ABSTRACT

Title of thesis: INTERMITTENT CONVECTIVE HEATING OF FINE LIVE WILDLAND FUELS

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Recent studies have investigated the role of convective heating advancing wildland fire spread through intermittent bursts or pulses of flames onto unburned fuels. This study seeks to expand on initial experiments investigating the role of this intermittent convective heating by exploring the ignition of live fuels with different moisture contents under these conditions. A modified Rubens' tube is used to generate periodic pulses of a small-scale diffusion flame over the surface of a fuel sample. Infrared imaging is used to track the surface temperature of the fuel leading up to ignition while the intermittent temperature is characterized using a fine-wire thermocouple. Ponderosa pine needles with a variety of moisture contents are tested at different heating frequencies to determine patterns in the process of ignition. The fuel moisture content is seen to have a significant effect on the ignition times of fuels, while the temperature at ignition is seen to vary with heating frequency. Ignition results are compared with past tests of dried dead fuels using the same apparatus. Model predictions of ignition times as a function of ignition temperature and moisture content are also compared to experimental values and discussed.

A STUDY OF INTERMITTENT CONVECTIVE HEATING OF THIN LIVE FUELS

by

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Soli Deo gloria.

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Chapter 1

Introduction

1.1 The Wildland Fire Problem

Ecosystems around the world rely on wildland fires as a natural part of their cycle, renewing and bringing in new growth and life in their wake. However, as the human population continues to expand, people are settling in areas with frequent fire regimes and are thus exposed to the dangerous conditions of wildland fires [1]. Studies have shown that specifically within the United States, the number of wildfires each year has decreased, while the size and severity of fires has increased at an alarming rate [2]. Much of this is attributed to a combination of years of fire exclusion principles, climate change, and an increase in urban settlement in areas adjacent to wildlands with frequent fire regimes.

The National Interagency Fire Center (NIFC) has coined the term 'megafire' to describe wildland fires that burn over 100,000 acres. Recent wildland fires of this size have leveled entire communities and cost millions of dollars in fire suppression, insurance losses, and damaged infrastructure [3]. According to the NIFC, wildfires within the past five years have burned over 39 million acres in the United States resulting in over 8 trillion dollars (US) in losses [4].

Historically, the primary motivator for fire spread research has been the need for practical tools and models to assist wildland fire suppression operations. This approach prioritizes finding tangible solutions often without establishing the necessary foundational theory behind wildland fires [5]. Current operational models lack a firm understanding of wildland fire theory, and instead rely on limited data within a range of conditions that have been previously studied. These models are limited in the scope of their application and are therefore prone to unknown errors. In order to equip future wildland fire models to correctly handle a variety of conditions, as well as evolve and maintain relevance in the future, there is a need to further the physical and theoretical understanding of wildland fires.

1.2 Role of Ignition

Ignition of combustible materials is an integral step in the process of fire spread. Quintiere described ignition as a three-stage process [6]. First, a flammable solid must be heated to a pyrolysis temperature where the solid begins to release vaporized fuel through the process of gasification. Next, this pyrolyzate moves through the fluid boundary layer to diffuse with air, which acts as an oxidizer and creates a combustible mixture. Lastly, ignition either occurs due to spontaneous ignition or piloted ignition. Spontaneous ignition is a rare source of ignition in wildland fires through which very high intensities of heat can initiate flaming combustion for a fuel without an external pilot source of flame [7]. Piloted ignition is considered the most prevalent source of ignition where gaseous fuels are ignited by direct contact with flames or firebrands [8]. This pilot flame raises the gaseous combustible fuels to the critical temperature for ignition.

The concept of fuel ignition temperature is a useful criterion for energy calculations in combustion. Since there is no general model for the varying heats of gasification of wildland fuels, ignition temperatures can be used to estimate the energy required to raise the fuels to a temperature necessary to initiate sustained gasification. Experimentally, the ignition temperature of a fuel is commonly determined as the point of inflection in temperature over the time of testing [9]. It should be noted however, that the concept of an ignition temperature for fuel is a fictional but useful approximation utilized in model calculations [10]. In a study of the ignition of wood samples exposed to constant radiative heating in a cone calorimeter, Spearpoint and Quintiere determined that ignition temperature varied in tests with heat fluxes below 20 kW/m^2 [11].Once heat fluxes reached over 20 kW/m^2, however, the ignition temperature was observed to remain relatively constant. Overall ignition temperatures for these tests exposed to constant radiative heating showed a sharp increase as the heat flux approached 20 kW/m^2, reaching a maximum just after 20 kW/m^2 and then decreasing to a steady value. The processes that motivate ignition are various and dynamic and are not governed by a species specific temperature for ignition; instead, they rely on various conditions being met through the three stages of ignition.

1.3 Overview of Flame Spread

The process of flame spread begins with the ignition of reactive gases within a fuel bed. The heat produced through combustion of these fuels is then transferred to unburned fuel, which absorbs the energy to the point where the fuel decomposes and releases reactive gaseous fuels. These fuels ignite and propagate the process of fire spread [12]. Sufficient heat must be created during this process in order to ignite the unburned fuels and continue the process of flame spread. The physical process of flame spread through a fuel bed is simple in concept, but the physics are situation specific, dynamic, and coupled, making it difficult to implement physically-based descriptions in wildland fire models [5].

The exploration of the physical processes of wildland fires began in 1940 with the observation that new fuel particles ignited after receiving sufficient radiative and convective heating from the burning region of fuels [13]. To this day, the respective roles of radiation and convection within wildland fire spread are not fully understood. Most models assume that radiation is the primary method of heat transfer in regards to wildland fire spread; however, research has shown that convective heating and cooling play a critical role in this process [14].

1.3.1 Current Models

Current wildland fire models systematically lack the fundamental theory of wildland fire spread and are vulnerable to incorrect applications and false validation [5]. Basing the success of a model solely on its agreements with observations can lead to a false grasp of the underlying theory behind fire behavior. Additionally, the validity of the majority of these models relies on their application to the specific situations for which they were developed, and they run the risk of being used beyond their original scope, compromising their reliability and accuracy.

In 2009, Sullivan sought to comprehensively survey physical and quasi-physical wildland surface fire spread models and the fundamental chemistry and physics behind them [15]. It was found that while many physical models attempt to address the underlying processes, the models do not share a common formulation or satisfactory explanation of these processes. Many of the equations that create the foundation for current models such as the Navier-Stokes and the conservation equations require assumptions and simplifications prior to implementation, and these assumptions should be guided by applicable theory. However, Sullivan's review revealed that the processes of particle ignition and fire spread are largely assumed without experimental basis. In order to achieve constructive advancement in fire behavior modeling, a true understanding of the theory and behavior of wildland fires must be achieved. Many challenges stand in the way of that goal.

1.3.2 The Need for Theory

Most wildland fire models today rely heavily on assumptions in order to create empirical equations describing the heat transfer within a wildland fuel bed. The heterogeneous nature of the fuel in regards to its size, orientation, moisture content, and chemistry are far more difficult to describe and predict than homogeneously-fueled fires that are well established in scientific literature. Many current wildland models either assume a homogeneous fuel and bulk heating or make the simplifying assumption that particle heating occurs through radiation alone [16].

Research by Rothermel and Baines suggests that radiation heating alone is insufficient for wildland fire spread [17] [18]. This is due to the sufficient convective cooling found in porous fuel beds typical of surface wildland fires, which offsets particle heating by radiation. Additionally, the heterogeneous nature and orientation of the fuel prevents radiation from heating unignited fuels until they are within centimeters of contact.

Instead, fuel particle size, flame contact, and convection have a noticeable effect on the heat transfer between fuel particles leading to ignition [19]. Fang and Steward found that convection heat transfer accounted for 60% of the energy required for ignition within 2 to 5 cm of the combustion interface [20]. However, inconsistencies in the conclusions of experimental research have limited the ability of convection to be included in modelling fire spread. Strong assumptions and unknown parameters are currently necessary for the inclusion of convection in these models, which expose them to unknown errors. A better understanding of the role of convective heating in fire spread would allow for greater consistency and reliability in these models.

The mechanisms of heat transfer within a heterogeneous fuel bed become even more complex with the consideration of live fuels with varying moisture contents and a diverse chemical composition. Current models make assumptions in regards to the behavior of these live fuels as well, basing them off the behavior of tested dried foliage. These assumptions are not theoretically sound, but they are currently necessary to provide results, as prone to error as those results might be [5]. This highlights the need for a deeper understanding of the physical processes that define wildland fire heating and spread.

1.3.3 Live Fuels

In previous research, live fuels were represented in experiments as conditioned wet fuels, that is, dried fuels that had been re-hydrated to a desired moisture content [21]. Recent studies have shown that live foliage contains a number of compounds, including ether extractives and non-structural carbohydrates which affect the way that the foliage burns, although the extent of their affect is still largely unknown [22]. These compounds are not present in dead or dried fuels and, therefore, have not been accounted for in much research on the ignition of live fuels. Correlations have been developed for specific species and moisture conditions, but these correlations are empirical in nature and can not reliably be applied to alternate conditions. Moisture content and the chemical composition of live fuels are seen to have an effect on ignition time in wildland fires, but more research must be done to understand the thermal and dynamic processes present in these fuels.

1.4 Previous Work

This paper is a continuation of the research done by Benny on the intermittent convective heating of fine wildland fuels [23]. Their work involved utilizing a modified Rubens' tube to explore the effects of intermittent convective heating on uniform fuel samples. Using an infrared camera, the temperature fluctuations leading up to ignition for a variety of samples, including birch, basswood, dried pine needles, and cardboard, were tracked. The work focused on this novel apparatus and its application to intermittent convective heating and cooling as well as the effect of different diameters of fuel on ignition behavior. A rudimentary numerical model was suggested to predict ignition times incorporating the concept of intermittent heating and cooling at varying frequencies. Benny's work was foundational to the work included in this paper, but it did not investigate the effects of moisture content and live fuels on the process of ignition. This paper seeks to expand on the knowledge compiled by Benny by using the same Rubens' tube apparatus to explore the trends and behaviours of live fuels during intermittent convective heating.

1.5 Summary

Wildland fires are a prevalent and growing concern around the world and specifically within the United States. In past years, wildfires have increased in size, danger, and cost within the United States. Currently, wildland fire models are used to attempt to predict areas with conditions prone to wildland fires, and to predict the spread and path of ongoing fires. These models rely heavily on simplifying assumptions that leave them prone to error and misuse. In order to develop wildland fire models with firm foundations in the theory of fire phenomena, more research must be done on the physics of fuel ignition and flame spread. This paper seeks to expand on the research conducted by Benny on the intermittent convective heating leading to ignition of fine fuels by expanding the scope of experiments to include fine live fuels [23].

Chapter 2

Literature Review

Determining the rate of flame spread is at the core of most wildland fire models. This rate is a function of fuel moisture content, wind, sloped surfaces, and modes of heat transfer within the flame front. Models address these variables in a variety of ways, but their approaches are often reliant on assumptions or deficient in their theoretical foundation.

2.1 Theory in Current Models

Rothermel's semi-empirical model is currently considered one of the most substantial contributions to the wildfire simulations used within the United States [24]. This model, however, lacks description or understanding of the modes of heat transfer contributing to the flame spread rate. Limited by its empiricism, this model is vulnerable to incorrect applications beyond the experimental scope for which it has been validated.

In a similar way, Albini's model assumes the domination of radiation heating for fuel particle ignition [25]. In other studies, Rothermel, Van Wagner, Byram, and others have questioned the sufficiency of radiation to heat fuels to ignition [24] [26] [27]. Experiments by Rothermel show that fuel particles heated by radiation do not reach ignition temperature until flame arrival [17]. Baines showed that radiation was not able to account for the necessary fuel temperatures for continued ignition, but instead that the majority of heating occurred within 0.025 m of the flame front, where the movement of the air and flames heats its surroundings primarily through convection [18].

The representation of convection in wildland fire models is inconsistent and often underestimated due to a lack of fundamental understanding of the role it plays in the ignition and spread of wildland fires. Understanding the dynamics and heat transfer mechanisms that help govern wildland flame spread is one of the first steps to developing a physically and theoretically sound model for the prediction of wildland fire behavior.

