, Aubrey and Samantha for never complaining, continuing to believe in me and constantly inspiring me to be a better person. Finally I’d like to thank my parents for all their support and guidance to allow me this special opportunity. Thank you all for never giving up on me.
ABSTRACT OF THE THESIS

Experimental Study of the Effect of Fuel Thickness on Opposed Flow Flame Spread over PMMA
by
Matthew N. Laue
Master of Science in Mechanical Engineering
San Diego State University, 2015

The research presented below intends to investigate the role of Poly methyl methacrylate (PMMA) fuel thickness on the spread rate of a downward spreading flame, the thermal radiation being emitted by the flame, and to compare results for both microgravity and normal gravity. To simplify the complex problem of flame spread over solid fuels, the concept of the thermal regime is used to find a constant spread rate for a given fuel thickness. In the thermal regime the opposed flow velocity is high enough to neglect losses due to radiation from the flame but still small enough to not affect the flame through finite rate kinetics. The microgravity results were performed on the International Space Station in the Bass-II Microgravity Science Glove box. This 7.62 cm square duct allows the variation of opposed flow velocity while holding pressure, oxygen and nitrogen constant during each run. The runs are recorded using a digital video camera for spread rate analysis and thermal radiation is read using a radiometer. For normal gravity, SDSU’s Flame Stabilizer was used to acquire the downward spread rate from video analysis and thermal radiation is read by a radiometer developed here at SDSU. With the use of a Matlab image analysis code, the videos are analyzed to obtain the spread rate for each fuel thickness. When compared, these results show good experimental agreement for spread rate and thermal radiation. These results, along with known thermodynamic properties and scaling analysis are used to refine the de Ris-Delichatsios formula for the thermal regime. With very few examples of the de Ris-Delichatsios formula being matched to experimental results it is hard to define where the thin regime ends and where the thick regime starts. The refined formula is applied to both the thin and thick regimes to show approximately where the transition lies between the two and compared to experimental results. This transition zone in both microgravity and normal gravity is of great interest for researchers trying to predict the behavior of flame spread both here on earth and in space aboard the International Space Station.
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<tr>
<td>$T_\infty$</td>
<td>Ambient temperature</td>
</tr>
<tr>
<td>$T_{vap}$</td>
<td>Vaporization temperature</td>
</tr>
<tr>
<td>$T_{ig}$</td>
<td>Ignition temperature</td>
</tr>
<tr>
<td>$T_f$</td>
<td>Flame temperature</td>
</tr>
<tr>
<td>$T_i$</td>
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<td>$T$</td>
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<tr>
<td>$V_f$</td>
<td>Flame spread rate, mm/s</td>
</tr>
<tr>
<td>$V_g$</td>
<td>Oxidizer velocity, cm/s</td>
</tr>
<tr>
<td>$V_r$</td>
<td>Relative flow velocity, cm/s</td>
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<tr>
<td>$V_{f,thin}$</td>
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<tr>
<td>$V_{f,thin,expt}$</td>
<td>Flame spread rate for thin fuel de Ris thermal limit from experiment, mm/s</td>
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<tr>
<td>$V_{f,thick,expt}$</td>
<td>Flame spread rate for thick fuel de Ris thermal limit from experiment, mm/s</td>
</tr>
<tr>
<td>$V_{g,e\text{ff}}$</td>
<td>Effective velocity of the oxidizer, cm/s</td>
</tr>
<tr>
<td>$\tau$</td>
<td>Half fuel thickness, (\mu m)</td>
</tr>
<tr>
<td>$\tau_{\text{transition}}$</td>
<td>Fuel thickness for transition from the thin to thick fuel, (\mu m)</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Field of view for radiometer, degrees</td>
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<tr>
<td>$w$</td>
<td>Half field of view for radiometer, degrees</td>
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<tr>
<td>$\phi$</td>
<td>Viewing whole diameter for radiometer cover plate, mm</td>
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<tr>
<td>$y$</td>
<td>Half viewing whole diameter for radiometer cover plate, mm</td>
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<tr>
<td>$\Omega$</td>
<td>Ohms</td>
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<tr>
<td>$V$</td>
<td>Volts</td>
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Voltage of the source for radiometer, Volts

Voltage of the noise for radiometer, Volts

Reference voltage for radiometer, Volts

Output voltage for radiometer, Volts

Hertz

Radiative Flux for radiometer, \( \mu V/cm^2 \)

Responsivity of radiometer, \( V/W \)

Watts

Parts per million

Length of radiometer cover plate, cm

Amps

Intensity of black body radiation, \( W/m^2 \times \pi \)

Stephan-Boltzmann constant, \( W/m^2 \times K^4 \)

Thermal conductivity of air at 700K, 0.052 \( W/m \times K \)

Thermal conductivity of solid PMMA at 700K, 0.43 \( W/m \times K \)

Density of air at 700K, 0.518068 \( kg/m^3 \)

Density of PMMA at 700K, 1190 \( kg/m^3 \)

Specific heat capacity of PMMA at 700K, 1.465 \( kj/kg \times K \)

Specific heat capacity of air at 700K, 1.183 \( kj/kg \times K \)

de Ris coefficient

de Ris coefficient from experimental results

de Ris coefficient from de Ris results

de Ris coefficient from adiabatic flame temperature

de Ris coefficient from

Full angle of the field of view for the webcam

Center of the thickness of cover plate viewing whole
<table>
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<th>Symbol</th>
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<td>$L$</td>
<td>Distance from fuel to the webcam, mm</td>
</tr>
<tr>
<td>$\Delta L$</td>
<td>Distance from the webcam to thermopile, mm</td>
</tr>
<tr>
<td>$d$</td>
<td>Half spot size for radiometer, mm</td>
</tr>
<tr>
<td>$D$</td>
<td>Spot size for radiometer, mm</td>
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<tr>
<td>$\alpha$</td>
<td>Half angle of webcam field of view</td>
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I’m extremely thankful to Dr Subrata Bhattacharjee for his patience, guidance and support throughout my career here at San Diego State University. I’m also very appreciative of Dr Ilenia Battiato and Dr Xiaofeng Liu for their participation in my thesis committee.

To all my good friends in the lab who helped me to accomplish the work for this research and kept me on track. Especially Kenneth Keivens for all his help with the MATLAB programming that is so very tedious.

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CHAPTER 1

INTRODUCTION

The research for this thesis intends to show how varying Poly (Methyl Methacrylate) PMMA fuel thickness will affect the flame spread rate for both thermally thin and thick PMMA fuels, where the transition between the thermally thick and thin regimes lies and show how a refined di Ris-Delichatsios formula can better theoretically predict this transition for both microgravity and normal gravity. It also shows the concept, design, manufacturing and testing of a Radiometer used to detect radiative flux coming off of a flame or solid surface. The radiometer will be used to show the change in radiative flux from a flame as the thickness of the solid fuel is varied for both microgravity and normal gravity.

This chapter introduces flame spread, the research on flame spread that has already been done by the combustion community and the purpose of the study.

1.1 INTRODUCTION TO FLAME SPREAD

Flame spread is the rate at which a flame will spread across the top of or consume a certain material. Flame spread can occur in many different orientations and under various conditions. Flames can spread horizontally on the top or bottom of a material. Flames can also spread in the upward direction or they can spread in the downward direction depending on the source of the fire. Even though all three orientations can occur in a fire the horizontal and upward spreading flames are very hard to investigate due to the ever changing size of the flame, whereas the downward configuration seems to have steady size and shape. The oxidizer, which is the chemical needed for the flame to propagate, usually O₂ here on earth and in the International Space Station, is fed to the fire through a flow. The flow can be a forced convective flow by the use of fans or wind, or a natural convective flow where buoyancy drives the velocity of the flow. The flow can be further separated into two distinct categories, concurrent and opposed. Concurrent flow moves in the same direction as the
flame is propagating. In concurrent flow the diffusion of O$_2$ at the flames leading edge and the convective heat loss from the flame both occur in the same direction. The virgin fuel surface located in front of the leading edge of the flame usually is preheated through conduction and radiation heat transfer. For concurrent flow the fuel surface sees higher rates of heat transfer due to high temperature combustion products helping heat the fuel surface through convection. This added mechanism of heat transfer leads to increased flame spread rate over time. Opposed flow is the exact inverse of concurrent, moving in the opposite direction that the flame is propagating. With diffusion and the convective loss of thermal energy occurring in opposite directions, spread rate remains relatively steady for both forced and natural convection situations. For continued simplicity the concept of the thermal regime will be implemented where the opposed flow is high enough to not affect the flame spread rate from losses due to radiation but low enough to neglect the effects of finite rate kinetics. In thin fuels this leads to a constant fuel temperature across the fuel thickness. For these reasons this study looks at opposed flow downward flame spread in the thermal limit.

"Figure 1.1. Opposed flow downward flame spread over a solid fuel."
Figure 1.1 above shows a diagram of an opposed flow downward flame spread for a solid fuel with thickness $2\tau$ or a half thickness of $\tau$. The figure shows a flame spreading downward in the same direction as gravity with a velocity of $V_f$. The oxidizer $O_2$ is diffused into the flame from the sides and bottom just under the leading edge of the flame through a buoyancy induced flow with a velocity of $V_g$. This leads to the relative velocity of the flame being calculated as $V_r = V_f + V_g$. The buoyancy induced flow also allows for the release of thermal energy through convection heat transfer from the tail of the flame in what’s known as the plume. For the flame to propagate, the unburned fuel just below the leading edge of the flame must have its temperature raised from the ambient room temperature $T_\infty$ to the vaporization temperature $T_v$. This is accomplished through conduction and radiation heat transfer to the unburnt fuel. Once the higher temperature $T_v$ is reached, pyrolysis occurs which is the thermochemical decomposition of the PMMA. Physically this is seen as the melting of the PMMA in front of the leading edge. As the temperature continues to rise, $T_{ig}$ is reached which is the temperature needed for ignition of the fuel and for the reaction to occur.

1.2 Literature Review

Opposed flow flame spread over solid fuels has been under investigation for three to four decades [1-3]. Researchers have long desired to understand and predict the behavior of fire in different situations and under different conditions. Using the opposed flow configuration of flame spread allows a simplification to the problem where the spread rate of the flame is unchanging even if the size of the fire grows. One of the many factors affecting the spread rate of a flame is the finite thickness of the solid fuel being burnt. The thickness of solid fuels can be separated into two distinct regimes, the thick and the thin. In the thin regime the spread rate of the flame is varying with the change in thickness of the solid fuel. In the thick regime the spread rate is independent of the fuel thickness and becomes constant. To simplify the problem even more only the thermal regime is considered where the fuel is uniformly heated by the spreading flame, the spread rate is independent of the opposed flow velocity and inversely proportional to the fuel thickness. The thermal regime is governed by the de Ris-Delichatsios formula [4], [5] for spread rate in an opposed flow. This formula takes into consideration the thermodynamic properties, fuel thickness and a non-dimensional
coefficient known as the de Ris coefficient \( F = \frac{(T_f - T_r)}{(T_v - T_\infty)} \), where \( T_f \) is the adiabatic flame temperature, \( T_r \) is the fuel vaporization temperature, and \( T_\infty \) is the ambient and virgin fuel temperature. To further validate the de Ris-Delichatsios formula, work has been done to modify the formula by Bhattacharjee et al. [6] and Bhattacharjee, West and Docker [7]. The formula is modified to more accurately reflect experimental data collected and to find closed form expressions for both thin and thick fuels in opposed flow microgravity situations in terms of the thermal limit of spread rate and a radiation number. These modifications lead to better prediction of thick fuel spread rate than the original formula.