2.2 Flame Spread Theory

Flame geometry has been more recently characterized by saw-toothed shaped flames followed by streaks of smoke and flames behind the primary flame zone [28]. Counter-rotating vortices of both flame and hot gases push flames downward into troughs and upward into peaks along the flame front [29]. This creates the oscillating peaks and troughs observed by Beer and others [30]. The combined behaviour of this flow movement, instability, and vorticity has been categorized in lab experiments as Taylor-Gortler vortex pairs [28]. The convergence of alternating upward and downward flows as a result of these pairs pushes flames down onto un-ignited fuels, heating them and allowing for the propagation of flame spread [31]. The interplay of these dynamics at the flame front can be seen in Figure 2.1.

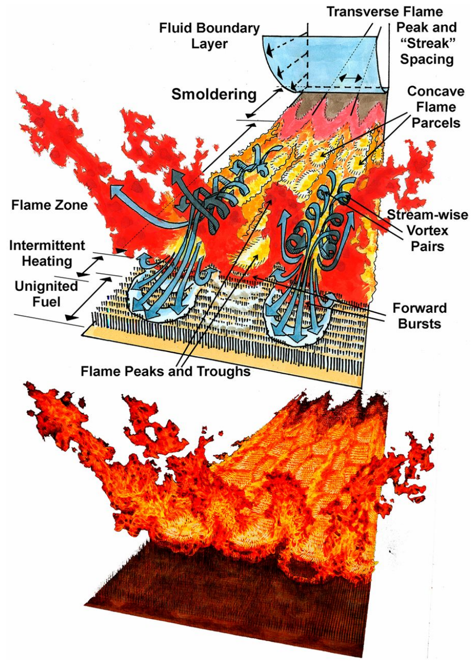

Figure 2.1: Illustration of flame dynamics around the flame front observed during experimental burns by Finney et al [19].

Behind the flame front, streaks located behind flame peaks correspond to smoldering combustion as seen in Figure 2.2 [32]. The average separation between these vortex pairs, characterized visually by the flame front peaks and troughs, have been found to scale linearly with flame length [28].

Finney used laboratory-scale fuel beds tests to investigate the role of radiation and convection on fine fuel particles with diameters of approximately 1 mm [19]. Using a thermocouple array to quantify temperature fluctuations during flame spread, Finney found that when exposed to radiation, the surface temperature of fuel particles increased slowly, but never rose above 100°C. Conversely, when the fuel particles were exposed intermittently by bursts of fuels and hot gases ahead of the flame front, their temperatures increased and decreased rapidly leading to a

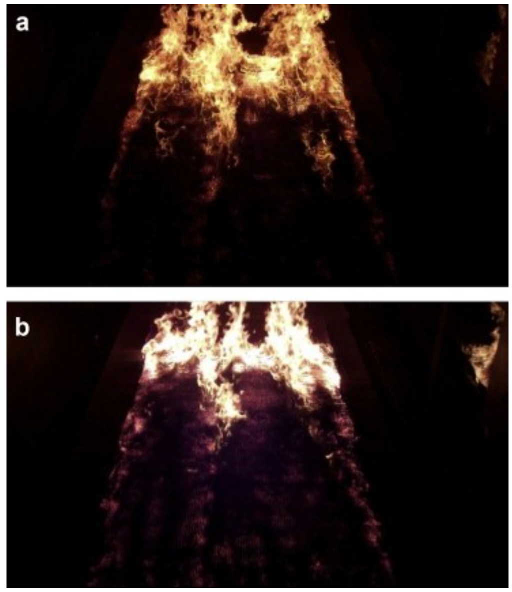

Figure 2.2: Downwind views of an experimental fire moving through a fuel bed showing trails of residual combustion behind the fireline [32].

stair-step heating of the fuels until ignition. Their work showed repetitive convective heating to be the critical mechanism of heat transfer for ignition and spread of these fine fuel surface fires.

2.2.1 Intermittent Heating and Cooling

Intermittent heating behaviour is caused by Taylor-Gortex pairs, which force the hot gasses and flames downwards and forwards from the flame front, creating the splaying intermittent horizontal bursts seen by Clark in their analysis of small-scale convective dynamics of crown fires [33]. These repetitive bursts cause intermittent flame impingement on unburned fuels near the leading edge of the fire line. The transverse motion of the peak and trough structures at the front of the fire line are responsible for the flame bursts ahead of the flame zone [19]. Longitudinal periodic motion contributes to the fluctuating temperature patterns, which together with transverse motion, govern the flame motion as they penetrate fresh fuel particles in the fuel bed [34]. These intermittent flame motions were found to produce predictable average frequencies in temperature fluctuations, which in turn affect the thermal boundary layers of fine fuel particles [35].

2.2.2 Roles of Radiation and Convection

According to work done by Morandini, fires with higher fuel loads are dominated by radiative heating, while surface fires with smaller fuel loads are considered wind-driven fires and experience significant convective heating [36]. The relationship between this turbulent wind flow during fire spread and its influence on the radiative-convective heating mechanisms is not well understood, and a further understanding can only be found through experimental investigation of convection within fire ignition and spread.

Radiation is the most researched and most often attributed heat transfer method in regards to flame spread; however, studies have shown that heat flux from radiation is not sufficient to support flame spread [37]. In 1969, Fang found that 60% of the energy required to produce ignition occurs within 3 cm of the flame front and consisted of convective and radiative heating, while radiation contributed 40% to the overall necessary heating to ignition of the fuel [20]. Additionally, models that account only for radiation have been seen to under-estimate the temperature found at the flame front during spread [14]. This points to the significant role that convection plays in flame spread.

2.3 Live Fuels

Live foliage has been observed to "burst" from the rapid evaporation of moisture inside the cell structure of the fuel. This rapid process creates large internal pressures that overcome the strength of the foliage cell walls and cause a rapid release of the moisture within the foliage [38]. In their paper, McAllister et al. theorized that flammable non-structural carbohydrates found within the cells of these live fuels compensate for the dilution of pyrolyzates from water vapor during ignition. This allows for live fuels to burn at much higher moisture contents than conditioned dead fuels used in previous experiments [22]. To evaluate this theory, McAllister ran ignition tests on both live and dried Douglas fir and Lodgepole pine needles. Samples were gathered over a course of a number of months in order to assess the seasonal changes in their natural moisture and composition. These samples were then exposed to external radiant heat fluxes under a constant airflow to determine their ignition time.

Among other conclusions, their work shows that there was little difference in ignition times between thermally thick and thermally thin assumptions for the needles. This agrees with research done by Benkoussas stating that despite their physical thickness, the combination of their low thermal conductivity and their exposure to high levels of heat flux create large internal temperatures gradients more typical of a thermally thick fuel [39]. Therefore, in calculations, pine needles and other physically thin surface fuels are considered thermally intermediate and should be assessed as both being thermally thick and thermally thin [40].

McAllister concluded that, in general, moisture content has a strong influence on the ignition times of live fuels. In their study, they compared numerous empirical and semi-empirical models to determine their potential application as a first approximation for live fuel ignition in wildfire models. Some models, most notably that of Babrauskas, matched promisingly with data, but the remainder of considerable variability of results serves as a reminder of the limitations of empirical models within their original conditions [41]. Additionally, this variability indicates some other controlling mechanism within the process of ignition of live fuels outside of moisture content. The work done by both McAllister and Jolly points to the characteristics of the chemical composition to be this other controlling mechanism within the ignitability of live fuels [42].

Numerous studies have concluded that moisture content does play a significant role in the ignition behavior of live fuels [40, 43, 44, 45]. Fuel moisture content affects both heat transfer and the process of combustion during both the solid and gas phases of evaporation [40]. In their work, Simms and Law found that higher moisture contents increased the value of the thermal properties of the wet fuel in a solid state, including thermal conductivity, volumetric specific heat, and density [43]. In the gas phase, the evaporation of the fuel moisture dilutes the pyrolyzate and absorbs energy, effectively altering the ignition temperature of the fuel.

For the purpose of this study, moisture content is represented as

$$MC(\%) = \frac{M_i - M_d}{M_i} \times 100 \tag{2.1}$$

where M_i and M_d respectively represent the sample's weight in grams at initial conditions and after being dried. Most literature that has considered fuel moisture content as a part of its formulation calculates it as a percentage of the fuel's dry weight. The reliability of this method for calculating moisture content is questionable, as it assumes a constant dry weight for species which might undergo natural fluctuations in mass and composition during seasonal changes. These effects of these seasonal changes have been observed by Kozlowski, McAllister, Jolly, and others [46, 22, 42].

Xanthopoulos looked at the processes governing the time to ignition for three western conifers when exposed to hot air convection [44]. Ponderosa pine, lodgepole pine, and Douglas fir branches were gathered and tested over the course of a year to observe the natural fluctuations in fuel moisture content of the live needles. Xanthopoulous determined in their study that seasonal changes did not have a critical effect on ignition behavior, and that live ignition required air temperatures of at least 400°C. For Ponderosa pine specifically, the ignition temperature for 0% moisture content and 33% moisture content was 280°C and 320°C, respectively according to work by Stockstad [45].

2.4 Experiments on Intermittent Ignition

The Rubens' tube was initially created to demonstrate the relationship between sound waves and pressure; Benny utilized this type of apparatus to emulate the convective heating found in wildland fires [23]. In a Rubens' tube, a pressurized flammable gas is fed into a horizontal aluminum cylinder through two holes on the side of the tube. On top of the tube, small holes are drilled in a line on top of the tube. The gas flows out of these holes, which is ignited to form a linear flame sheet. One end of the tube has a speaker secured to it, while the other end is sealed with rubber.

Figure 2.3: Standing wave pattern on Rubens' tube [23].

During experiments, sounds of different frequencies are played through the speaker, causing pressure differentials within the tube, resulting in differing amounts of fuel being pushed through the holes in the top of the tube. The flame lengths created by these pressure differentials give a visual representation of a standing wave pattern as seen in Figure 2.3. The effects of pressure and flow rate on the flame height within the Rubens' tube was researched by Ficken and Stephenson [47]. By the use of the incompressible Bernoulli equation, they showed that for high gas flows, the pressure nodes within the Rubens' tube corresponded to the flame maxima, while for low gas flows, the flame maxima occurred at the anti-nodes as seen in Figure 2.4.

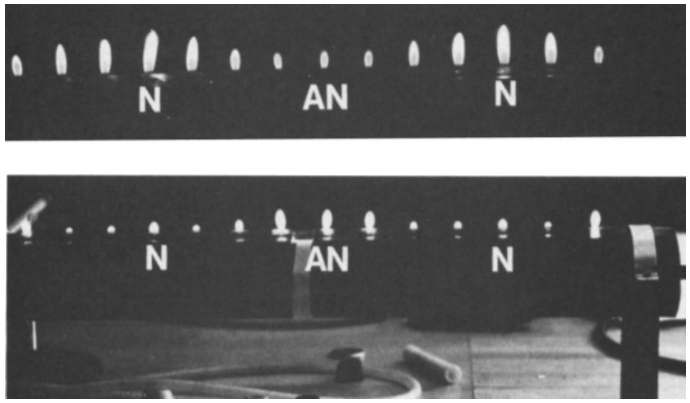

Figure 2.4: Experiments by Ficken et al. where N and AN represent the nodes and anti-nodes respectively on a Rubens' tube [47].

Benny used a modified Rubens' tube apparatus to evaluate the ignition behavior of various dried wooden fuels when exposed to intermittent convective heating [23]. They found that, while intermittent convection caused ignition at slower rates than constant flame heating, it was still able to ignite fuels over a wide range of distances, frequencies, and fuel diameters. Benny found that fuels with larger diameters took longer to ignite than smaller fuels at the same conditions, due to a combination of extended convective cooling and conduction.

An important factor that Benny defined in their experiments was the temperature difference between the ambient air and the temperature peak created by the flame sheet passing over the fuel [23]. Represented by ΔT, Benny used this parameter as another way to explore the relationship between the fuel height, gas flow rate, and frequency of heating and to see their collective effect on the ignition of fine fuels. In order to ensure that the fuel surface temperature could be obtained reliably in between flame pulses, a large ΔT was desired for all testing heights and frequencies. Benny used a ΔT of around 700 K to determine their testing heights, and this same method was adopted in this thesis.

A slight deviation from the methodology set forward by Benny lies in the flow rate of the flammable gas used to create the linear flame sheet on the Ruben's tube. In their work, they regarded the flow rate as another variable to manipulate in experiments, varying it along with the fuel height, flame frequency, fuel type, and fuel thickness. In order to create a more cohesive understanding of the relationship between the intermittency of heating and the behavior of live fuels, the gas flow rate was held constant at 0.6 lpm during all experiments of Ponderosa pine needles conducted as a part of this study. The major effect of this decision is that the ΔT of tests at different frequencies, heights, and moisture contents varies by as much as 200 Kelvin between tests. However, all temperature differences determined through testing vary around and are close to the value of 700 K so this change is considered acceptable in regards to later comparisons to data gathered by Benny.