Much research has been done in the field of thin fuel opposed flow flame spread. The boundary layer effect and humidity inside an experimental apparatus has been shown to drastically change the velocity seen at the fuels surface and spread rate for thin cellulose filter paper fuels by Bhattacharjee et al. [8] and Etoh, Nakamura and Yamashita [9]. Olson [10] and Frey and Tien [11] have shown that opposed flow velocity and the oxygen concentration have huge impacts on the spread rate seen by thermally thin cellulose fuels. The opposed flow temperature, pressure and buoyancy also all play huge roles in the spread of a flame over cellulose fuels in the opposed flow configuration as seen by Olson [10] and Altenkirch, Eichhorn and Shang [12]. The latter studied buoyancy effects on downward spread rate over index cards. They found that as buoyancy increased the flame spread rate decreased until the flame extinguishes due to extreme buoyancy. Olson et al. [13] conducted a narrow gap study for cellulose materials in actual and simulated microgravity to show how the flow velocity, oxygen concentration and gap size effected heat loss when the flame is propagating in small gaps like those between walls or electronic equipment. She concluded that when flow velocity is reduced the flame front breaks down into flamelets and that these flamelets can persist in small gaps where they are hard to detect. To see how a partially premixed atmosphere might affect the structure and spread rate of a flame over cellulose paper, Yamamoto, Ogata and Yamashita [14] mixed the incoming flow to the downward spreading flame with hydrogen, methane and propane. They ran three different thicknesses of cellulose and found that the premixed atmosphere enlarged the flame regions leading to increased spread rate. They also changed the temperature of the incoming flow which showed the same increase in spread rate for both methane and propane, but a much higher
increase in spread rate with the hydrogen air mixture due to an increased pyrolysis zone. Rybanin [15] continued with thin paper/inert sheets to find to distinct cases for flame spread rate and structure of a diffusion flame. First when the flame size is large, the spread rate increases due to thermal conductivity of the solid phase. Second when the flame size and heat transfer from the flame to the virgin fuel are small, the spread rate decreases due to convective heat loss from the preheating zone to the gas flow.

Another critical parameter associated with flame spread rate is the finite solid fuel width. Zhang and Yu [16] studied the three dimensional effects of varying opposed flow velocity, oxygen concentration and fuel sample width on flame spread rate in a narrow channel apparatus. They concluded that with a fixed oxygen concentration of 20%, flame spread rate shows no change with sample width at flow velocities of 10 cm/s or greater, went up with width for flow velocities around 5 cm/s and went down and then back up for low flows less than 3 cm/s. Rangwala et al. [17] also investigated the effect of PMMA fuel width on the height of the flame for an upward flame spread configuration. It was found that for sample widths of 2.5 cm to 15 cm flame height becomes smaller as the fuel width is decreased possibly caused by a reduction in excess pyrolyzate because the diffusion of fuel to the side of the sample is decreased. This reduction in the size of the flame leads to lower spread rates for the flame. Olson and Miller [18] used the drop tower at NASA Glenn to perform concurrent and opposed flow forced convective microgravity tests on cellulose. They found that opposed flow flames in flows of 5-20 cm/s spread faster than the concurrent flow flames under the same atmospheric conditions typically found in spacecraft. The thermally thin regime is explored by Di Blasi [19] for varying thicknesses of cellulose fuel and shows that spread rate decreases as thickness is increased for this regime. Hsu and T’ien [20] also vary the width of fuels such as machine paper tape and kimwipes for a three dimensional concurrent flow flame spread analysis. They vary sample width, gravity, flow velocity, pressure and oxygen concentration to simulate spread rates and extinction limits. It was found that there numerical model matched quite well with experimental results for both buoyant and forced flow except for the extinction limits which were just slightly lower than expected.

The thick regime is also full of research to try to understand how the fire behaves under certain conditions as the fuel becomes infinitely thick. Spread rate and temperature
distributions are some of the parameters studied experimentally by Wu et al. [21]. As the opposed flow velocity and temperature are varied, ignition delay time is seen to increase with decreasing opposed flow temperature or increasing opposed flow velocity. Foam fuels have also been used by Son and Ronney [22] to show that thick fuels can spread in a quiescent microgravity environment especially when carbon dioxide is employed. Oxygen and pressure effects are shown, the transition from thermally thick to thermally thin is shown by a decreasing bed size. Consalvi et al. [23] used thick slabs of PMMA to investigate vertical wall flames and how flame height can be defined by a threshold value based on the wall heat flux. These threshold values where used to determine flame heights from a two dimensional time-dependent CFD model which showed consistent flame heights with experimental results. Also looking into upward flame spread over thick PMMA slabs is Pizzo et al. [24]. The effect of fuel width is studied and for widths greater than or equal to 10 cm the flame spread rate is independent of width due to the flame remaining laminar. For the 2.5 cm and 5 cm widths the flame spread rate decreased as the width decreased because the flame transitions to turbulent. Two-dimensional direct numerical simulations of upward flame spread over thick PMMA was conducted by Xie and Desjardin [25] for different angles of inclination over a range of spread rates. The simulations showed that the heat flux to the preheat region of the fuel varied considerably with time which contradicts employed assumptions in known spread rate calculations. Sibulkin, Kulkarni and Annamalai [26] chose to look at a vertical natural convection diffusion flame that is thermally thick with the properties of PMMA. For a short sample where the flame is laminar they found that the surface burn rate has a strong dependence on surface radiation and a weak dependence on chemical reaction rate. This showed that the effects of gas phase radiation are not significant to the surface burn rate.

Some researchers have also looked at both thin and thick fuels instead of choosing one regime to explore. Ayani, Esfahani and mehrabian [27] explored PMMA sheets from 1.5 mm to 10 mm thick in quiescent air for the mechanisms of flame spread rate. It was found that the flame spread rate decreases with increased thickness until the thick regime is reached where spread rate becomes independent of thickness. Kleinhenz et al. [28] used pressure-gravity modeling to simulate upward flame spread over vertical samples in partial gravity like the moon or mars. The experimental tests were done onboard the NASA Reduced
Gravity Aircraft and were conducted on thin cellulose samples. These tests lead to correlations for partial gravity flame spread for a thin fuel with a laminar flame. Since the correlation is based on steady gas-phase considerations only, it is expected to apply to instantaneous flame growth rates over thick solid fuels even if the flame becomes turbulent. Bhattacharjee et al. [29] compared numerical simulation, experimental results and presented a simplified parabolic theory for thin cellulose fuel and thin and thick PMMA. The computational results are shown to agree quite well with the experimental results for both cellulose and thin and thick PMMA. The simplified closed form solution for the temperature fields reproduces the flame shape within acceptable limits for the thick regime but does not work well for the thin fuels.

Other research has been conducted on different materials and other shapes beyond rectangular to see the effects of material choice and shape factors on flame spread rate and other mechanisms of flame propagation. PMMA cylinders were considered as a shape factor with opposed turbulent flow being forced through the cylinder via a hole through the center of the material to study blow off extinction limits by Hashimoto et al. [30]. The first set of experiments showed that the flow velocity at the point of blowoff extinction increased with ambient pressure, contradicting the expression for the well-known Damköhler number which is the ratio of the characteristic flow time to the characteristic chemical time. A second set of experiments was conducted to clarify this effect by studying the flow field near the leading edge of the flame. This showed that when the friction due to velocity was large enough to reach a critical value, blowoff occurred due to the absence of flow separation. Gonzalez et al. [31], investigated ethane as a gaseous fuel for the propagation of two-dimensional planar edge flames by using a laminar wind tunnel to inject the gas down the centerline of the airstream and ignite a downward flame representing a flame moving down through a flammable plume or flammable layer in microgravity. They found by increasing the transverse fuel gradient that the spread of the flame increased until a maximum spread rate is achieved. Extruded polystyrene foam (XPS), which is a typical thermal insulation material, was studied by Zhang et al. [32] too find the effects of sample scale on flame spread rate. They find that flame spread rate decreases with sample scale in the convective regime but increases in the radiative regime. Sidebotham and Olson [33] used the NASA Glenn drop tower to study opposed flow flame spread in microgravity over polyvinyl chloride tubes.
(PVC) for both horizontal and vertical orientations with pure oxygen in the center of the tubes and the chamber full of nitrogen. They varied the pressure from 1 to .5 atm, and saw that for flows greater than 5.2 cm/s that there was no change in flame spread rate, but that the spread rate increased by square root dependence with respect to opposed flow velocity.

Radiation is also a key mechanism for flame spread over solid fuels. Heat transfer through radiation affects the flame spread rate by losing heat to the surrounding air and by aiding conduction in the preheating of the virgin fuel surface. Son and Ronney [22] looked at the effect of a radiative diluent gas such as CO₂, being added to the atmosphere and how this affected the flame spread rate. They proposed that radiative heat transfer would continue to allow steady spread of the flame even if conduction to the virgin fuel was negligible. It was found through measuring the spread rate and radiative flux over varying thicknesses of a foam fuel that the radiative effects are very significant in microgravity situations due to increased flame thickness and volume of radiating combustion products being quite large. Because in the international space station they currently use CO₂ fire extinguishers, they thought that helium might be a better choice in microgravity. T’ien [34] explored diffusion flame extinction in the stagnation point of a condensed fuel to see the effects of radiative loss. He solved numerically a theoretical analysis of the extinction limit of a flame when the flames stretch rate becomes small, where it was shown that this limit occurs when the flame temperature is reduced due to substantial radiative loss in comparison to combustion heat release. To understand how radiative transfer to the virgin fuel surface at varying oxygen concentrations can impact the spread rate of a flame, Beaulieu and Dembsey [35] used black PMMA in both vertical and horizontal orientations and oxygen concentrations of 20.9%-40% to measure the heat flux back to the fuel over a range of applied heat flux. They concluded that in higher oxygen concentrations the horizontal bench scale test does not simulate large scale flame heat flux, but in the vertical orientation it shows a more severe large scale geometry useful for evaluating a materials vertical flame spread potential. Takahashi et al. [36] experimentally and analytically investigated the flame spread of thin PMMA sheet in microgravity and the effect of radiative loss. Through scale analysis they conclude that a reduction in flow velocity helps enlarge the preheat zone of the virgin fuel increasing the loss due to radiation, reducing the flame spread rate and possibly causing extinction to the flame. Using the 4.5s drop tower in Gifu, Japan and varying opposed flow, fuel thickness and
oxygen concentration they show that the scale analysis is correct and that the radiative loss is significant when flow velocities are small. To understand how a surrounding fire affects the flame spread over wood and particle board, Brehob and Kulkarni [37] used infrared heating panels to supply radiant fluxes to the sample. It was found that as more external radiative flux was applied to the sample the flame spread rate increased. Bhattacharjee and Altenkirch [38] looked into the effect of surface radiation on flame spread in a microgravity environment. They find that when surface radiation is significant the solid fuel acts as a heat sink removing heat from the flame and causing the spread rate to decrease.

1.3 Purpose of Study

The purpose of this study is to try to understand and predict the mechanisms of flame spread in microgravity for different materials and atmospheric conditions. Understanding these mechanisms can eventually lead to a better understanding of material flammability, how the fire will grow and spread, what causes this growth and how to deal with the fire once it has occurred. As space travel becomes more common, understanding flame spread in microgravity and under space station and rocket atmospheric conditions will help engineers better choose materials for construction. The ultimate goal is to try to prevent, slow or extinguish a fire before disaster occurs. Instances like the fire onboard the Russian Space Station Mir in 1997, due to a faulty oxygen generator have shown us just how deadly and hard to extinguish low gravity fires can be.

The finite fuel thickness has a significant effect on the way a flame behaves under both microgravity and normal gravity. To try and correlate data between the ISS and SDSU the concept of the thermal regime for flame spread is applied. The problem is the thermal regime for flame spread is not well defined. The flame spread rate in an opposed flow configuration is dominated by radiation loss at the lower opposed flow velocities and as the velocity increases at some point finite rate kinetics take over and the flame experiences blow off extinction. In between these two effects were the chemistry for combustion is complete is known as the thermal regime. This research sets out to discover this thermal limit in microgravity and correlate that to the well-known de Ris formula for thin fuel spread rate solving for the de Ris coefficient. This coefficient is then used to make a comparison between the microgravity results and downward normal gravity results. If they agree the
modified de Ris formula can be used in downward spread configurations in normal gravity to help dictate the behavior of a microgravity flame. The de Ris coefficient is then used to solve the de Ris thick fuel formula and experimental data is used to make a comparison. Once the trends are verified the thin and thick fuel de Ris formulas for thermal limit flame spread rate can be used to determine the transition between the two regimes. This work will help researchers understand the behavior of flame spread in microgravity and make better design choices for future space travel rockets and stations. It will also help to understand how to deal with a fire once it has occurred in a low gravity situation and possibly how to slow it down or extinguish it.

It is also clear that thermal radiation plays a huge role in microgravity flame spread. NASA conducts many experiments on PMMA flame spread rate onboard the International Space Station and as part of these experiments the thermal radiation being emitted by the flame is always monitored for analysis. The second goal of this research is to construct a radiometer to measure thermal radiation being emitted by a flame. Once the device is manufactured and proof of concept experiments have been performed, it will be used to help compare the signals obtained onboard the ISS with downward results for normal gravity. The ultimate goal is to find a way to recreate the microgravity data without having to actually be in microgravity.

These two studies will also help with the verification of a computational model. The experimental results will help to ensure the computational model is accurate in predicting flame spread behavior with varying atmospheric conditions. Many factors affect the flame spread of a solid fuel. Some are very easy to vary experimentally while others are extremely hard. The computational model has the ability to quickly change these factors and see the effects that the factor has on flame spread. This will help do what is very hard experimentally, and broaden the amount of research achievable here on earth.
CHAPTER 2

EXPERIMENTAL APPROACH

This chapter outlines the hardware used for the collection of data and the software implemented for control. The concept of a radiometer to measure radiative flux is discussed in detail from the choice of detector, design of the system, manufacturing and implementation of the device. The hardware used for experimentation on a downward spreading flame, microgravity flame spread and the software used to analyze this data is also discussed.

2.1 Radiometer Hardware

In flame spread research one of the contributing factors for flame spread is the thermal radiation being emitted by the flame. A radiometer is implemented to measure the radiative flux being emitted by the spreading flame. The radiometer has multiple parts including the detector, electronic circuitry, microprocessor, a webcam for recording the flame and software to control its operation from a desktop computer. Figure 2.1 below shows a picture of the full assembly of the radiometer.

2.1.1 Detector Choice

Thermal radiation is emitted from solid bodies that are at a temperature above 0 Kelvin, in the form of electro-magnetic waves. When trying to measure the emitted thermal radiation there are many choices in methods and detectors which can be simple to very complicated. There are many temperature dependent phenomena that can help detect the thermal effects of incident infrared radiation. One of these phenomena is the heating of a material with a certain temperature-dependent electrical resistance. This type of measurement is used by a bolometer. The bolometer uses a metal or semiconductor, absorptive element to absorb the incoming thermal radiation and change temperature. The temperature is then
compared to a thermal reservoir via a thermal link and the change in temperature can be read by either a resistive thermometer or through the resistance of the absorptive element. The down side to this method is the time it takes for the element and reservoir to return to room temperature is quite long. Another of these phenomena is thermal expansion. Golay cells are used in infrared spectroscopy as a type of opto-acoustic detector. The device uses an infrared absorbing material with a moveable diaphragm inside a gas filled enclosure to absorb incoming infrared radiation causing the gas to heat and the diaphragm to flex. This flex is measured by reflecting light off the diaphragm measuring the motion of the diaphragm through a photodiode which produces a change in signal to the diode. The downfall is that the detector is very sensitive to any mechanical vibrations. Underhill-Shanks and Hudson [39] looked at fixed and scanning infrared radiometers with lead selenide (PbSe) detectors to study flames and rocket motor plumes. The fixed radiometer used interference filters and mechanical phase adjustment to narrow the wavelengths considered to only the 4.4 – \( \mu m \) carbon dioxide band and the 2.7 – \( \mu m \) water vapor band. The scanning radiometer used a circular variable filter (CVF) to allow a range of wavelengths from 2.1 – 4.7\( \mu m \) to be read. Camperchioli [40] designed, manufactured and built a narrow angle wide spectrum radiometer at the NASA Glenn Research Center for the study of the Radiative Enhancement Effects on Flame Spread. The detector needed to be able to detect thermal radiation ranging
from 0.6–30\(\mu\)m in wavelength and have a narrow angle field of view. The thermopile type detector was chosen for its ability to be manufactured with a wide array of viewing windows allowing for different wavelengths to be detected and the ability to change the field of view by either the use of a lens design or a pinhole arrangement without the lens. Son and Ronney [22] also used the thermopile type detector for flame spread research at the University of Southern California for the wide range of available options listed above.

After researching many methods of detecting thermal radiation from a flame it became quite clear that a thermopile type detector was the easiest solution to this problem because they are cost effective, require only simple circuitry, have a small package size allowing for implementation in almost any situation and have a very broad range of easily changed characteristics.

### 2.1.2 Thermopile Detectors

A thermopile detector works through the basic principle of thermoelectric effect, which is made up of three separate effects known as the Seebeck effect, Peltier effect and Thompson effect. The Seebeck effect is how a difference in temperature between to dissimilar metals attached together is directly converted into a voltage. Measurement of the electromotive force (emf) allows for conversion from current flow to temperature at the junction between the two metals. When the junction is connected to an external circuit and heating or cooling can occur at an electrified junction possibly compromising the emf, the Peltier effect is present and could be a possible source of error. The Thompson effect will occur when the exposed surfaces of the metals have a temperature gradient causing an effect to the measured emf. Emf measurement is mostly dependent upon the temperature at the hot junction, so the Seebeck effect is the most prominent in the thermopile detector.

A thermopile detector is made up of an array of small thermocouple junctions connected in series as differential pairs. Figure 2.2 below shows a schematic of a 2M thermopile circuit overlay from Dexter Research. The Seebeck effect is created by the Arms, which are the hot and cold junctions of the differential pairs made of alternating p-type and n-type materials. In between the hot and cold junctions a temperature gradient is formed and a voltage proportional to the gradient is outputted. From Dexter Research two types of thermopiles are available with different alternating materials. The first is a thin film based
Figure 2.2. Schematic of 2M detector circuit overlay courtesy of Dexter Research.

type which has arms that consist of antimony (Sb) and bismuth (Bi). The second type is a silicon based thermopile which has arms made of alternating n-type and p-type Poly-Silicon or n-type with either gold (Au) or aluminum (Al). Around the outside of the substrate opening is the cold junction of the differential pairs which are thermally connected to the housing of the detector. The hot side of the differential pair is coated with an energy absorbing material which allows the spectral response to be typically flat from the ultraviolet to far infrared, and located in the center of the detector, making up the active area of the detector. These hot pairs must be thermally isolated from the rest of the detector to eliminate heat transfer between the hot and cold junctions so they are suspended on a thin membrane. The reason for this isolation is because to calibrate a thermopile detector for a thermal radiation reading, the cold junction temperature must be known. Since the cold junctions are thermally connected to the housing a reading of the housing temperature can be made by either a chip in glass thermistor or an active device like the National Semiconductor LM20 used by Dexter Research. To accurately read the detector housing temperature the sensor must be in close proximity to the housing and thermally connected to it.

There are many decisions to make when choosing the exact thermopile detector needed for the application. Dexter Research offers a magnitude of options when it comes to types of detectors, from the gas that is encapsulated in the housing, the window material used to view the thermal radiation, the active area size and shape, the amount of cold and hot
junctions, the angle seen by the detector and the overall size of the housing. The encapsulation gas used as a thermal path for the active area to dump its thermal energy can affect the performance of the detector. To limit the spectral sensitivity of the detector a wide range of window materials are used as filters for certain wavelengths of incoming thermal radiation. After much consideration of all the options available by Dexter Research, the 2M thermopile was chosen.

The 2M thermopile is a thin film type consisting of arms made from antimony (Sb) and bismuth (Bi) with 48 junctions making up the active area. The 2M thermopile by Dexter Research is shown in Figure 2.3 below. Options for the optical filter and the encapsulation gas are some of the first considerations to be made. The optical filter or viewing window sets the wavelengths that the detector can see. For the 2M thermopile a sapphire window was chosen to filter the wavelengths between $0.1 \, \mu m$ and $7 \, \mu m$. This covers from the ultra violet through the visible and into the infrared spectrum. The sampling rate for the detector is typically 80 Hz without the webcam and is reduced to 20 Hz when the webcam is in operation. The typical encapsulation gas for the 2M is Argon (Ar), but to help increase the sensitivity of the detector, Xenon (Xe) gas was chosen. Because of a difference in the molecular thermal conductivity of the gases, the thermal resistance of the detector is changed. This change alters the output voltage $V_s$, the Responsivity $\mathcal{R}$, the time constant and the Signal-to-Noise ratio. Dexter’s data sheet for the 2M thermopile is calculated using

![Figure 2.3. Picture of 2M thermopile courtesy of Dexter Research.](image-url)
Argon (Ar) as the encapsulation gas, so they implement an approximated multiplier for these four parameters of 2.4 to find the parameters for Xenon (Xe) within a 25% fluctuation. This aids the detectors sensitivity by increasing each of those parameters by 2.4 making it a better choice for encapsulation gas.