Benny created a rudimentary mathematical model to combine the effects of convective heating and cooling at various frequencies as well as radiative effects to predict the ignition time of fuels. Their work further underlined the important role that intermittent convective heating plays during the ignition and spread of wildland fires, but did not explore the behavior of live fuels.

2.5 Motivation

This thesis will attempt to explore the relationship between moisture content and ignitability under intermittent heating for live fuels, specifically Ponderosa pine needles from Montana, USA. Recent research has highlighted the need for a deeper understanding of the behavior and effects of moisture content on the ignition of live fuels. Additionally, the role of intermittent convective heating in the ignition and spread of wildland fires is significant, but not well understood. Using the apparatus designed by Benny for the intermittent convective heating of fine fuels, the relationship between live fuel moisture content and the frequency of convective heating will be investigated. The behavior of live fuels under these conditions will provide much needed insight into the complex dynamics at the foundation of wildland fire ignition and spread. As the wildland fire problem continues to grow, so does the need for models that can accurately account for these physical phenomena.

Chapter 3

Experimental Apparatus

An apparatus resembling a Rubens' tube developed by Benny for the intermittent convective heating of fine fuels was adjusted for the testing of live fuels [23]. In contrast to the steady heating methods commonly used for previous laboratory experimentation, this gas burner set up allowed for flame sheets to be intermittently pulsed over the selected fuel, mimicking the convective heating found in wildfires.

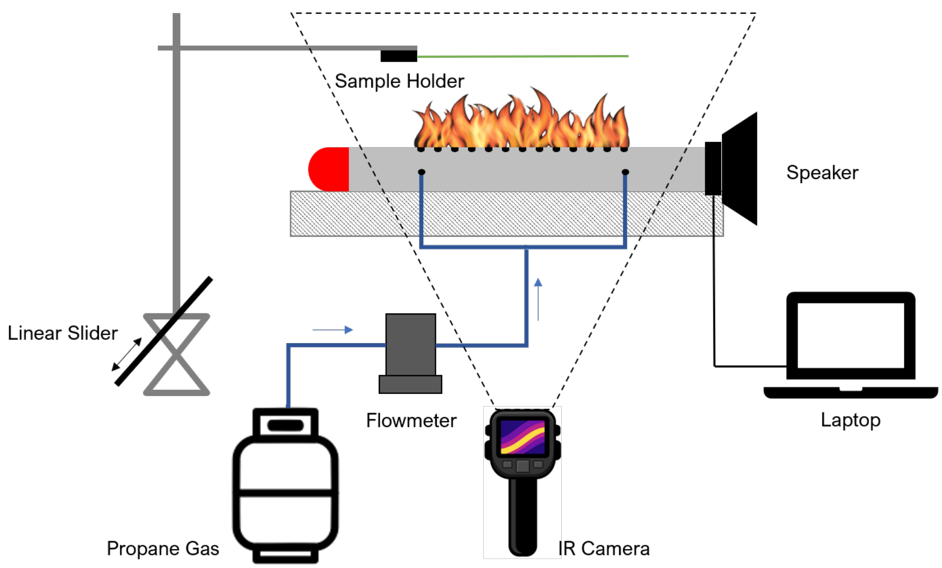

Figure 3.1: Rubens' tube experimental setup

For this specific apparatus, an 40 cm long aluminum cylinder with a diameter of 5 cm was used. On top of the tube 31 holes with 2 mm diameters were drilled in a line 5 mm apart. A rubber casing was used to seal one end and on the other end of the tube, a speaker assembly was secured inside a square-based pipe flashing and sealed onto the tube. The tube and speaker were then secured onto a framing system so that the upper surface of the tube was 20 cm from the top of the counter. A linear slider was positioned to extend the sample over the holes on the surface of the Rubens' tube. The height of this slider was adjustable to allow for variance in sample heights over the burner. This slider could be pulled away from the burner to allow for the experimental samples to be positioned and removed from over the flame at the beginning and end of testing. Polyurethane tubes were secured to two holes centered on the side of the tube that led first to a flow meter and then to the tank of propane gas used in experiments. The propane tank was equipped with a two-stage cylinder regulator to maintain a constant flow of gas throughout the experiment. The flow meter regulated the amount of flammable gas flowing into the tube and, therefore, the height of the flames. An IR camera was then positioned approximately 1 meter away from the burner to record experiments. This setup is visualized in Figure 3.1.

3.1 Flame Characteristics

A steady flow rate of 0.6 lpm of propane was applied for all experiments. For the sake of comparison, the same sound frequency and settings that were developed and used by Benny were applied to this research [23]. Benny created audio files with specific on and off times for the audio, which allowed for the flame sheet to break off from the tube and propagate upwards without extinguishing the flame at the base of the tube. For this research, varying frequencies of 0.5 Hz, 1 Hz, 3 Hz, and 5 Hz were used on samples of various moisture contents. Each frequency featured a pulsation "on-time" of approximately 0.1 seconds, with varying lengths of "off-time" in between pulses. The 0.5 Hz frequency had the longest "off-time" between pulses, and the 5 Hz frequency had equal on and off-times. These pulsation frequencies were verified by applying a Fast Fourier Transform (FFT) to a temperature signal revealing the frequency of intermittent flame sheets. Temperature readings of these frequencies show relative reliability in their behavior, and their thermal characteristic fluctuations can be seen in Figure 3.2.

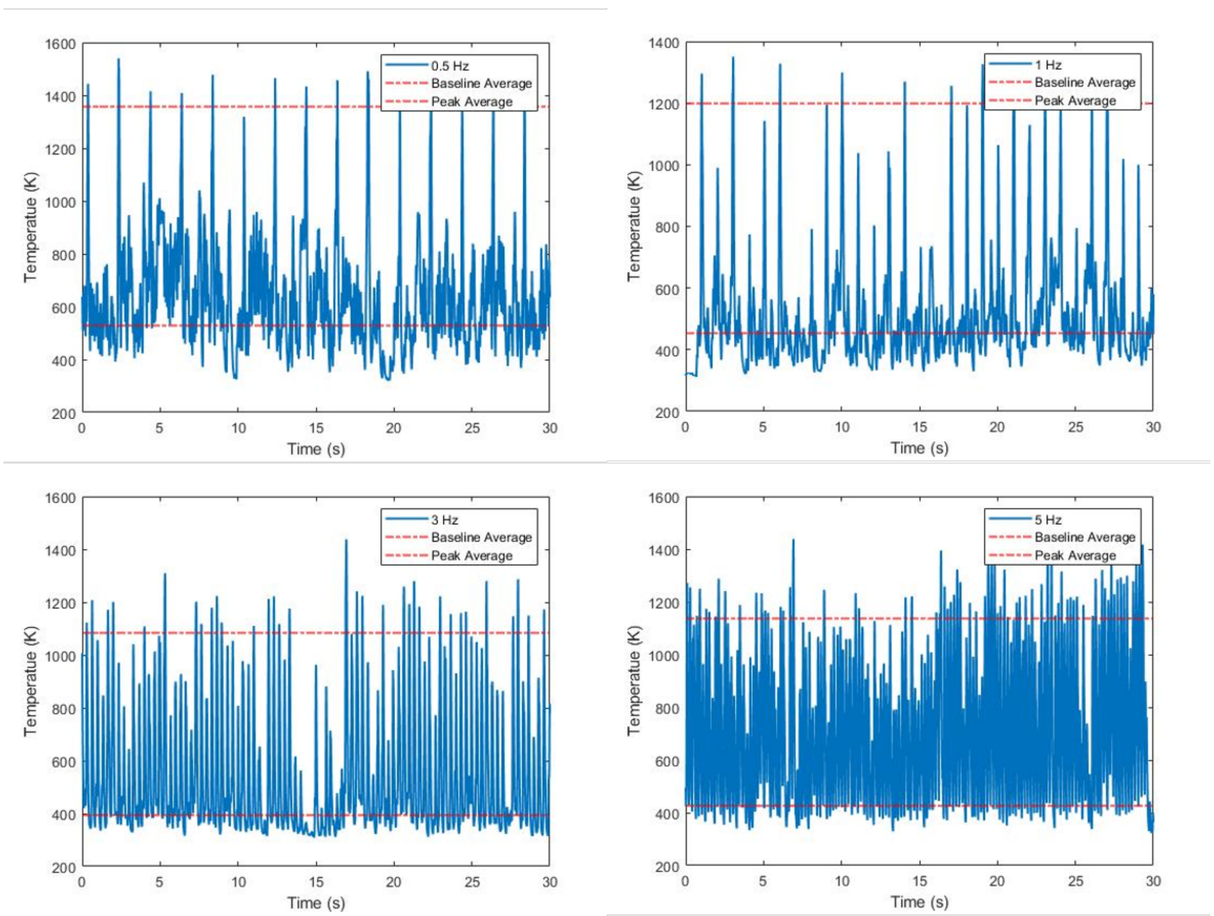

Figure 3.2: Thermocouple data for varying frequencies

3.2 Modifications to Apparatus

In contrast to the wooden fuels used by Benny, in which only one end needed to be secured to the linear slider for ignition tests, the pine needles used in this research necessitated both ends being secured during testing. This was done to prevent the needles from curling or bending during testing and instead maintain an even horizontal orientation. Therefore, an additional arm was added to the Rubens' apparatus as can be seen in Figure 3.3. This arm extended 17 cm above the sample holder at a sufficient distance from the burner to avoid disrupting the heating of the samples. It extended 45 cm across the length of the burner and extended down so that the lower part of the arm aligned with the sample holder. A metal clamp was attached on the lower portion of the arm and was adjusted for the varying lengths of the fuel samples.

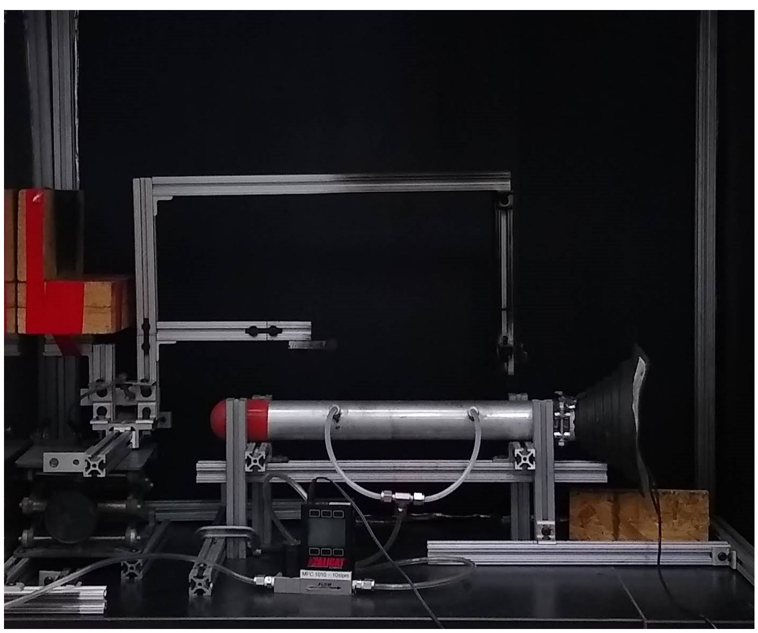

Figure 3.3: Experimental apparatus with modified arm

In order to maintain the level of the arm, counter weights were secured to the opposite side of the linear slider to ensure the pine sample was uniformly distributed over the flames and that clear ignition could be recorded. This setup was placed beneath a ventilation hood, and surrounded on three sides by aluminum panels in order to prevent ambient air disturbances to the flow of the heat and gases during experimentation. This entire setup is shown in Figure 3.3.

3.3 Instrumentation and Software

During fuel ignition experiments, a FLIR E95 Advanced Thermal Camera was positioned on a tripod approximately 1 meter from the apparatus to capture the thermal fluctuations before and during the ignition of the samples at a rate of 30 frames per second.

This camera had a spectral range of 7.5 - 14.0 µm, a temperature range of 0-650° C with an accuracy of ±2° C, and recorded real time temperature readings during experimentation [48]. During experiments, the emissivity of the sample was set to 0.88 in accordance with work done by Benny. A software created to work with the FLIR camera called Research IRmax was used to evaluate and plot the temperature readings. The user interface for Research IRmax is shown in Figure 3.4

While the temporal results are at risk of being affected by the off-gassing and soot created during the experiments, the period of time between flame sheet pulsations was adequate for the camera to determine the lower temperature value of the needle. The ignition location of each test was determined visually along the

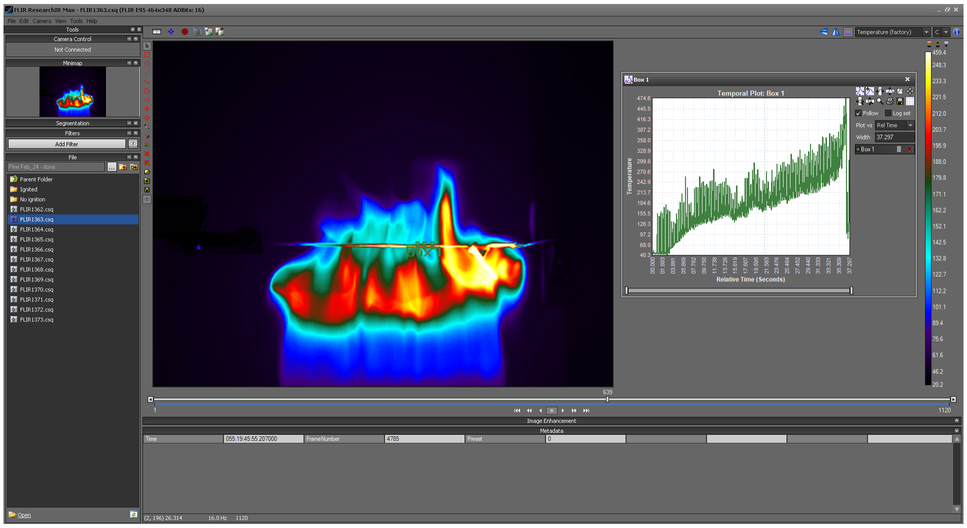

Figure 3.4: ResearchIR temporal analysis interface

needle, and the temperature at that point was plotted over the duration of the experiment. These temperatures were then compared to thermocouple temperature readings at the same height to determine the validity of the readings and the effect of the flame sheets on the readings.

3.4 Measurement Methodology

For testing, the samples were secured on both ends to a linear slider that was moved over the line of the flame at the beginning of the test and removed either upon sample ignition or after 180 seconds without ignition. In contrast to the wooden fuels used by Benny, Ponderosa pine needles of varying moisture contents were used in these experiments. Samples were received from the USFS Rocky Mountain research station in Missoula, Montana. Immediately after obtaining the samples, they were placed in cold water and refrigerated in order to maintain quasi-live conditions over the course of testing. The moisture content of the ambient samples remained

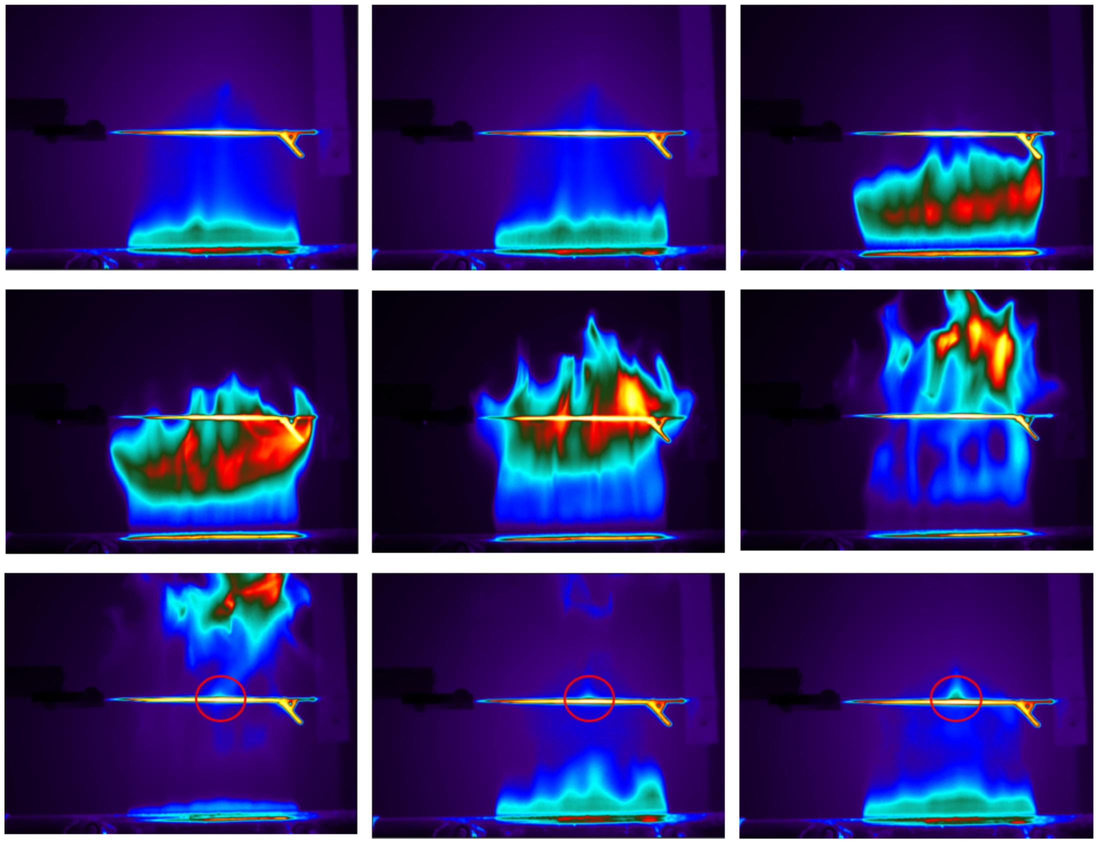

Figure 3.5: Infrared images of a 1 Hz test of a fascicle of dried needles leading up to ignition. The point of ignition is identified by a red circle in the last three frames.

within a range of 5% over six months of testing and showed little to no signs of browning during that time. Moisture contents on a wet mass basis were analyzed using thermogravimetric analysis through use of an A&D MF-50 moisture analyzer. For intermediate moisture content levels, needles were dried in a convective oven for 5 minutes at 135°C to obtain average moisture content levels of 28%. For dried conditions, pine needles were placed in a convective oven for a period of 24 hours at a temperature of 135°C. The baseline moisture content for the ambient Ponderosa pine samples was determined to be in the range of 47-52%, while the fully dried needles were measured as having a moisture content of 1-2%. For this study, ambient

Table 3.4-1: Summary of test conditions

	0.5 Hz	**1 Hz**	**3 Hz**	**5 Hz**
Moisture	Dried- 3%	Dried- 1%	Dried- 3%	Dried- 1%
	-	Mid- 28%	Mid- 28%	-
Content	Ambient- 44%	Ambient- 47%	Ambient- 51%	Ambient- 47%

moisture content (MC) and dried moisture content are defined as 47% and 1% respectively.

The combinations of moisture contents and heating frequencies tested are summarized in Table 3.4-1. For each test condition, the samples were exposed to a specific frequency, and the height was adjusted in increments of 0.5 cm to determine the farthest distance from the burner at which the samples would reliably ignite within 180 seconds. This height is defined as the limit height for each testing scenario. Once a limit height was determined for specific parameters, that test was conducted a minimum of three times in order to establish trends in the data, and hopefully allow for ignition criteria to be established. This does mean however, that the average gas temperatures each test is exposed to differs between conditions, as can be seen in the ΔT results.

Each test was recorded with the infrared camera in order to determine the particle temperature during the test and specifically at ignition. Once three tests were conducted for each condition, a thermocouple test was also run in order to document the temperature fluctuations occurring during the intermittent flame ex-

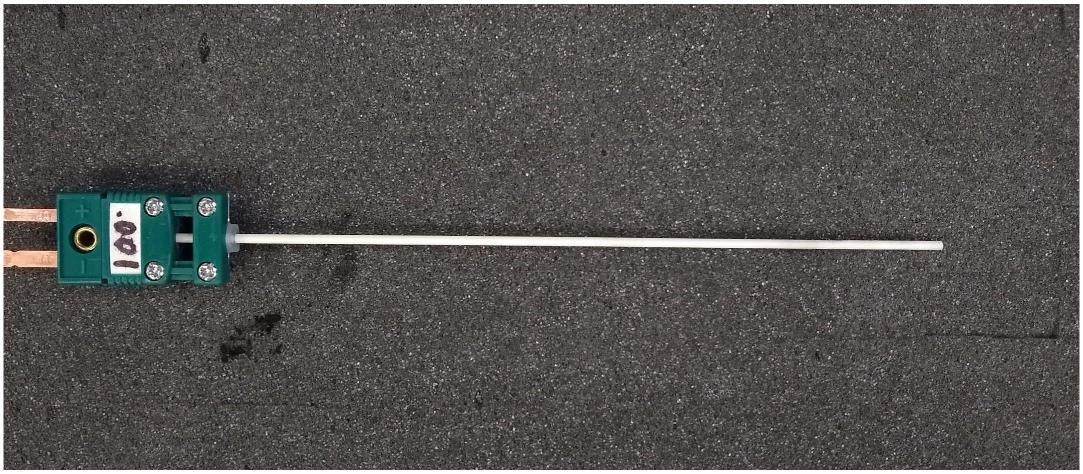

Figure 3.6: 0.0025 mm R-type thermocouple

posure. The thermocouple was placed at the previously determined limit height for each test criterion and the flame temperatures were recorded.

For these tests, an R-type thermocouple with a wire diameter of 0.025 mm was used to minimize the lag time, temperature error, and radiation errors within the readings. This thermocouple can be seen in Figure 3.6, extending 0.2 cm from the end of a ceramic casing. The thermocouple was wired to a C-Series NI-9124 DAQ chassis with a built-in cold-junction compensation circuit and an included auto-zero channel: both of which offset errors and give the DAQ chassis a measurement accuracy of 0.37°C [49]. The thermocouple had a response time of 0.05 seconds and gathered data during testing at a rate of 95 Hz [49]. The thermocouple tests served to provide the temperature of the flame pulsations under the same conditions as the testing using the IR camera technology.

3.5 Ponderosa Pine

Ponderosa pine trees are known to grow over 69 meters in height and have trunks up to 1.2 meters wide. Historically, Ponderosa pines have been considered one of the most fire-resilient pine species of the western United States, and have been observed to rely on fires for the natural pruning of their lower branches [50].

Figure 3.7: An open park-like stand of old-growth Ponderosa pine on the Klamath Indian Reservation in Oregon in the 1930s [50].

Research has shown that the Ponderosa pine stands of the west were characterized by large park-like stands with significant spacing between the large trees, and very little debris on the forest floor as seen in Figure 3.7.

Due to the policy of fire exclusion in the 1900s and aggressive suppression efforts made since, low intensity fires that these areas relied on to clear out the forest under-story have been prevented, which has led to a buildup of surface fuels in these areas. In addition, shade-tolerant and fire-susceptible species such as Douglas fir have begun to grow in the understory of Ponderosa pine stands. During wildfires, these smaller trees have been observed to act as a ladder fuel, spreading the fire to the Ponderosa crowns and causing the fire to reach problematic intensities. Pine needles represent a typical fine fuel in wildland fires. Therefore, understanding the way in which these pine needles ignite is fundamental to obtaining a deeper understanding of the science behind wildland fires.

3.6 Ignition Test Parameters

The goal of this study is to further the understanding of the ignition of fine fuels when exposed to intermittent convective heating. For this purpose, the ignition of pine needles at varying moisture contents, heating frequencies, and distances from the burner were tested and compared. Ignition was determined visually and was confirmed through a spike in the surface temperature of the fuel at the time of ignition. Due to the heterogeneous makeup of natural fuels such as pine needles, a number of ignition behaviours were observed, including visible off-gassing, smoldering or browning without visible ignition, one needle breaking and igniting before the others, and the needles igniting near the metal clamp. For the purposes of this study, ideal ignition was considered to take place in the center of the sample simultaneously for all pine needles in a cluster, and these tests are the ones that are considered in the analysis section.