The thin film type was chosen over the silicon type because it has a higher Signal-to-Noise ratio due to lower resistance and lower noise voltage and a larger active area compared to most silicon types. The data sheet which gives the parameters below is available from Dexter research [41]. The signal noise generated is equal to the same noise generated by a resistor of equal resistance as the detector which is $10k\Omega$. The 2M thermopile with Xenon (Xe) gas has a Signal-to-Noise ratio of $\frac{V_s}{V_n}$ which is the voltage of the source $V_s$, typically $600\mu V$ and the voltage of the noise $V_n$, typically $12.8 \frac{nV}{\sqrt{Hz}}$ giving the detector $46874\sqrt{Hz}$ Signal-to-Noise ratio. The active area of the detector is $2\times2\text{mm} \text{ or } 4\text{mm}^2$. The sampling rate is limited by the time constant which is $204ms$ but provides stable reading of DC thermal radiation up to this limit. Operating temperature for this thermopile is $-50^\circ C \text{ to } 100^\circ C$ which is well within our parameters. The 2M thermopile is tested with a 500 Kelvin black body where the active surface is located 10 cm from the 0.6513 diameter black body aperture, giving a radiative flux (H) of $330 \frac{\mu V}{cm^2}$. This radiative flux is then used to determine the responsivity ($\mathcal{R}$) of the detector which is $\mathcal{R} = \frac{V_s}{HA}$ where A is the detector area in $cm^2$. This gives a responsivity of $45.45 \frac{V}{W}$ for the 2M thermopile with Xenon gas encapsulation.

Figure 2.4 below shows the engineering drawing of the 2M detector from the side and top view. The aperture size for the 2M is 0.150 inches and is located 0.093 inches from the top of the aperture opening. These distances set the field of view (FOV) for the detector at $38^\circ$ for the umbra section and $95^\circ$ for the penumbra portion. The umbra is the middle section of the FOV where every point of incoming thermal radiation will illuminate 100% of the active area making the response to the point source constant and a maximum. For the penumbra, the section comprised between the umbra and penumbra has a gradient for
response starting at the maximum for radius of the umbra and tailoring down to zero at radius
equal to penumbra. Outside the penumbra the detector does not see any of the incoming
thermal radiation and should read zero. The aperture size and geometry dictates the FOV and
can be manipulated by use of external filters.

2.1.3 Thermopile Measurement

There are few options when it comes to measuring the output from the 2M
thermopile. First the cold junction temperature must be known for proper calibration of the
sensor. This can be accomplished by a chip in glass thermistor, an internal temperature
sensor or an external temperature sensor. The output voltage must be amplified depending on
the magnitude of the incoming thermal radiation and the distance from the source. This can
be done by a simple circuit with a potentiometer to control the gain or with fixed gain
circuitry.

To cut down on the time consumed and complexity of building the circuitry, the
choice was made to use the 1000 gain Mini Amp PCB Board from Dexter Research. Figure
2.5 shows a picture and schematic of the PCB board. This PCB board is comprised of three
main components the LT1790 micropower low dropout reference, the AD8628 amplifier and
the LM20 temperature sensor.
The LT1790 is a linear voltage regulator allowing the regulation of output voltage even when the input voltage is very close to the output. This regulator is manufactured by linear technologies as a micropower low dropout series reference with a very small package size, low power dissipation, high accuracy and low drift. It has a low temperature coefficient due to curvature compensation and gets its high accuracy from trimmed precision thin-film resistors which are then post-packaged trimmed to obtain even better results. The LT1790 has an accuracy of 0.05%, a very small drift of $\frac{10}{C} \text{ppm}$ and is operable between the temperatures of $-40°C$ to $85°C$. The reference voltage $V_{ref}$ for this detector is 1.25 V.

The amplifier for this detector is an Analog Devices AD8628 operational amplifier or Op-amp. An Op-amp is an electronic voltage amplifier that produces an output potential relative to the ground that is much higher than the potential difference of the DC input, positive and negative terminals. The AD8628 has some unique characteristics to allow for little or no sources of error. The voltage offset is $<1\mu V$ with drift of $<\frac{0.005\mu V}{C}$. It is chopper stabilized with a low bias current of 100 pA, will operate with input voltages ranging from 2.7 V to 5 V and temperature ranges of $-40°C - 125°C$.

For cold junction temperature measurement, the LM20 by National Semiconductor is used. The LM20 is a precision analog output temperature sensor that has a mostly linear transfer function. For the small parabolic curvature of this transfer function, the sensor has a temperature error of $\pm 1.5°C$ for room temperature. To deter self-heating the quiescent
current is kept to below 10\(\mu\)A which allows for a very small 0.02\(^\circ\)C of self-heating in calm room temperature air.

![Figure 2.6. Schematic of Mini Amp PCB circuit courtesy of Dexter Research](image)

These three components make for a well thought out and highly accurate way of reading the thermopiles analog input/output, amplifying the signal and taking the measurements needed for calibration of the detector. Above in Figure 2.6 is a schematic of the 1000 gain circuit formed by these three components to form the Mini Amp PCB. From this schematic, six different analog input and outputs are shown for wiring the PCB. The voltage to the source \(V_s\), must be wired to an analog 5 volt source and grounded to the same source. The voltage out \(V_{out}\) is the measured voltage of the incoming thermal radiation to the thermopile detector, basically the radiative flux from the flame in volts. Temp1 is the measured cold junction temperature from the LM20 sensor needed for proper calibration. NC/Temp2 is normally closed unless an external cold junction temperature sensor is used, like a thermistor which is not the case here. The reference voltage \(V_{ref}\) is a known reference voltage supplied by the PCB board itself.
2.1.4 Thermopile Assembly

For the PCB to read the thermopile output, the thermopile must be connected to the board. Great care must be taken when connected these two components together. The PCB board has a max temperature rating for soldering the leads on of 300°C for no more than 60 s. To accomplish this, micro soldering had to be done under a microscope for visual aid and to control the heat input to the board. If too much heat is applied to the board, the delicate circuitry could be damaged. Position of the thermopile relative to the board is also critical to correctly read the cold junction temperature. The LM20 temperature sensor is located centered between the connections for the thermopile on the board. When placing the thermopile on the board for soldering, it must be all the way down almost touching the temperature sensor and positioned centered over it. This position will allow the use of a conductive paste between the back of the thermopile case and the LM20. Cooler Master Corporation’s Thermal Fusion 400 was chosen as the conductive thermal paste for the assembly. After soldering, the thermal paste is applied between the thermopile and PCB board allowing for the cold junction temperature to be read via conduction from the back of the case to the LM20. Figure 2.7 below shows a Solid works assembly of the components and a picture of the real assembly after the micro soldering and thermal pasting was done. It also shows the leads for the six analog input/outputs for the board.

Figure 2.7. (a) Solidworks screenshot of thermopile assembly, and (b) Actual thermopile assembly after soldering.

2.1.5 Microcontroller

To help process the outgoing analog signal from the PCB board and control the thermopile detector the choice of a microcontroller must be made. There are many different
types of microcontrollers like Launchpad, Raspberry Pi, BeagleBone and Arduino which all have different options and complexities of integration to be considered. After much research into the options offered by different microcontroller manufacturers, Arduino was chosen as the best option for this application. Even though many of the other manufacturers make a very similar product, Arduino had the edge for a few simple reasons. The cost of an Arduino is significantly less than other comparable microcontrollers. Another huge advantage over other microcontrollers is the compatibility with not just windows based PC’s but also with Macintosh OXS and Linux operating systems. It also has a very user friendly programming environment for beginner users all the way to the most advance programmers.

![Arduino Uno SMD Edition](image)

**Figure 2.8. Arduino Uno SMD Edition courtesy of Arduino**

The Arduino Uno that was chosen for this project is shown above in Figure 2.8. The Arduino Uno is a simple microcontroller board that allows for a computing platform to help sense or control physical phenomena from your desktop computer. It is open-source for users and provides its own software for programming that then can be loaded onto the board for use as stand alone or in conjunction with another program like Labview or Matlab. This software also allows for serial monitoring so text data can be sent to and from the board. The unit is powered through a high speed 2.0 USB cable from Media Bridge. It has fourteen digital input/output pins, six of which can be used for Pulse Width Modulation (PWM), six analog pins, 32 kb of memory and a clock with speed of 16 MHz. The Arduino Uno also has 5 V and 3.3 V outputs to power external sensors along with the associated ground pins.
needed to complete the circuit. It communicates to the computer via serial communication over a standard USB cable and shows up on the computer's software as a virtual com port for easy connection. The Uno has standard 10 Bit resolution which was the only downside to the device for thermopile measurement. To up the resolution of the readings an external Analog to Digital converter (ADC) was considered.

### 2.1.6 External A to D Conversion

To easily integrate an external ADC with the Arduino Uno, Arduino recommends the Adafruit ADS1115 16 bit ADC. This four channel converter provides 16 bit resolution at 860 samples/second over \( I^2C \). The four channels can either be used as single input or as two differential channels. It also includes a programmable gain amplifier to boost signal up to 16 times and can be run on supply voltages ranging from 2 V to 5 V. Figure 2.9 below shows a picture of the hardware.

![Adafruit external 16 bit analog to digital converter](image)

**Figure 2.9. Adafruit external 16 bit analog to digital converter courtesy of Adafruit**

### 2.1.7 Electrical Circuitry

To connect the thermopile assembly, Arduino, external ADC and the computer together, a circuit had to be designed and implemented. A block diagram and electronic circuitry for the radiometer are shown above in Figure 2.10 and Figure 2.11 respectively.
The base of the circuit shown above in Figure 2.11 is the Arduino Uno. The Arduino is first attached to the computer through a USB cable providing serial communication between the computer and the microcontroller and providing the +5 V required for the Arduino to operate. The Arduino then sends the required +5 V to the thermopile assembly and allows for the common ground between the two. Once the thermopile assembly is active,
it supplies the necessary +5 V to the external ADC and the ground for the ADC is run back to the Arduino. Now that all the hardware has the voltages required to run, the wires transferring the analog and digital data from the detector to the Arduino can be connected. First the analog cold junction temperature $T_1$ and the analog voltage out $V_{\text{out}}$, which is equivalent voltage to the incoming thermal radiation seen by the thermopile are connected from the thermopile assembly to the external ADC analog pins A2 and A3 respectively. The external ADC then converts the analog signals to digital signals with 16 bit resolution. The ADC outputs the digital signal through the serial clock (SCL) and serial data (SDA) outputs to the Arduino’s analog pins A4 and A5 through $I^2C$ communication. The digital data is read in by the software loaded onto the Arduino and then transmitted through the USB via serial communication to the computer. This process is then repeated at the sampling rate dictated by the hardware and software.

2.1.8 Web Camera

The Logitech C615 Webcam was the best choice for this application and is shown below in Figure 2.12. This high definition widescreen 1080p camera has a premium autofocus that can retain its focus even at a very close range of 10 cm from the target. Some experimenting with this camera showed that it would even autofocus on an object as close as 4 to 5 cm away. This is very important due to the close proximity of our radiometer to the

![Figure 2.12. Logitech C615 webcam courtesy of Logitech.](image-url)
flame itself. Through special software this camera also allows for high definition still photos of 8 megapixels. Logitech’s proprietary algorithm, Fluid Crystal allows for the highest picture quality by automatically adjusting the sharpness, color saturation and frame rate to match the conditions being recorded. This camera is simply powered and controlled through a standard hi-speed 2.0 USB cable. Once the case was removed, the circuitry and camera itself are quite small, perfect for designing the new housing to incorporate it with the thermopile.