Chapter 4

Experimental Results

4.1 Fuel Characteristics

Ponderosa pine needles grow in long, flexible fascicles of three, with needles averaging a length of 18 cm. A representative fascicle is shown in Figure 4.1

Figure 4.1: Ponderosa pine needle

This species of pine was chosen due to the length of the needles, as it allowed for the needles to be secured on the apparatus without concern for impeding boundary flow from their points of being secured. Fuel characteristics from Benny are included in Table 4.1-1 [23].

Table 4.1-1: Physical properties of dried pine needles taken from literature [23]

ρ (kg/m^3)	c_p(kJ/kgK)	k (W/mK)	$T_{ig}(K)$	L (cm)	d (cm)
270 $\pm$60	1.5	0.15	553	24.5 $\pm$3	0.14 $\pm$0.02

4.2 Visual Analysis

As stated in the previous section, an infrared (IR) camera was used to record ignition tests, and the results were processed using ResearchIR software. The IR camera setup is seen in Figure 4.2

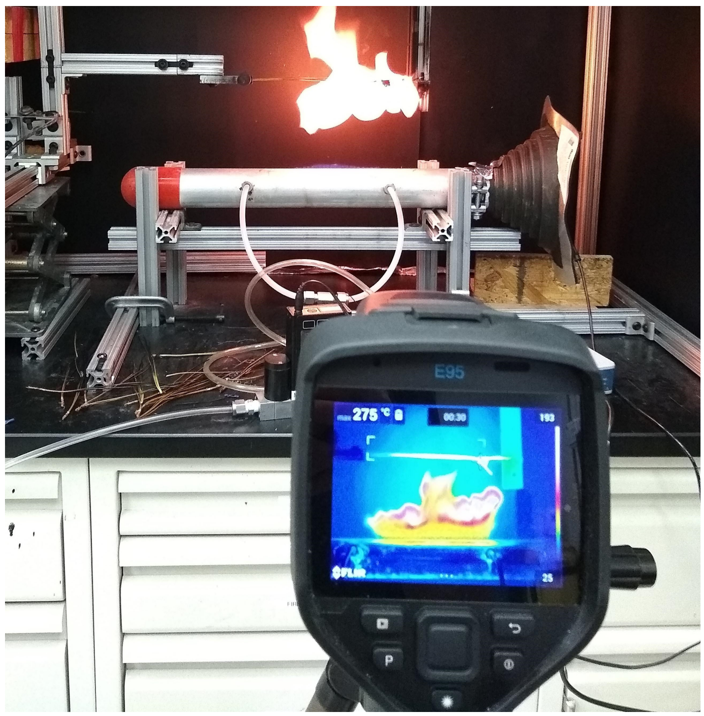

Figure 4.2: FLIR experimental setup

Once all experiments for each set of ignition conditions was completed, the infrared recordings were run through the proprietary FLIR Research IRmax software and temporal plots of the surface temperature of the fuels at the location of ignition were recorded. Thirty frames were captured for each second of testing, and a box of approximately 2 cm by 0.5 cm was selected around the determined area of ignition. The temperature of this box was averaged over the area of the needle and was tracked through each frame leading up to the point of ignition. The time at ignition was determined visually, through visible presence of flame in the IR video in between flame pulses from the burner, and was confirmed through a spike in the surface temperature of the fuel at the time of ignition. A progression of infrared frames of an experiment leading up to the determination of ignition can be seen in Figure 3.5. These temperature vs. time plots were then analyzed using a custom script written in MATLAB. Spikes in the infrared temporal readings from the flame passing over the surface of the fuel were removed through a MATLAB function, 'envelope' which isolates the lower values in the peaks and returns results that correspond more closely to the true value of the fuel surface during testing as seen in Figure 4.3.

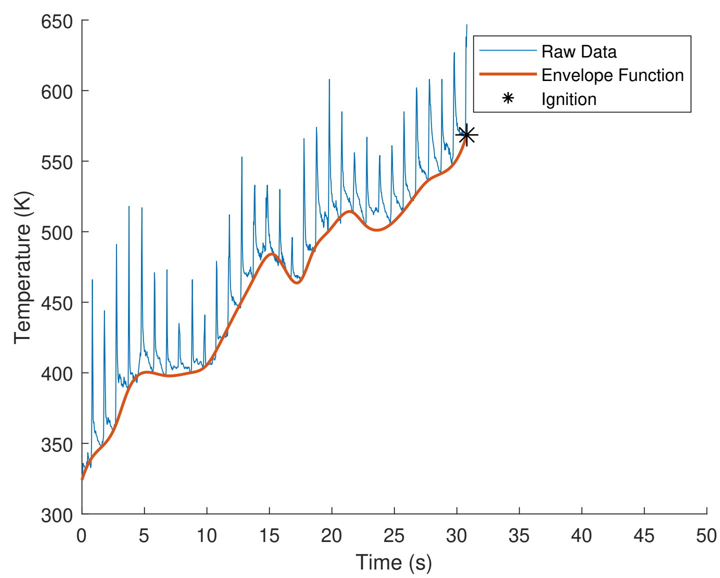

Figure 4.3: Selection of lower temperature points observed on the surface of a pine needle from an IR recording through the envelope function in MATLAB

4.3 Test Conditions

The majority of testing was conducted on pine needles in ambient conditions, which had moisture contents ranging from 42-51% and needles that had been dried sufficiently to achieve a moisture content value of 1-2%.

A challenge in dealing with live fuels is the innate variability present in live fuels on a physical, chemical, and molecular basis. During testing, visible off-gassing of the live needles was often observed prior to ignition and is shown in Figure 4.4. Differences in the temperature of the fuel at ignition between cases could be due to the amount of moisture or ethers that were evaporated prior to ignition. In cases in which the needles were situated past the critical distance for ignition, off-gassing was observed without visible ignition. In these situations, the moisture content of the unburned needles was again analyzed after testing and was found to have between 8 and 13% moisture content. This indicates that a certain amount of the moisture previously present in these needles had evaporated without prompting ignition of the needles.

During numerous tests, one of the three needles from the fascicle was observed to either break or become unsecured and dip down towards the standing flame at the top of the Rubens' tube. This needle ignited more quickly than the rest of the sample, and the flame from this portion was often seen to serve as a pilot ignition source to the rest of the fascicle, causing ignition through direct exposure to flame instead of the intermittent convective heating. This form of inconsistent ignition through piloted ignition is seen in Figure 4.4.

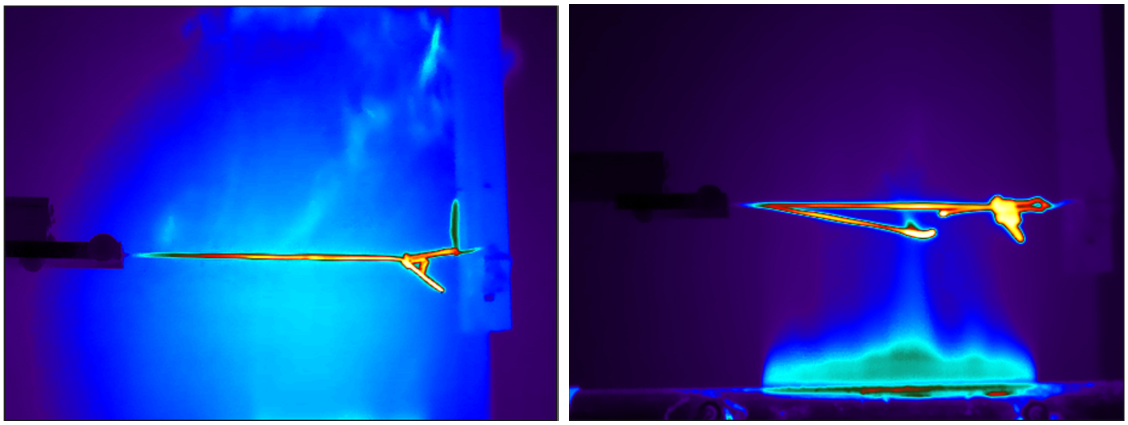

Figure 4.4: Infrared frames showing potential complications during testing including needle off-gassing during experiment (left) and broken needles leading to piloted ignition (right).

These challenges in dealing with live fuels can serve as a road map for improvements to future experimentation. More work on the selection and preparation of live fuels to gain more accurate repeatability in live fuel tests as well as tests on individual needles is needed to further understand the heating and ignition mechanisms of these fuels.

Tests that showed clear and simultaneous ignition near the center of needles were chosen for analysis and accepted as reliable data, whereas cases of no visible ignition or single-needle ignition were ignored. It should be noted that due to unprecedented global circumstances, testing was only partially completed for this paper. The number of tests with clear visible ignition and the corresponding limit heights found for each testing scenario are outlined in Table 4.3-1.

Tests were conducted under a hood in an ambient space, and efforts were made to limit the amount of interference to the flame buoyancy by air movement in the

Table 4.3-1: Successful number of ignition tests for each condition and their corresponding limit heights (LH)

MC	0.5 Hz		1 Hz		3 Hz		5 Hz	
	LH	Ignitions	LH	Ignitions	LH	Ignitions	LH	Ignitions
1%	10 cm	5	10.5 cm	17	10.5 cm	5	14 cm	6
28%			9.5 cm	4	9.5 cm	7		
47%	8 cm	8	9 cm	24	9 cm	8	10 cm	10

lab space. However, cases were seen where the flame flow was pushed back behind the fuel suspended over the tube by ambient airflow. These conditions often led to late, messy, or no ignition and were also ignored in the analysis. Future testing should make efforts to reduce the impeding airflow during experimentation.

4.4 Test Results

An overall summary of tests can be seen in Table 4.4-1. Important variability and conclusions can be drawn from the ignition results across both pulsation frequencies and fuel moisture content. Test results are categorized and summarized accordingly in the following sections. First, the behavior of the fuel at different moisture contents is examined for each frequency. Next, trends are examined for the same moisture contents across different pulsation frequencies.

All tests were conducted with fuels at both ambient conditions and dried conditions with moisture contents averaging 47% and 2% respectively. More tests were

Table 4.4-1: Average time to ignition (t_{ig}) and temperature at ignition (T_{ig}) for each test condition at their corresponding limit heights (LH)

MC	0.5 Hz		1 Hz	
	t_{ig} (s)	T_{ig} (K)	t_{ig} (s)	T_{ig} (K)
1%	32.34 ±19.2	462.5 ±34.1	14.8 ±5.9	574.9 ±30.3
28%			33.8 ±12.1	562.8 ±48.5
47%	29.8 ±7.1	488.8 ±40.7	46.8 ±16.7	496.1 ±42.1
MC	3 Hz		5 Hz	
	t_{ig} (s)	T_{ig} (K)	t_{ig} (s)	T_{ig} (K)
1%	15.4 ±7.1	549.5 ±57.8	18.4 ±9.4	601.2 ±46.6
28%	16.5 ±4.2	605.1 ±28.4		
47%	35.2 ±9.6	540.3 ±27.5	26.5 ±15.5	529.9 ±34.5

planned at intermediate moisture contents, but due to unprecedented and uncontrollable circumstances, only two frequencies were able to be tested at intermediate moisture contents. The results of testing needles with an average 28% moisture content are included in the results for 1 Hz and 3 Hz tests and are discussed in their corresponding sections. For each frequency condition, plots of multiple tests at each moisture condition show the variability and trends of successful ignitions. Additionally, for each moisture content and frequency condition, a representative test was chosen that closely resembles the average of the results for that condition. These representative plots for each moisture condition are compared within the same frequency, and then in a later section representative plots of the same moisture content are compared across frequencies. The point of ignition is symbolized on all plots as an asterisk symbol (*). Noticeable trends in results are outlined, while comparisons to literature values and current models are discussed in the following chapter.

4.5 Results by Frequency

Pine needles were exposed to flame pulsations at 0.5 Hz for the first set of tests. This frequency is characterized by a pulsation "on-time" of approximately 0.1 seconds and an "off-time" of 1.9 seconds per period. This test condition was the lowest frequency of intermittent heating tested and had some of the highest ignition times (t_{ig}), while having some of the lowest recorded ignition temperatures (T_{ig}).

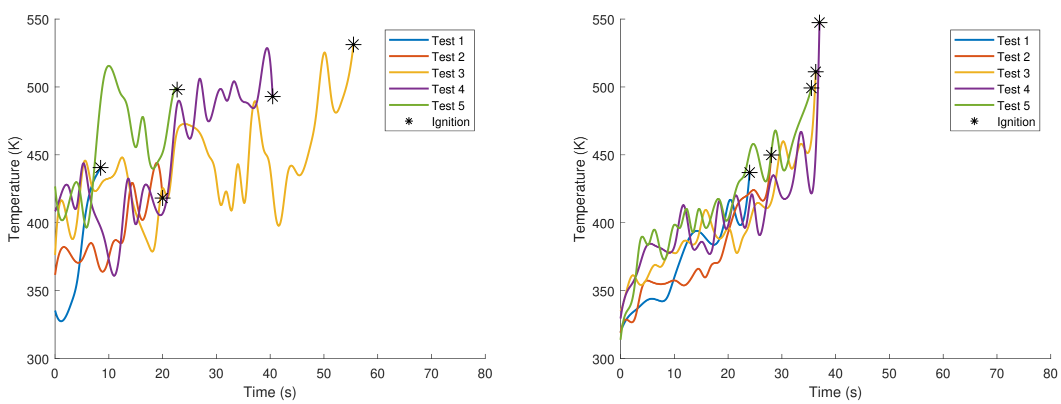

Figure 4.5: Data for multiple tests at 0.5 Hz for dried conditions (left) and ambient conditions (right)

Ambient tests were conducted at a moisture content of 44% and had an average ignition time of 29.8 seconds for 8 successful ignition tests. Ignition for the dried samples with a moisture content of 3% occurred at an average time of 32 seconds from 5 tests. The results of two tests that closely represent their corresponding average results can be seen in Figure 4.6, and the variability between numerous tests can be seen in Figure 4.5. As seen in Figure 4.5, the results from dried needles burned at 0.5 Hz showed high variability both in the time to and temperature at ignition. However, trends in the ambient test results for 0.5 Hz show similar trends to the process of heating until ignition. As described by Finney, a stair-step process of convective heating and cooling can be seen in the data, despite the variability in the ignition temperatures and times [28].

As stated in the previous section, the limit height (LH) for each frequency and moisture content was determined as the highest point above the intermittent convective flame source that ignition could be repeatedly obtained in tests. For these tests, a limit height of 8 cm and 10 cm were determined for the ambient cases and the dried cases respectively. At these limit heights the temperature difference, ΔT, between ambient conditions and the peak flame temperature passing over the fuel was determined. Much like the results for ignition time, the ΔT observed during 0.5 Hz experiments also varied with moisture content, with dried needles igniting with a height corresponding to 707 K and ambient needles igniting at a lower height but a higher characteristic ΔT of 837 K.

For the 1 Hz test scenario, a pulsation on-time of 0.1 seconds was used, followed by an off-time of 0.9 seconds per period. Three moisture content values were evaluated at this frequency. Twenty-four ambient tests were done with a moisture content of 47% and resulted in an average ignition time of 46.8 seconds. The mid-dried conditions were tested at a moisture content of 28%, and resulted an average

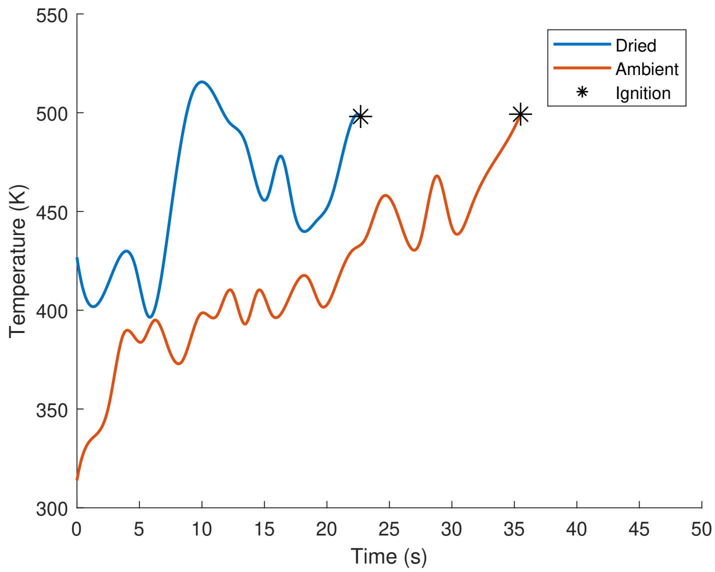

Figure 4.6: Representative results for 0.5 Hz ignition tests at each moisture content

ignition time of 33.8 seconds from 4 tests. Dried conditions at 1 Hz had a moisture content of 1% and an average ignition time of 14.8 seconds. Seventeen tests ignited successfully for dried samples at this height. Multiple tests for each moisture content are shown in Figure 4.7.

Despite significant differences in the time to ignition for dried fuels, the temperature of ignition for dried tests were all similar to the average seen in Table 4.4-1. Large variability was seen in the mid-dried conditions and would require further tests to establish a reliable average for this moisture content. Ambient tests very clearly demonstrated the same stair step heating seen in 0.5 Hz ambient tests. Three tests had very similar lower times and temperatures at ignition, while six ignitions occurred at higher temperatures and times. The representative plots of the average results for each testing condition are compared in Figure 4.8. The average ignition temperatures for all three fuel MCs tested at 1 Hz were similar. They followed

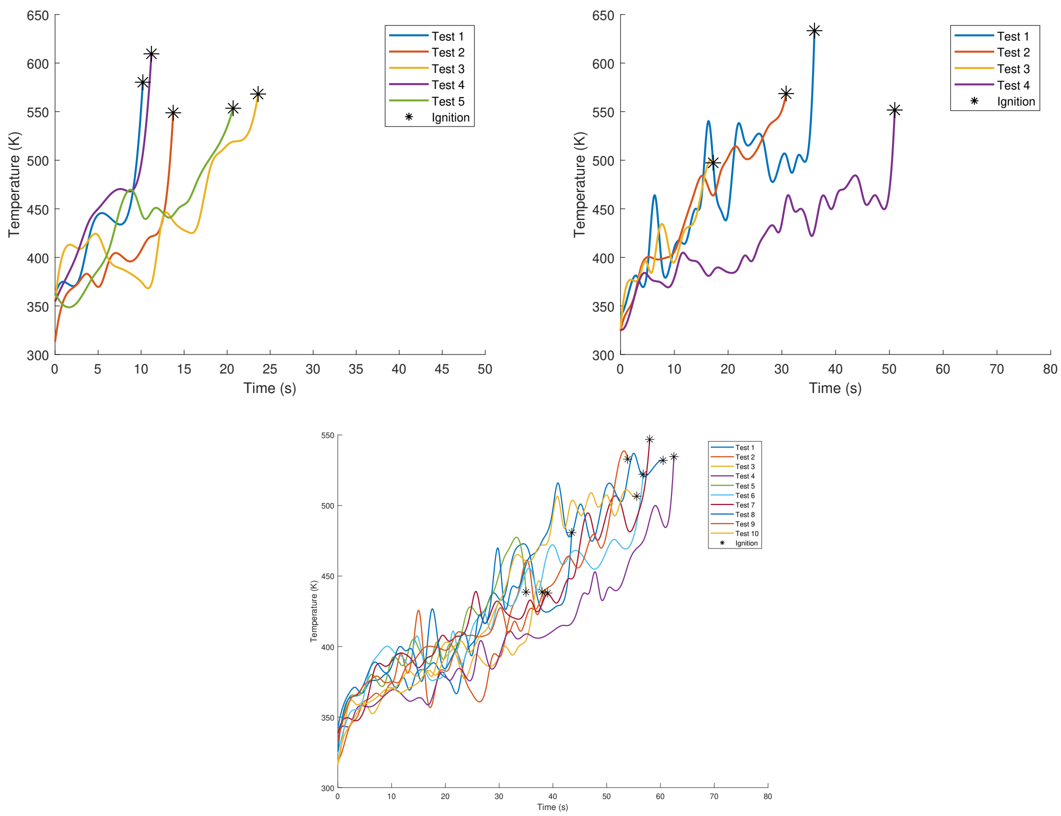

Figure 4.7: Data for multiple tests at 1 Hz for dried conditions (left) mid-dried conditions (right) and ambient conditions (bottom)

the pattern observed in the 0.5 Hz tests of dried fuels, with dried needles having the shortest time to ignition, mid-dried needles taking longer, and ambient needles requiring the most time to ignite on average.

The limit heights for ambient, mid-dried, and dried conditions was determined to be 9 cm, 9.5 cm, and 10.5 cm respectively. Similar to the 0.5 Hz limit heights, the farthest distance of ignition from the burner is inversely related to the moisture content of the fuel, with the higher moisture content corresponding to the lowest limit height. The ΔTs observed at these limit heights are in agreement for the ambient and dried cases, with values of 844 K and 853 K respectively, despite igniting at heights 1.5 cm apart. Conversely, the mid-dried needles burned at a limit height between those of ambient and live needles, but had a ΔT of 669 K, which is much lower than the other moisture contents at this heating frequency. More testing would be required to determine whether this is a verifiable trend or a result of minimal testing.

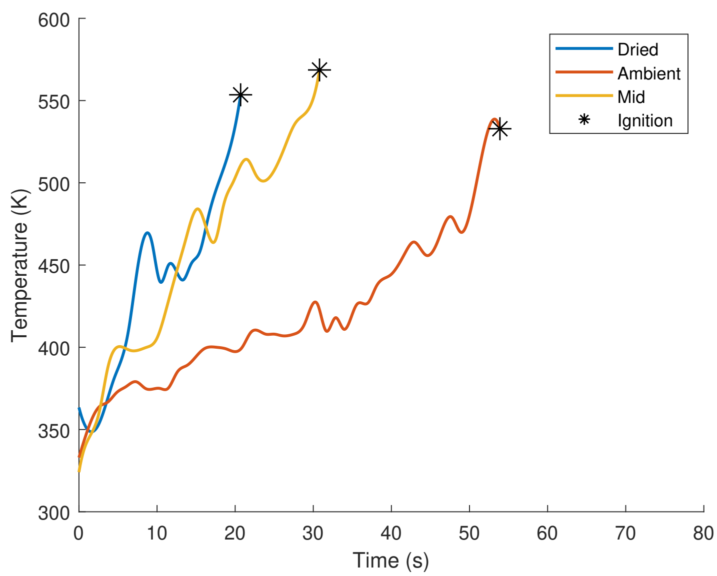

Figure 4.8: Representative results for 1 Hz tests at each moisture content

Tests at 3 Hz were also run for three different moisture contents. For this frequency, an on-time of 0.1 seconds was again used, while an off-time of 0.243 seconds was used per period. The results are found in Table 4.4-1.

Multiple tests for each moisture content are shown in Figure 5.5 to visualize the variability between tests. Ambient needles had an MC of 51% and an average ignition time of 35.2 seconds from 8 tests. Mid-dried conditions with a MC of 28% had 7 successful tests with an average ignition time of 16.5 seconds. The fully dried

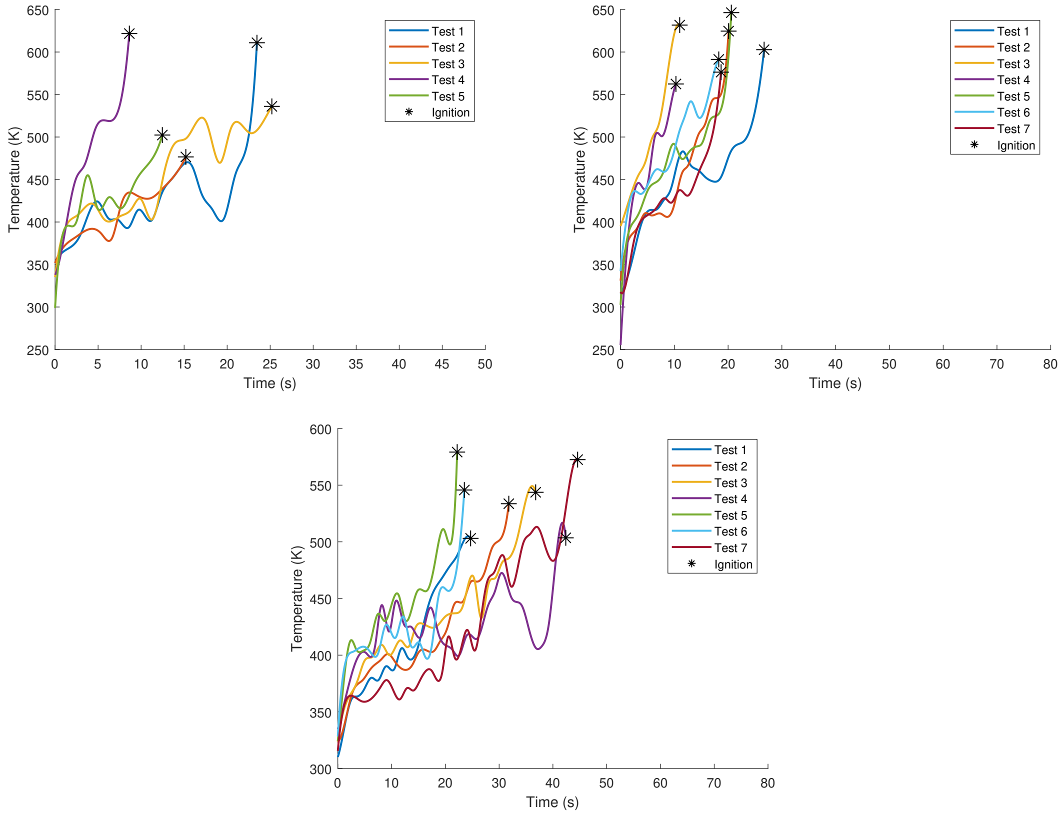

Figure 4.9: Data for multiple tests at 3 Hz for dried conditions (left) mid-dried conditions (right) and ambient conditions (bottom)

needles were tested 5 times at an MC of 3% and an average ignition time of 15.4 seconds.