2.1.9 Radiometer Housing

The housing for the radiometer hardware was designed to be lightweight, portable, easy to access and repair, simple to manufacture and allows the user to implement it in a wide variety of orientations and situations. The concept for the design was created in SolidWorks 3-d CAD software, where parts, assemblies and final drawings for the housing were produced for manufacture. Figure 2.13 below shows a screenshot from SolidWorks of the radiometer housing with the webcam on top and thermopile assembly located at the bottom.

![SolidWorks screen shot of Radiometer housing with integrated webcam](image-url)
The housing design was 3-D printed on a Fortus 400mc 3-D printing machine using thermoplastics. The thermoplastic used for this housing is PC-ABS or polycarbonate-ABS which is one of the most widely used thermoplastics for 3-D printing. The polycarbonate gives it superior strength and heat resistance while the ABS still allows for the flexibility of a tough plastic making it the best of both worlds. The 400mc uses a type of patented modeling known as Stratasys Fused Deposition Modeling (FDM) to achieve very durable parts from production grade thermoplastics for the manufacture of real parts used in manufacturing tools, quick concept models, working prototypes and for marketable products. The 400mc can manufacture products up to 14 x 10 x 10 inches in the XYZ respectively, and can hold tolerances of ±0.005 inch with very smooth surfaces. It is very easy to use and comes with its own software package Insight and Control Center which only requires a STereoLithography (STL) file, which describes the geometry of the 3-D model without color or textures, to create the part.

Figure 2.14 below shows an exploded view of the Radiometer assembly which includes the webcam. After the 3-D printing was completed two inner retaining plates were manufactured to hold the thermopile assembly and the webcam safely in place inside the housing. The retaining plates were manufactured out of 0.125 inch 6061 T-6 Aluminum. The outer contours were created using a Flow WaterJet Mach2 1313b and the holes were manufactured on a Hass Yf 2YT CNC vertical milling center. The thermopile assembly and webcam are orientated in the housing by a recessed cavity keeping them in the position desired. The retaining plates are then slipped over the thermopile assembly and webcam then into the housing and are attached to the housing using 2-56 stainless steel hardware at the

![Figure 2.14. (a) SolidWorks exploded view of Radiometer assembly.](image)
four corner holes for each plate. These plates hold the orientation for the thermopile assembly and webcam keeping them from being vulnerable to movement while not obstructing the view of the thermopile or webcam. A ¼-20 thread runs through the housing allowing for easy mounting and orientation anywhere a ¼-20 bolt can be secured, which includes the standard thread on a tripod making the housing very portable and easy to mount. Figure 2.15 below shows the finished product for the radiometer housing fully assembled.

![Figure 2.15. Radiometer housing after manufacturing and assembly.](image)

The wiring for the thermopile assembly and webcam are run through cavities in the housing, exiting at the rear of the housing for easy connection to the microcontroller, external ADC and the computer. The USB from the webcam is directly plugged into the computer and the wiring for the thermopile assembly is soldered to a male TIA/EIA 568B Ethernet cable directly behind the housing. To house the microcontroller and the external ADC, a small box was manufactured using 0.25 inch acrylic. The acrylic was cut on the WaterJet and then glued together using Weld-On acrylic glue #4. Acrylic was chosen for this housing to ensure durability, long life and ease of visibility for wiring and diagnosis of problems due to its clear see through finish. The Arduino is mounted to the bottom of the box on plastic standoffs and 2-56 stainless steel hardware holds it in place. The external ADC is mounted
on a bread board which is glued to the side of the box. All the wiring for both the Arduino and the external ADC is then soldered to a male TIA/EIA 568B Ethernet cable, which through a female/female connector can be connected to the thermopile assembly wiring. This configuration for the wiring was chosen so that the detector itself could have a small package size, have quick disconnects at either end, be located any distance desired from a computer and in any orientation without being limited by the electronics but only by the length of the Ethernet cable which come in almost any length desired. Figure 2.16 below shows the finished electronics housing.

![Figure 2.16. Electronics housing with Arduino Uno and Adafruit external A to D converter.](image)

### 2.1.10 MATLAB Software

MATLAB or matrix laboratory was developed by MathWorks to be a multi-paradigm numerical computing environment with its own special language, separate but similar to and able to interface with Fortran, Python, Java, C or C++. MATLAB has the ability to do very complex mathematics and simulations for matrix manipulation, creating graphs of data or functions and the application of algorithms. Simulink is an add-on for MATLAB that allows the creation of block diagrams for Model-Based Design through a graphical multi-domain type simulation. This package works extremely well for the design and implementation of a
feed-back control system with PID gains. MATLAB also offers a large array of other add-ons called toolboxes which allow everything from image analysis to motor control. It also comes with what is known as GUIDE which is a GUI development environment. GUI or graphical user interface is the screen the user sees when using a computer program that allows the user to interact with the program without having to see or manipulate the underlying code. The GUIDE is an easy to use GUI that lets the programmer decide how the GUI’s screen will look and how the user will interact with the program.

Figure 2.17 below shows the GUI and video preview window created for the radiometer software that was developed by Kenneth Keivens in MATLAB. The video preview window allows for instantaneous viewing of the flame as it is burning during a run. This gives great feedback as to what the flame looks like and how the run is progressing in real time. The webcam is set to shoot 2 frames/second in the MATLAB code at full 720P high definition resolution which is 640 x 480 in pixels for the size of the screen in view. The GUI is very user friendly with only the necessary buttons for operation of the radiometer supplied. The save and record buttons are for saving the radiometer data to a text file and recording the images from the webcam to a file for later use. The X-Axis and Y-Axis drop down menus allow for choices of plots that can be generated immediately after a run has occurred. Figure 2.18 below shows an immediate plot of $V_{out}$ vs. time for a 50$\mu m$ thick
sample of PMMA at a distance of 15 cm from the detector. The other choice of immediate output from the GUI is Temp vs. Time, which is the cold junction temperature over the length of a run. It is important to monitor this temperature to ensure that the cold junction temperature is constant over the run so that proper calibration of the radiometer can be achieved.

![Graph](image)

**Figure 2.18. Sample output from MATLAB radiometer control for a 50\(\mu\)m PMMA sample at a distance of 15 cm from the detector.**

The radiometer is mounted to the Flame Stabilizer apparatus for control of position with respect to the fuel holder. The vertical and horizontal positions are controlled through linear actuator systems with stepper motors driving the motion. The horizontal actuator system is attached to the vertical actuator system through an aluminum mounting plate allowing for the control of both directions. A platform is attached to the horizontal actuator system and consists of aluminum T-slot bars and an aluminum plate to place measurement equipment on. The radiometer is mounted to the T-slot structure by the ¼-20 thread in the housing. This positioning system allows for very precise measurement of the position of the radiometer with respect to the fuel. The position of the platform is controlled through another MATLAB GUI also developed by Kenneth Keivens. Figures 2.19 and 2.20 below show the MATLAB GUI for position control and the radiometer mounted to the platforms T-slot.
Figure 2.19. MATLAB GUI for probe position control.

Figure 2.20. Radiometer mounted to positioning platform T-slot.
2.2 Radiometer Field of View

The Dexter Research 2M thermopile has certain internal geometry that sets the field of view (FOV) for the incoming thermal radiation that it can see and measure. The field of view can be determined by the area of the active area, the aperture size and geometry and the distance from the aperture to the active area. This FOV can be manipulated by changing anyone of these internal factors or adding a cover plate over the detector and changing the geometry externally.

2.2.1 Full Field of View

The full field of view for the radiometer is determined by the original geometry for the Dexter Research 2M thermopile. The active area for the 2M is \(4mm^2\) with an aperture located 0.093 inches above the active area with an opening 0.150 inches in diameter. This allows for a 95° field of view for the penumbra and a 38° field of view for the umbra. To consider all of the incoming thermal radiation being seen by the active area, the 95° field of view will be used for this research. Figure 2.21 below shows a schematic of the full field of view geometry.

![Figure 2.21. Radiometer geometry for full field of view.](image)
2.2.2 Webcam Field of View

To change the radiometers field of view to match the webcams field of view, first the geometry for the webcam had to be solved. The Radiometer was positioned 19.2 cm from the fuels surface and a picture of the sample holder with a scale attached to it was taken with the webcam. From this picture the vertical length of the webcams field of view was determined to be 18.2 cm at a distance of 19.2 cm from the fuel surface. From these measurements it was determined that the webcam sees \( \arctan \frac{9.1cm}{19.2cm} = 51^\circ \) field of view.

Now the geometry for the thermopile has to be manipulated to match the webcam. Since the webcam and the thermopile are offset from each other in the housing by 12 mm, the geometry gets a little more difficult for this manipulation. Figures 2.21 and 2.22 below show the geometry used to modify the field of view for the thermopile allowing it to view the same field of view as the webcam through a cover plate design.

![Figure 2.22. Webcam and Cover plate geometry used to modify field of view for thermopile.](image-url)
Figure 2.23. Cover plate geometry used to modify field of view for thermopile.

Through the use of the geometry shown above and a series of equations shown in the Appendix, with a fixed viewing hole diameter of $\phi = 5\, mm$ it was found that the cover plate must be $l = 10.84\, mm$ thick to accomplish the needed $51^\circ$ field of view for the thermopile to match accordingly with the webcam. Once these two parameters where known the cover plate could me manufactured and attached to the radiometer. Figure 2.24 below shows the cover plate attached to the radiometer and ready for use.

Figure 2.24. Cover plate installed on the radiometer.
2.2.3 Line of Sight Field of View

The line of sight field of view is of particular interest because it allows for a spot type measurement with the radiometer. When the spot size is very small it can be compared to a spot measurement of temperature done with a thermocouple but without the effects of the detector coming in contact with the fuel or the flame. The contact of a thermocouple to the flame can introduce conduction from the flame to the detector lowering the temperature of the flame and disturbing the spread rate of the flame. The radiometer takes a non-contact measurement of the intensity of thermal radiation from the flame that can be correlated to the temperature at that spot. Because the flame is considered optically thin the temperature can be found through the total blackbody intensity given by $I_b = \frac{\sigma T^4}{\pi}$. This can allow for precise temperature measurements in the flame field without disturbing the flame. Figure 2.25 below shows the geometry of the line of sight field of view.

![Figure 2.25. Radiometer geometry for line of sight field of view.](image)
Using the geometry for a cover plate shown in Figure 2.23, a thickness $l = 5.08cm$ and a viewing hole diameter $\phi = 2mm$ were used to create the cover plate for the geometry shown in Figure 2.25 above. This cover plate gives a field of view angle of $\theta = 4.5^\circ$. From the field of view angle it was determined that the spot size is $5.47mm$. This angle and spot size are small but not quite small enough. Figure 2.26 below shows the finished cover plate mounted to the radiometer.

![Figure 2.26. Cover plate for line of sight installed on the radiometer.](image)

To really obtain a line of sight field of view the angle should be as close to zero as possible. To obtain this even smaller geometry the viewing hole diameter or the length of the tube must be modified. To make it easier to modify these two geometric properties a brass tube with an inner diameter $\phi = 1.67mm$ was chosen to be attached to a thin cover plate to mount it to the radiometer housing. This tube can be cut to any length desired which is a lot easier than changing the thickness of the cover plate. The tube used was cut to $l = 103mm$ giving the thermopile an angle of $\theta = 1.86^\circ$ which is much closer to actual line of sight. At a distance of 4.4 cm from the fuel it sees a spot size of $3.1mm$. Figure 2.27 below shows the new cover plate with tube insert mounted on the radiometer.
The field of view for the thermopile can easily be manipulated by the use of these cover plates. With the cover plates any geometry conceivable can be achieved, like bigger or smaller angles of view or even square or rectangular views.