In the case of 3 Hz testing, dried conditions showed large discrepancies in both the time and temperature at ignition. Results for t_{ig} varied by as much as 25 seconds, while the differences in ignition temperatures were as much as 150 K. In contrast to the mid-dried moisture content tests at 1 Hz, there is significantly more agreement in the fuel surface temperature leading up to ignition for the tests done at a 3 Hz frequency. Needles tested at an ambient moisture content at 3 Hz showed more variability than the mid-dried needles. Some of these live needles ignited at times and temperatures close to those seen in mid-dried needles, while others took much longer. The range of ignition temperature values found at both the mid-dried conditions and the ambient conditions varied within 100 K, with the mid-dried conditions having higher overall ignition temperatures.

Limits heights and their corresponding ΔT values were found for each testing condition at 3 Hz. Representative tests that closely resemble the average results are shown in Figure 4.10. Ambient needles once more had the lowest limit height of all moisture contents at 9 cm above the burner, while having the highest temperature difference at 759 K. The limit height for mid-dried needles was found to be 9.5 cm and resulted in a ΔT of 640 K. Agreeing with the inverse relationship seen in the 0.5 Hz tests, the dried needles had the highest limit height at 11 cm, and the lowest ΔT of 610 K of all the moisture contents at this heating frequency.

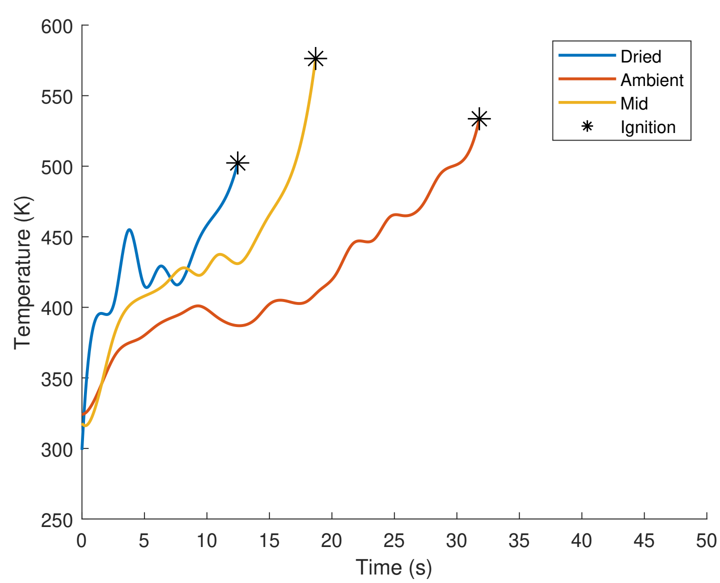

Figure 4.10: Representative results for 3 Hz tests at each moisture content

As is seen in Figure 4.10, the same trend of lower moisture contents correlating to lower ignition times, higher limit heights, and lower temperature differences is seen for 3 Hz heating as well. The average ignition temperatures for all three moisture contents vary around 550 Kelvin.

The highest frequency of intermittent heating evaluated in this study was 5 Hz, with equal on-times and off-times of 0.1 seconds per period. Ambient and dried needles were tested with moisture contents of 47% and 1% respectively. For the needles at ambient conditions, an average t_{ig} of 26.5 seconds was determined over 10 tests. Dried needles ignited during 6 trials at an average ignition time of 18.4 seconds. The variability of numerous tests can be seen in Figure 4.11, and average results are shown through representative tests in Figure 4.12.

Dried needles ignited at the 5 Hz heating frequency resulted in some of the highest ignition temperatures out of all conditions tested. Ambient needles at this frequency had the shortest average time to ignition of all the live needles tested. Agreement of the surface temperatures during heating was observed more frequently with the dried samples than with the live needles at this frequency. Ambient conditions show a wide variability both in the time to ignition and the temperature of ignition.

For the 5 Hz heating frequency, limit heights of 11 cm and 14 cm were established for ambient and dried needles respectively. Again, higher fuel moisture contents are seen to correlate with lower limit heights and higher temperature differences, with ambient needles having a ΔT of 711 K and dried needles only 600 K.

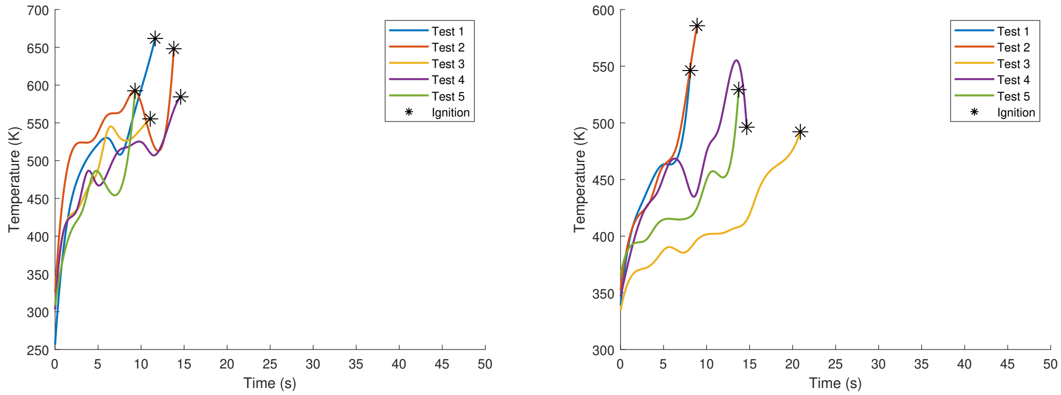

Figure 4.11: Data for multiple tests at 5 Hz for dried conditions (left) and ambient conditions (right)

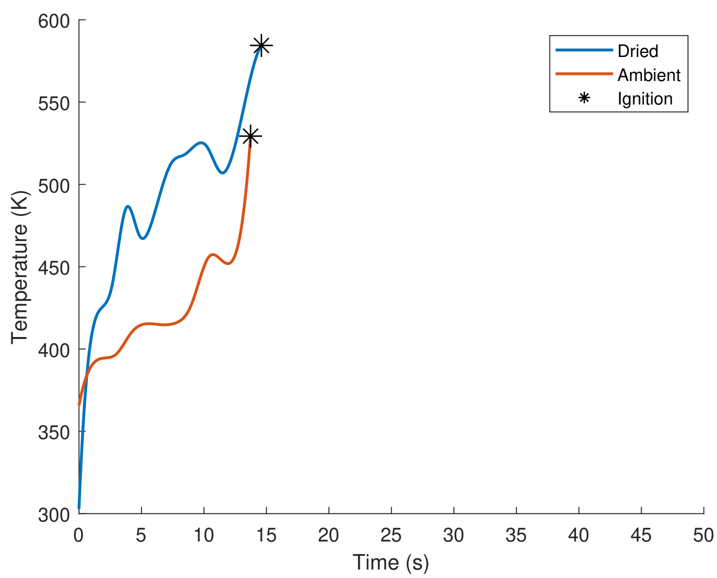

Figure 4.12: Representative results for 5 Hz tests at each moisture content

4.6 Results by Fuel Moisture Content

The results for ambient moisture content conditions were compared across all frequencies. The tests summarized in Figure 4.13 are the same representative tests included in the figures in previous sections, but have been compiled for ease of comparison. All heating frequencies except for 0.5 Hz had very similar ignition temperatures of around 520 K, while the 0.5 Hz had a T_{ig} of around 480 K. All else being equal, there is no statistical significance for the average temperature of any ambient ignition tests at a 95% confidence integral due to limited sample size. In regards to ignition time, higher frequencies had lower ignition times on average, except for the case of 0.5 Hz frequency. It is not clear at this time why the ambient needles behaved differently than expected at the 0.5 Hz heating frequency. More testing, including testing at intermediate moisture contents for 0.5 Hz heating frequency, would further the understanding of this behavior. The similarities of ignition temperature for ambient needles at the other frequencies indicate that the T_{ig} value for live Ponderosa pine needles, that is needles with moisture contents between 47% and 52%, is around 530 K when exposed to convective heating and cooling.

In a similar way, representative results for all dried conditions have been compiled and summarized in Figure 4.14. In contrast to the ambient results, the average behavior of the dried needles shows less unity in regards to ignition temperature. Additionally, the time to ignition shows no correlation to the frequency at which each moisture content was tested. It should be noted, however, that less tests were run for dried needles than those at ambient conditions. Further testing of dried needles when exposed to this intermittent method of convective heating would likely shed light on the behaviour of these fuels at different frequencies.

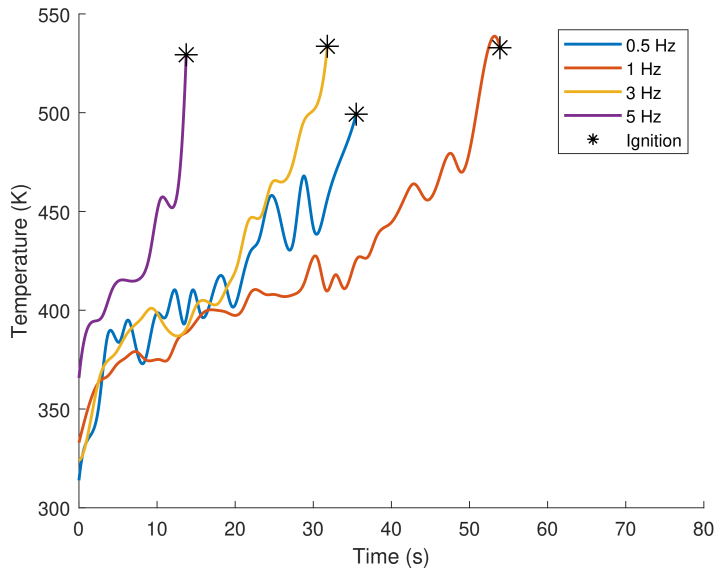

Figure 4.13: Summary of median results through representative tests for all tests with ambient fuel conditions

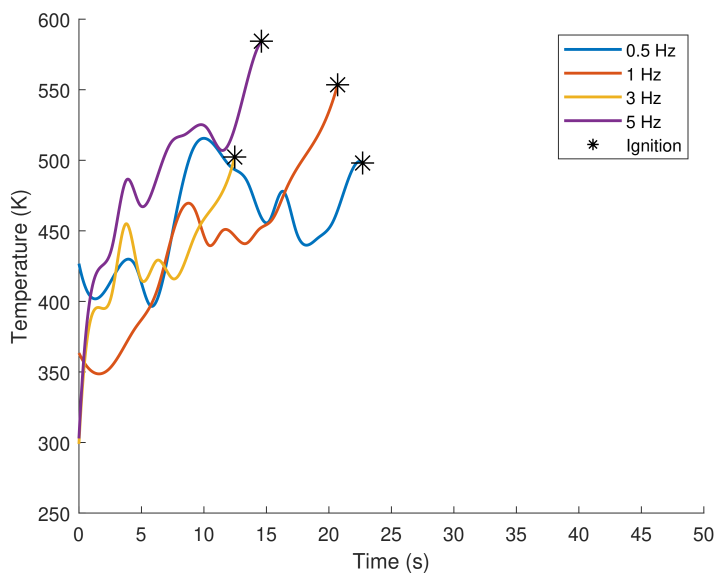

Figure 4.14: Summary of median results through representative tests for all tests with dried fuel conditions

Chapter 5

Discussion

The comparison of experimental results to previous work on the heating of fine wildland fuels provides insight into the behavior governing fire ignition and spread as well as highlighting deficiencies within current theory and models. The effect that intermittent convective heating and moisture content have on ignition temperature, ignition time, and limit height are compared to results from past studies as well as current predictive models in the following sections.