### 2.3 Downward Spreading Flame

The downward spreading flame experiments were conducted at SDSU in the combustion laboratory. The thin PMMA samples are held in a stainless steel sample holder that is orientated in the vertical position by an aluminum frame. The PMMA samples are 20mm in width and 13cm long. The thickness for the thin PMMA samples were varied from 25μm to 3mm. The sample is loaded into the sample holder and is sandwiched between two thin stainless steel plates to ensure no flame propagation on the edge of the sample and the plates are secured with magnets to ensure proper orientation. A stainless steel scale is also attached to the sample holder. Tests are conducted at 21% oxygen concentration and an ambient temperature of 22°C with pressure being 1 atm. Piloted ignition is used to ignite the sample from the top and a Nikon D5000 camera is used to record the flame propagation from the top-view. All videos are recorded on the Nikon D5000 in high definition 1080P with a resolution of 1920 x 1080 for the highest quality video available. After the run is completed,
the sample holder is allowed to cool to room temperature and then the next sample is loaded and the process is repeated. Figure 2.28 below shows the sample holder used for the thin fuel downward flame spread experiments.

Figure 2.28. Stainless steel sample holder for thin PMMA downward spreading flame experiments.

Figure 2.29. Stainless steel sample holder for thick PMMA downward spreading flame experiments.
Two thick PMMA samples were also considered in this set of experiments. The width of the samples was $20 \text{mm}$ and the length was $95 \text{mm}$. The two thicknesses used were $6.35 \text{mm}$ and $12.7 \text{mm}$ with the latter of the two being two pieces of the $6.35 \text{mm}$ glued together using acrylic glue. The samples were held by two thin strips of stainless steel clamped to the edges to prevent edge propagation of the flame. Piloted ignition was also used for these samples and the flame spread was also recorded on the Nikon D5000. Figure 2.29 above shows the method used to hold the thicker samples.

### 2.4 Microgravity Flame

The microgravity experiments were conducted with the Burning and Suppression of Solids-II (BASS-II) setup onboard the International Space Station (ISS). A schematic of the Bass-II setup is shown below in Figure 2.30. It is a $76 \text{mm}$ square duct combustion tunnel used to conduct opposed flow flame spread research. PMMA samples $20 \text{mm}$ in width and $95 \text{mm}$ in length are sandwiched between stainless steel plates making up the sample holder and placed into the apparatus. Figure 2.31 below shows a comparison of the microgravity and normal gravity sample holders. The PMMA samples range in thickness from $100 \mu \text{m}$ to $400 \mu \text{m}$ and are burned in a horizontal orientation. The fan on the right hand

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**Figure 2.30. Bass II apparatus onboard the ISS.**
Figure 2.31. Comparison of microgravity sample holder on the right and downward spread sample holder on the left.

side forces oxidizer, which is a mix of oxygen and nitrogen, from right to left through a set of flow straighteners to ensure laminar flow inside the tunnel. The sample is ignited on the left hand side by a built in igniter using a current passed through a kanthal wire and burns towards the right hand side. A steady flame will occur depending on the opposed flow velocity and oxygen concentration for the particular run. The velocity can be varied from 0 to 50 cm/s and the oxygen concentration adjusts from around 21% to slightly below. The opposed flow velocity is calibrated to the fan voltage through the use of a hot wire anemometer. This calibration determines the actual opposed flow velocity.

The Bass-II experiments were conducted onboard the ISS in what is known as the Microgravity Science Glovebox. Two astronauts are given instructions from the ground crew at NASA Glenn Op Center as the experiments are conducted. They start by setting the fan voltage to create the desired opposed flow velocity for the particular experiment and waiting until the flow has completely stabilized. The kanthal wire igniter is then turned on until the flame is present at which point the kanthal wire is then turned off. The side view of the sample is captured with a high definition video camera and the top view is shot with a high resolution still shot camera with a frame rate of 1 frame/second. To minimize the amount of tests conducted, some of the runs have varied opposed flow velocity during flame
propagation to help maximize the amount of data collected for different conditions. The thermal radiation from the flame is being read by a thermopile type detector in the upper left hand corner which views the flame from an angle.

2.5 Flame Spread Data Analysis

For analysis of the flame spread rate and other flame related information from a top view video a MATLAB based image processing software has been developed at SDSU called Flame Analyzer. The still images captured from the Bass-II experiments are converted into videos through the use of Camtasia video editing software. These converted videos and the top view videos of the downward experiments are then uploaded to http://flame.sdsu.edu for easy storage and access when needed for analysis or comparison.

Figure 2.32(a) below shows a color frame at 18 seconds into the video of a 75μm thick PMMA sample in the downward flame spread configuration. To help display the spatial resolution of the image a horizontal red dotted line is placed in the center of the image with the dots being 6mm apart. To achieve intensity from this color image each of the RGB values in the frame are converted to intensity values by use of specially designed MATLAB imaging tools. Figure 2.32(b) above shows the flame as a two dimensional representation of width averaged intensity values. Figure 2.32(c) above shows the variation of these width averaged intensities in the x-direction. To determine the leading edge of this flame a fixed intensity threshold must be chosen. For this particular run a fixed intensity threshold of 70 was chosen and is represented by the vertical white dotted line shown in Figure 2.32(b) above. After testing this threshold for a few different frames at different times during the video it was determined that this was a good choice of threshold for tracking the leading edge during this run.

To show the tracking of the leading edge in Flame Analyzer, 100μm thick tests were chosen for both microgravity and downward spread. Figure 2.33 shows the leading edge position vs. time comparisons for these two runs. The two runs are conducted under the similar atmospheric conditions except for the opposed flow velocity of 3cm/s that the microgravity flame is subjected to. The flame spread rate for these two runs is then determined by finding the slope of the linear regression analysis through the use of consecutive leading edge locations for each run. Figure 2.34 below shows a plot of the flame
Figure 2.32. (a) Color picture of a frame at 18s into the video, (b) two dimensional representation of the flame from averaged intensity values, and (c) variation of width averaged intensity in the x-direction.
Figure 2.33. Comparison of microgravity and downward spread leading edge vs. time plots.

Figure 2.34. Comparison of microgravity and downward flame spread rate vs. time plots.
spread rate vs. time comparison for the microgravity and downward runs. Averaging the consecutive leading edge locations over 5 seconds of flame propagation gives a good sample size leading to a good compromise between noise and temporal precision when calculating the spread rate to ensure it is accurate.
CHAPTER 3
RESULTS AND DISCUSSION

This chapter discusses the results obtained for the radiometer proof of concept and the study of the thickness effect on flame spread rate over a solid fuel PMMA. For the radiometer proof of concept section 3.1.1 shows the repeatability of the experiments and section 3.1.2 discusses the method used to correlate the output voltage to a temperature. Section 3.1.3 shows how the camera field of view cover plate is used to compare images of the flame to the output voltage. The effect of changing the distance from the detector to the fuels surface is covered in section 3.1.4 and how the thickness of the fuel effects the output is shown in section 3.1.5. Then a comparison of thermal radiation readings from microgravity and normal gravity is shown for 21% oxygen concentration and 100μm sample thicknesses.

The effect of fuel thickness on flame spread rate is covered next in section 3.2. The scaling analysis leading to the modified De Ris formula is discussed in section 3.2.1 and microgravity results from the ISS are used to solve for the unknown de Ris coefficient in section 3.2.2. Section 3.2.3 shows the downward flame spread rate data collected at SDSU and compares that to the theoretical thin and thick limits of the modified De Ris formula. Then in section 3.2.4 a comparison is shown for the microgravity results, downward flame spread results the theoretical thin and thick limits and how that all compares to Fernandez-Pello and Williams results for downward flame spread.

3.1 RADIOMETER

This section shows the proof of concept for the radiometer and its ability to accurately measure thermal radiation being emitted from a surface. The radiometers proof of concept experiments were conducted in the combustion lab at SDSU. It also covers the Bass-II flame spread experiments onboard the ISS and the thermal radiation readings they collected.
3.1.1 Repeatability

One of the most important parts of proving that a scientific measurement device is working is showing that the same experiment can be repeated more than once. The radiometer was tested for repeatability by conducting three sets of experiments, one for each field of view to show that the experiments are repeatable and that the cover plates have no effect on the repeatability of the experiments. These tests were conducted on the Flame Stabilizer apparatus in the combustion lab at SDSU. The samples are in the downward flame spread configuration with a coordinate system using the nomenclature as follows. For a downward spreading flame the vertical direction is the x-axis. Upstream is in the direction the flame is propagating and considered negative below the leading edge and downstream is in the direction of the natural convective flow towards the tail end of the flame and is considered positive above the leading edge. The y-axis begins at the fuel surface at \( y = 0 \) mm and moves in the positive direction away from the fuel surface. For each set of experiments, three runs were conducted back-to-back to ensure the same atmospheric conditions of 21% oxygen, 1 atm and 22°C with similar ambient lighting for all three runs. 75 \( \mu m \) thick PMMA was chosen for the test runs with a width of 30 mm and a length of 33 cm which gave an average run time of about 76 seconds with a sampling rate of 80 Hz. The radiometer was positioned at \( y = 14 \) cm from the fuel surface and centered on the fuel at \( x = 16.5 \) cm for the start of the run. The sampling rate for the radiometer is approximately 80 Hz but to reduce the instantaneous fluctuation of the readings only readings at 1 second intervals are considered to show the overall trend. Each run starts at the reference voltage of 1.25 volts and increases from there. Figures 3.1, 3.2 and 3.3 below show the results of these three runs of full field of view, webcam field of view and line of sight field of view respectively.

The three sets of experiments show good repeatability for all the cover plate geometry’s and seem to get better as the field of view decreases. The small offsets in the readings could be due to the timing of the piloted ignition for each experiment being just slightly different. The spikes towards the end of the thermal radiation readings shown in Figures 3.1 and 3.2 are due to the extinction of the flame occurring at that spot. The reading continues even after extinction due to the plum of hot combustion gases still rising from the extinguished flame. Figure 3.3 shows the plum effect very clearly by the change in slope.
Figure 3.1. Radiometer Full field of view repeatability.

Figure 3.2. Radiometer Webcam field of view repeatability.

Figure 3.3. Radiometer line of sight field of view repeatability.
from extremely steep on the upstream side to a more gradual slope on the downstream side where the radiometer is not only seeing the flame but also the plum of hot gases left in its wake. No spike occurs in Figure 3.3 because the flame is outside the detectors field of view where only the reference voltage of 1.25 volts is seen.

3.1.2 Webcam Field of View

The webcam field of view for the radiometer is very useful for allowing the researcher to get a physical understanding of the output from the radiometer for a particular run. Since the geometry for the webcam and radiometer are the same, any output from the radiometer at a certain time can be correlated to an image at that same instant. The image captured by the webcam contains only the thermal radiation being seen by the radiometer so anything not captured in the image is ignored. This allows for a better understanding of how the flame shape, size and color, basically the visible flame, effects the thermal radiation being seen by the radiometer.

The experiment is conducted in the same manner as discussed above with atmospheric conditions of 21% oxygen, 1atm and 22°C. The 75μm thick PMMA sample is again located at y = 14cm and is centered on the fuel at x = 16.5cm, with a width of 30mm and a length of 33cm. This time the webcam field of view cover plate is attached to the radiometer allowing for the field of view to be 51°. Figures 3.4 and 3.5 below show an image array collected from the webcam still images and the graph of output voltage vs. time that corresponds to the run.

The image array is marked at the bottom in red with the time the image was taken from the run and the corresponding output voltage from the radiometer. Above the array, each image is labeled with a letter which is then superimposed on the plot in Figure 3.5 to show were on the plot the image and output voltage were taken. The output voltage remains low as the flame first enters the view of the radiometer but a slow rise in the output voltage from 20 seconds to 27 seconds were the photo is taken indicates the radiometer was seeing the radiative preheating of the virgin fuel even before the actual visible flame enters its field of view. The measurement continues to increase as the flame propagates downward toward the center of the field of view. The peak of the thermal radiation does not however occur when the flame is in the center of the field of view as shown in the third image at 41 seconds.
Figure 3.4. Radiometer image array with webcam field of view at different locations with time and output at the locations.

Figure 3.5. Radiometer plot of output from webcam field of view with different locations marked to indicate correlate the image array and plot.
The peak thermal radiation actually occurs a few seconds later which is confirmed in the plot of the output voltage to be around 43 seconds with a peak output voltage of 3.74 volts. This is expected due to the plum effect discussed earlier where the rising of the hot combustion gases are blending with the actual thermal radiation being emitted by the flame leading to the peak radiation being shifted slightly below center of the field of view. As the flame progresses further downward the output voltage does not drop off as sharply also due to this effect. Then as the flame leaves the field of view the plum is still well visible to the radiometer as indicated by the plot in Figure 3.5.

### 3.1.3 Distance from Fuel Surface

The trend of the thermal radiation being seen by the radiometer as the distance from the fuel surface in the y-direction increased was also considered. This trend is important to help determine if the radiometer is operating properly. The thermal radiation seen by the detector should drop as the distance from the fuel is increased due to the attenuation of the signal as it travels through a participating material like air in this case.

The radiometer is positioned at $y = 14\, \text{cm}$ and centered on the fuel at $x = 16.5\, \text{cm}$ to begin the first run. The distance from the fuel surface is then varied in $2\, \text{cm}$ increments away from the fuels surface up to $y = 20\, \text{cm}$. Atmospheric conditions are the same at 21% oxygen, 1atm and $22^\circ \text{C}$. The $75\, \mu\text{m}$ thick sample of PMMA is loaded in the downward flame spread orientation and piloted ignition is used. The width is $30\, \text{mm}$ and the length is $33\, \text{cm}$ with a full $95^\circ$ field of view. Figure 3.6 below shows the results for the test runs conducted.

The results shown above are consistent with the signal attenuating as it moves through a participating medium. As the radiometer is moved away from the fuels surface the thermal radiation being seen by the detector is being reduced due to it traveling through the air. The trend in the thermal radiation is the same for all four runs but the peak is shifted slightly down in a non-linear fashion as the radiometer is moved away from the fuels surface. At $y = 14\, \text{cm}$ the full field of view is saturating the detector at 5 volts when the flame reaches just below the center of the run at about 52 seconds which is why the graph appears flat with no defined peak at this point for a few seconds. The changes in the slopes for each run become gradually less and less as the distance increases to $y = 20\, \text{cm}$ where the peak is hard
Figure 3.6. Radiometer plot of the change in distance from the fuels surface.

to define. At some y-distance away from the fuels surface the thermal radiation signal will be fully attenuated by the air and the detector should read flat at the reference voltage of 1.25 volts at that point which the trend shown is indicating.

3.1.4 Change in Fuel Thickness

The finite thickness of a solid fuel plays a critical role in the thermal radiation being emitted by a flame. When the fuel thickness is varied, a change in the size and temperature of the flame affects the amount of radiation it can emit.

Three sets of experiments were conducted one with each field of view to verify the change in the thermal radiation and how the field of view affects the detectors reading. 50\(\mu m\) and 75\(\mu m\) thick samples of PMMA were chosen for this set of experiments. The radiometer is again positioned at \(y = 14cm\) and centered on the fuel at \(x = 16.5cm\), with fuel width of 30\(mm\) and a length of 33\(cm\). Atmospheric conditions are 21% oxygen, 1atm and 22\(^\circ\)C for all runs of the experiment. One set of runs were run for each of the three fields of view to determine any factor this may play on the thermal radiation emitted. Figures 3.7, 3.8 and 3.9 below show plots of the results for each field of view and both thicknesses chosen.
Figure 3.7. Radiometer plot of the change in fuel thickness for full field of view.

Figure 3.8. Radiometer plot of the change in fuel thickness for webcam field of view.

Figure 3.9. Radiometer plot of the change in fuel thickness for line of site field of view.
The results show that the thermal radiation does increase with increased fuel thickness just as predicted. Increasing the amount of available fuel to the propagating flame increases the flames temperature, size and overall shape leading to an increase in thermal radiation. The field of view does not seem to affect the thermal radiation being seen by the detector it only reduces it by the same trends shown in repeatability for one thickness of PMMA when changing from one cover plate to another. The peaks become smaller and shift slightly to the left for the thinner fuel, basically the peak is seen sooner in time due to the increased flame spread rate for the thinner fuel allowing it to reach the center of the detectors view earlier than the thicker fuel. The peak for the thinner fuel is also seen for less time by the detector due to the increased flame spread rate leading it to be smaller and less pronounced than the thicker fuel. The trends for the thermal radiation are still similar decides the few things discussed above helping prove the radiometer is operating correctly.

3.1.5 Comparison to Microgravity Results

One of the main goals of this research is to determine if normal gravity research conducted here on earth can be compared to what is seen onboard the International Space Station in microgravity. If a comparison can be made then it will help researchers conduct earth based experiments which are much easier to conduct than onboard the ISS, and allow predictions to be made about the behavior of flame propagation in microgravity from earth.

To make a valid comparison between the experiments at SDSU and the experiments onboard the ISS the geometry and conditions must be the same with the exception of gravity. The geometry for the Bass-II apparatus was shown above in Figure 2.30 and from this schematic a similar geometry was obtained here at SDSU shown in Figure 3.10 below. The radiometer was positioned in this geometry using the data acquisition control MATLAB GUI and the experiment was conducted using the actual Bass-II sample holder shown in Figure 2.31 that was delivered by NASA to SDSU to ensure the same geometry and heat losses through the sample holder for a better comparison.

The microgravity results were conducted onboard the ISS in the manner discussed in section 2.4 above. The thickness of the PMMA fuel was 100\(\mu\)m and the thermal radiation was monitored with a Dexter Research 2M thermopile. The opposed flow velocity was very
low around $3 \text{cm/s}$ with 21% oxygen, 1 atm and remote kanthal wire ignition was used. To make a direct comparison a 100$\mu$m sample sent to SDSU from NASA was used for the normal gravity run. The sample was loaded into the Bass-II sample holder and the sampler holder was fixed to the Flame Stabilizer sample holder in the downward flame spread configuration so the probe positioning system could be used to recreate the exact geometry. The radiometer was moved into the same configuration as the Bass-II experiment shown in figure 3.10 above. Atmospheric conditions of 21% oxygen, 1 atm and 21°C were present at the time of the run. The width of the sample was 20$\text{mm}$ with a length of 95$\text{mm}$ and piloted ignition was used to ignite the flame. The radiometers full field of view was chosen for this run. Figure 3.11 below shows the results of the microgravity and normal gravity runs.

The trends in the plot in Figure 3.11 seem to agree quite well. The first peak in the Bass-II experiment is due to the remote kanthal wire ignition and the time it takes to raise the fuel temperature from $T_s$ to $T_{vap}$ for ignition to actually occur. The SDSU data shows a slow rise to this same point due to piloted ignition. Once past the ignition point for both
experiments the thermopiles see the same trend in thermal radiation until the Bass-II result starts drop off to extinction. The difference between the microgravity and normal gravity extinction points is due to the slight difference in the opposed flow velocity seen by both and changing the flame spread rate slightly.

### 3.2 Thickness Study

The finite thickness of a solid fuel plays a significant role in the flame spread rate. The thermal limit helps to simplify the complex behavior of flame spread rate and its dependence on heat loss to radiation and convection. The thermal limit is achieved when the opposed flow is high enough to neglect losses to thermal radiation but still low enough that finite rate kinetics has not taken over and forced the flame to extinguish. In the thermal limit the opposed flow flame spread rate is constant. The finite thickness of a solid fuel can be separated into two distinct categories the thick regime and the thin regime. The well-known de Ris formula [4] for spread rate in the thermal limit governs the behavior of the spread rate as the fuel thickness is varied. This formula works quite well for data collected here on earth but little is known on how to correlate it to the microgravity regime.

100\text{um} \text{ samples of PMMA were burned both here at SDSU and in microgravity onboard the ISS. For the downward spreading flame experiment at SDSU an average spread rate of } 2.0 \text{mm/s} \text{ was found shown in Figure 3.12 below. The average spread rate is}
considered steady with the shape of the flame also remaining quite steady during a run even though the instantaneous spread rate does fluctuate a tiny bit. The fluctuations could be due to many random factors like manufacturing errors, but due to the opposed flow being driven only by buoyancy, a steady spread rate is expected. In microgravity for the same fuel thickness of 100 µm has opposing flow velocities ranging from \(40 \text{ cm/s}\) all the way down to \(1 \text{ cm/s}\) for the run. The highest spread rate observed for this run was \(2.2 \text{ mm/s}\) which is considered the thermal limit. At very low velocities radiation losses dominate the flame and extinction occurs whereas when the opposed flow velocity is very high finite rate kinetics take over and lead to blow-off extinction. The thermal limit spread rate observed in microgravity of \(2.2 \text{ mm/s}\) is similar to the \(2.0 \text{ mm/s}\) seen in the downward spread experiment.

![Graph showing microgravity and downward flame spread rate vs. time plots.](image)

Figure 3.12. Comparison of microgravity and downward flame spread rate vs. time plots.

Figure 3.13 below shows an image array of different thicknesses of PMMA comparing the microgravity flame and the normal gravity flame. The flame shape and size are similar even though the downward flame has some dripping at the leading edge caused by gravity and the flame appears to be slightly different in color. Even with these differences the
flame spread rate is almost the same. This leads to the belief that with 21% oxygen concentration the downward spreading flame is in the thermal regime and that finite rate kinetics play a minimal role.

Because the downward and microgravity flames are not in the kinetic regime, gas-phase kinetics which are described by the Damkohlar number, the ratio of the residence time to the gas-phase combustion time, are in control and the flame spread rate is independent of the opposed flow velocity. Because the flame for both microgravity and normal gravity is in the thermal regime it should follow the de Ris formula for spread rate as the thicknesses of the fuel are varied. If the de Ris formula is modified by a factor of $\frac{\pi}{4}$ and known thermodynamic properties that are listed in the nomenclature are used the de Ris formula can be expressed as:

$$V_{f,\text{thin}} = \frac{\pi}{4} \frac{\lambda_g}{\rho \alpha c_v} F = 2.34 \times 10^{-8} \frac{F \tau}{\tau}; \quad \text{and} \quad V_{f,\text{thick}} = \frac{\rho \alpha c_v \lambda_g}{\rho \alpha c_v \lambda_g} V_g F^2 = 9.72 \times 10^{-5} V_g F^2 \left[ \frac{\text{m}}{\text{s}} \right] \quad (3.1)$$
From the thin fuel formula using the known spread rate from the microgravity experiments of $2.2 \frac{mm}{s}$ and the half thickness of the fuel $\tau = 50 \mu m$, the unknown de Ris coefficient $F$ can be solved as $F = 4.76$. The microgravity value for the de Ris coefficient which was solved for experimentally is very similar to other well-known coefficients that are published in literature:

$$F_{\text{expt}} = \frac{\tau V_{f,\text{thin}}}{2.34 \times 10^{-8}} = 4.76; \quad F_{\text{de Ris}} = \frac{T_{f,\text{thin}} - T_v}{T_v - T_\infty} = 5.54; \quad F_{\text{adb}} = \frac{T_{f,\text{adb}} - T_v}{T_v - T_\infty} = 4.89; \quad F_{\text{eql}} = \frac{T_{f,\text{eql}} - T_v}{T_v - T_\infty} = 4.41 \quad (3.2)$$

Figure 3.14 below shows the plot of the microgravity results for varying fuel thicknesses and how the modified de Ris formula solved by the one data point correlates to the other data. The de Ris thin thermal limit fits extremely well with the other experimental thicknesses from the microgravity results. Now that the de Ris coefficient has been solved in microgravity, Figure 3.15 below shows the microgravity data, the thin thermal limit and 10 downward flame spread experiments for comparison.

**Figure 3.14. Plot comparing microgravity and the de Ris thermal limit.**
The experimental results for both microgravity and normal gravity seem to be in good agreement which is quite a find due to the fact that one set has gravity and the other is in microgravity. The experimental results also agree quite well with the thermally thin regime calculated from the de Ris formula for the one data point in microgravity. To take this one step further, the fuels finite thickness was increased to try and create a thick fuel in the downward configuration to see how well the de Ris coefficient solved for experimentally would compare, to try and delineate the thin fuel and determine where the transition lies between the two regimes. Extruded PMMA was readily available but created a huge drip effect which was quite undesirable and lead to an unsteady spread rate. The cast PMMA for thick fuels seems to show no dripping and has a very steady spread rate so this was chosen as the fuel to use. 2cm wide samples of PMMA with thicknesses of \(3.2\, \text{mm}\), \(6.4\, \text{mm}\) and \(12.7\, \text{mm}\) are used to try to determine a thick limit transition experimentally. The \(12.7\, \text{mm}\) thick PMMA gives a flame spread rate of \(0.044\, \text{mm/s}\) which is determined to be the average spread rate for a thick fuel in the thermal regime. Because the flame spread rate in the thermally thick limit is dependent on the opposed flow velocity seen by the flame and it is unknown, an effective velocity will replace it and must be solved. Using the de Ris thermally
thick formula with the known coefficient and the experimental thick flame spread rate of 0.044 mm/s, the effective velocity is:

\[ V_{g,\text{eff}} = \frac{V_{f,\text{thick,exp}}}{9.72 \times 10^{-3} F_{\text{exp}}^2} = 0.01998 \frac{m}{s} = 2.0 \frac{cm}{s} \]  

(3.3)

Now that the effective velocity is known, Figure 3.16 shows a plot of the experimental results for microgravity, thin and thick fuels for normal gravity and the thin and thick de Ris thermal limits for a comparison.

![Figure 3.16. Plot comparing microgravity and downward flame spread at different thicknesses of PMMA.](image)

The results for the thick fuel seem to agree with the thick thermal limit but due to complications with containing edge flame propagation for the thick fuels based on the current sample holder, the thickest fuel that could be used was 12.7 mm. To help show that the thick thermal limit exists in this area, experimental data from Fernandez-Pello and Williams [42] is superimposed on the plot shown in Figure 3.17 below.

Now that the de Ris formulas for thin and thick fuels have been shown to agree quite well with experimental results, the transition thickness can be expressed by equating the thin and thick fuel formulas that we solved for:

\[ V_{f,\text{thin,exp}} = V_{f,\text{thick,exp}} \Rightarrow \tau_{\text{transition}} = \frac{\pi}{4} \frac{\lambda_s}{\rho_g c_g V_{g,\text{eff}} F_{\text{exp}}^2} \text{[m]} \]  

(3.4)
Figure 3.17. Plot comparing microgravity, downward flame spread and Fernandez-Pello and Williams data at different thicknesses of PMMA.

This leads to a transition thickness of $2\tau_{\text{transition}} = 5.07\,\text{mm}$ which is exactly where the two thermal regimes intersect on the plot in Figure 3.17. The transition point for opposed flow flame spread over PMMA can vary depending on the opposed flow velocity. It also can depend on the oxygen level and its dependence on $F_{\text{exp}}$, with pressure and its dependence on $\rho_g$ and the boundary layer development and its dependence on $V_{g,\text{eff}}$. 
CHAPTER 4

CONCLUSION

An experimental device for the measure of thermal radiation emitted by a propagating flame has been manufactured. Many types of detectors where explored to properly decide which method of thermal radiation measurement was ideal for the situation. Dexter research 2M thermopile type detectors where chosen and the Dexter Research mini amp PCB board was used for simplicity in design and easy setup. An external ADC was wired into the system and mated with an Arduino microcontroller to allow easy communication between a computer and the sensor. A MATLAB script was implemented with GUI’s for radiometer control and for probe positioning. The proof of concept experiments were conducted on PMMA for downward flame spread, showing very good repeatability. A webcam was mounted on the radiometer and images of the downward spreading flame were correlated to the output seen by the radiometer helping to better understand the physical characteristics of flame as they relate to the output from the radiometer. The trend in thermal radiation as the radiometer is moved away from the fuels surface and the effect of varying the finite fuel thickness of PMMA were also investigated. As the radiometer is moved away from the fuels surface a decrease in thermal radiation seen by the detector was observed, which agrees well with radiation traveling through a participating medium. Varying the finite fuel thickness of the PMMA showed that as thickness increases so does the thermal radiation seen by the radiometer. The thicker the fuel the more heat it takes to raise the temperature of the virgin fuel from $T_\infty$ to $T_{vap}$ leading to a bigger higher temperature flame resulting in higher levels of thermal radiation being emitted which is what the experiments showed. Finally a comparison of microgravity and normal gravity thermal radiation readings were shown to be in good agreement for the trends they produce. This lead to the assumption that making the comparison between the thermal radiation emitted by microgravity and downward flame
spread was reasonable. For future work with the radiometer, a means of correlating the output voltage of the radiometer to a temperature should be investigated. Using the line of sight field of view for the radiometer and an IR thermometer with the same spot size, a piece of aluminum could be heated to a high temperature and readings from the radiometer and IR thermometer could be used to create a calibration curve for output voltage vs. temperature. This will allow the radiometer to be used for radiative intensity and temperature measurements through the black body intensity equation. This will lead to the investigation of temperature and radiation profiles surrounding the flame with a fixed coordinate system obtained on the Flame Stabilizer with a stabilized flame.

Varying finite fuel thickness was also investigated for both microgravity and normal gravity flame spread. The microgravity results for thin PMMA were used to determine the de Ris coefficient and a comparison was made between the de Ris thin fuel thermal limit of flame spread and the microgravity experimental results which showed good agreement. Downward flame spread over thin fuel PMMA was then compared to the thin limit and the microgravity results. This showed that in the thin thermal limit, that microgravity flame and downward spreading flame behaved similarly with respect to flame spread rate with similar atmospheric conditions and thicknesses. More downward flame spread experiments were conducted over thicker samples of PMMA and the de Ris coefficient was used to compare the downward results and the de Ris thick fuel thermal limit formula. Good agreement was found between these results leading to the belief that the de Ris coefficient that was solved for is correct. Due to sample holder limitations, the thickest fuel used was 12.7 mm thick, so experimental data from Fernandez-Pello and Williams was superimposed on the plot to show that the trend for the thick thermal limit was consistent to for PMMA thicker than 12.7 mm. To find the thickness of PMMA consistent with the transition from thin to thick fuel, the de Ris thin and thick fuel thermal limit formulas were set equal to each other and a transition thickness of 5.07 mm was found. For future thick fuel experiments a new sample holder must be designed and manufactured. This will help show that the trend found for downward spread at SDSU for thick PMMA and the de Ris thick thermal limit formula agree and proving that thick fuel spread rate is independent of the finite fuel thickness.
REFERENCES


APPENDIX
CALCULATIONS

A.1 GEOMETRY FOR RADIOMETER COVER PLATE

The calculations for the cover plate are governed by the geometry shown in Figures A.1 and A.2 shown below.

Figure A.1. Webcam and Cover plate geometry used to modify field of view for thermopile.

The cover plate calculation is a bit tricky due to the offset of the radiometer and the webcam with respect to the distance from the fuel surface. From Figure A.1,

\[ \alpha = \beta / 2 \quad \text{and} \quad C = L + \Delta L - l / 2 = L + 12 mm - l / 2 \]

and from Figure A.2 the diameter of the viewing hole is,

\[ \phi = 2y \]

Where,
\[ d_{\text{webcam}} = L \tan \alpha \quad \text{and} \quad d_{\text{radiometer}} = C \tan w \quad \text{where} \quad w = \theta/2 \]

Wanting the distances to be the same,

\[ L \tan \alpha = C \tan w \quad \text{or} \quad L \tan \alpha = (L+12\text{mm} - l/2) \tan w \]

If the length of the cover plate \( l \) is fixed,

\[ w = \frac{\theta}{2} \quad y = \frac{\phi}{2} \]

\[ \theta = 2w = 2 \arctan \frac{y}{l} \]

Figure A.2. Cover plate geometry used to modify field of view for thermopile.

\[ w = \arctan \frac{L \tan \alpha}{L + 12\text{mm} - l/2} \]

\[ y = \frac{l}{2} \tan [\arctan \frac{L \tan \alpha}{L + 12\text{mm} - l/2}] = \frac{l}{2} \left( \frac{L \tan \alpha}{L + 12\text{mm} - l/2} \right) \]

The diameter of the cover plate hole is calculated as,

\[ \phi = 2y = l \left( \frac{L \tan \alpha}{L + 12\text{mm} - l/2} \right) \]

If the diameter of the viewing hole is fixed,

\[ L \tan \alpha = (L + 12\text{mm} - l/2)(\phi/2) \]

\[ l \left( \frac{L}{\phi} \tan \alpha + \frac{1}{2} \right) = L + 12\text{mm} \]

The length of the cover plate is calculated as,
To solve the angle of the field of view from Figure A.2,

\[ \theta = 2w = 2 \arctan \frac{2y}{l} \]

To solve the spot size seen at that field of view,

\[ D = [\tan w(L + 12\text{mm} - \frac{l}{2})]^2 \]