5.1 Temperature Dependence on Ignition

Previous research has used the concept of an ignition temperature to define the amount of energy a fuel must absorb prior to pyrolyzation and subsequently, ignition [10]. In live fuels, moisture content has been seen to affect the rate of evaporation, as well as the observed dynamics of "bursting" involved in the ignition processes. Some models account for this by approaching ignition temperature as including a variable fuel moisture content, while others use one ignition temperature to define an entire fuel. Stockstad found that the ignition temperature of Ponderosa pine varied by as much as 50 K between a 0% moisture content and 33% moisture content [45]. Work by Xanthopoulos confirmed this variance with moisture content, but found that the range of temperatures for ignition lay between 673 K and 713 K, which was higher than any temperature observed during testing [44]. This discrepancy is likely due to the constant convective heating used in their tests as compared to the intermittent testing used here. In their previous work, Benny defined Ponderosa pine as having a T_{ig} of 553 K, disregarding the moisture content.

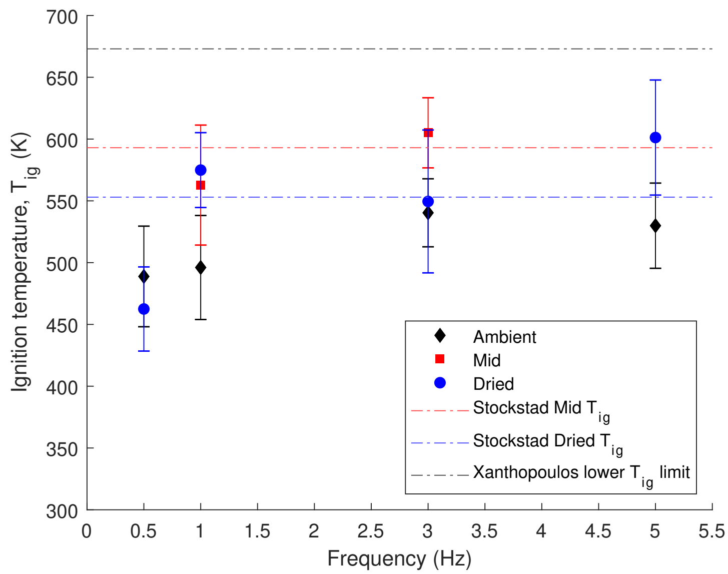

Figure 5.1: Average ignition temperatures for all conditions compared to literature ignition temperatures [45]

Test results show similarities within the temperature of ignition for fuels across differing frequencies and in some cases between moisture contents. As shown in Figure 5.1, ambient tests had a trend of a lower than average ignition temperature across all frequencies. The distinction between the mid-dried and dried cases is not as clear. All else being equal, compared to ambient tests at 1 Hz frequency, the difference in mean temperature for dried tests at the same frequency is statistically significant at a 95% confidence integral. Also, all else being equal, compared to mid-dried tests at 3 Hz frequency, the difference in mean temperature for ambient tests at the same frequency is statistically significant at a 95% confidence integral. Lastly, all else being equal, compared to dried tests at 5 Hz frequency, the difference in mean temperature for ambient tests at the same frequency is statistically significant at a 95% confidence integral. There are no other statistically significant differences of mean temperatures for each frequency across moisture contents due to sample size. Mid-dried ignition at 3 Hz frequency is seen to ignite at nearly the same temperature as fully dried tests at 5 Hz. Therefore, it is likely that the moisture content not only affects the temperature at ignition, but it may also be affected by the rate at which the fuel is heated in the cases of intermittent convection. This agrees with the conclusions by Spearpoint and Quintiere, where lower rates of heating showed variation in ignition temperatures of thermally thick fuels until a heating threshold was reached [11]. In their work, this threshold was determined to be approximately 20 kW/m^2 of constant radiative heating. While the amount of heating in experiments using the Rubens' tube is calculated to be above this threshold, heating is accomplished in intermittent bursts, allowing for bursts of convective heating followed by periods of convective cooling. Calculations of the intermittent heating using the Nusselt correlation for flow over a cylinder resulted in an approximate convective heat flux of 41.6 kW/m^2. This number varies from the constant heat flux found by Spearpoint in that samples in this study experienced varying frequencies of periodic heating and cooling during testing. The variance in ignition temperatures between different heating frequencies as seen in Figure 5.1 is therefore similar and comparable to the trends seen in the tests with lower heat fluxes by Spearpoint and Quintiere [11]. In their work they identified an ignition temperature maximum occurring around their threshold heat flux before the observed T_{ig} of tests plateaued to a constant value. Whether this same peak is observed in intermittent convective tests requires further testing at more numerous frequencies in order to establish a definite visible trend among tests of various moisture contents.

5.2 Comparison to Dead Fuel Tests

In their work, Benny sought to characterize the behavior of various dead fuels when exposed to intermittent convective heating [23]. This thesis expanded on that work by incorporating live fuels. Therefore, a comparison between the results of the two studies provides insight into the differences of ignition behavior between live and dead fuels when exposed to convective heating comparable to that found in wildland fires. The ignition times, temperatures, and the limit heights established for fuels in both studies are compared in Figures 5.2 and 5.4.

The limit heights shown in Figure 5.2 show a slight trend with increasing frequency. As described in Section 3.4, the limit height tests were performed at each frequency both to match the ΔT from hot gases and determine the maximum height at which ignition could occur at different frequencies. The increasing limit height with increasing frequency may be due to the fact that the peak temperatures experienced with pulses tended to decrease with higher frequencies, shown in previous work by Benny [23]. This is seen in Figure 5.3 by the correlation that the increasing limit height maintained the characteristic ΔT of approximately 700 K across frequencies and moisture contents. This behavior is useful in identifying the difference

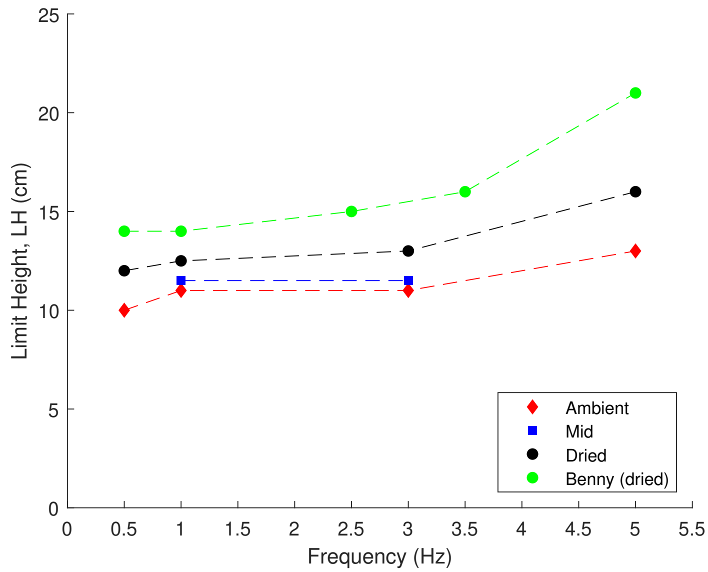

Figure 5.2: Ignition limit heights for all conditions tested compared with limit heights found for dead dried Longleaf pine by Benny [23]

between the ignition and no-ignition zones for each test condition.

Their work similarly showed an increasing limit height with increasing frequency, while the ΔT corresponding to each limit height was seen to decrease with increasing frequency. Benny tracked the temperature difference of fuels at their characteristic limit heights for dried basswood at numerous sizes. The smallest samples tested had a thickness of 0.08 cm, which is smaller than the thickness of a fascicle of pine needles. The comparison between the basswood results seen in Figures 5.2 and 5.3 and the experimental results from the pine tests show the same trends with increasing heating frequency. The presence of chemicals and extractives that likely are found within the cell walls of pine needles, even under dried conditions contribute to the disparity of results between the live dried needles and the dead dried basswood samples. However, the results from Benny's tests show the exaggerated relationship

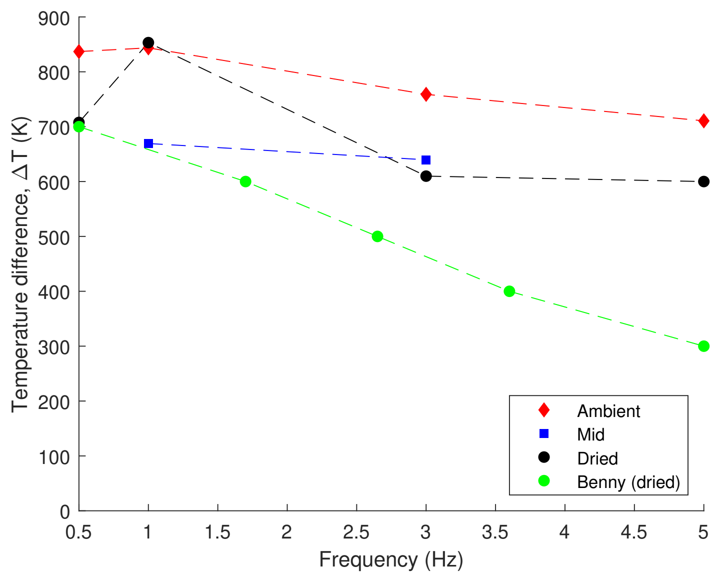

Figure 5.3: Temperature differences between minimum fuel and flame sheet temperatures across all tests at their limit heights including comparisons to results from Benny of longleaf pine [23]

of high moisture contents to high temperature differences and lower limit heights. This correlation of higher fuel moisture contents to lower limit heights could be contributed to the chemical makeup of these fuels, pre-ignition off-gassing, stability during testing, or other unknown factors. More testing will be required to further understand this observation.

5.3 Time to Ignition Correlations

Ignition times from Benny's experiments on dried pine needles are shown in Figure 5.4 and show a much more drastic drop in the ignition times with a rise in heating frequencies than those found in current experiments [23]. It should be noted

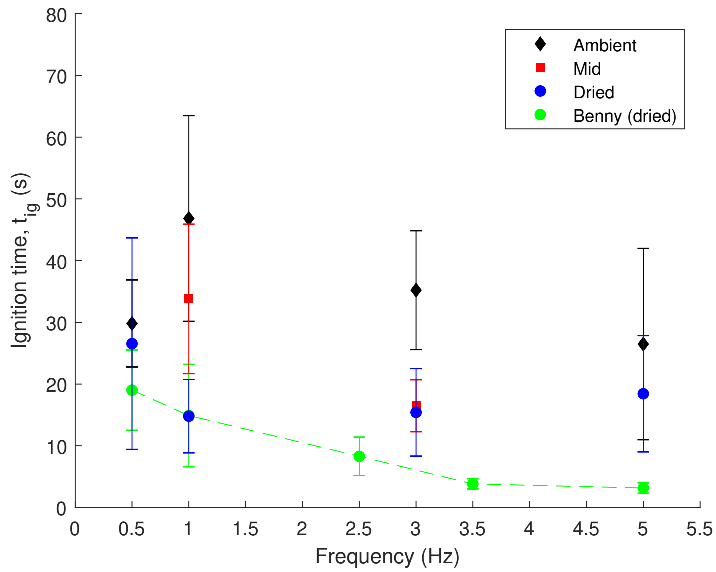

Figure 5.4: Average ignition times of fuels tested at various moisture content and frequencies compared to experiments done by Benny of dead dried Longleaf pine needles [23]

that the dried needles used in Benny's experiments were Longleaf pine that had been dried and stored over an extended period of time and had a brown coloration. Those fuels can be considered dead and dried, while the fuels used in these experiments were initially live and then dried for a controlled amount of time as well as of being of different species. The differences in ignition times between these two fuels is likely indicative that the chemicals present in live needles and differences between species, even at lower moisture contents, effect ignition behavior in these fuels and the manner in which moisture evaporates from them.

The steep decline of ignition times in lower temperatures for all moisture contents is seen to reach a plateau as the heating frequency increases. As the heating frequency increased, the cooling period between flame bursts decreased, and this

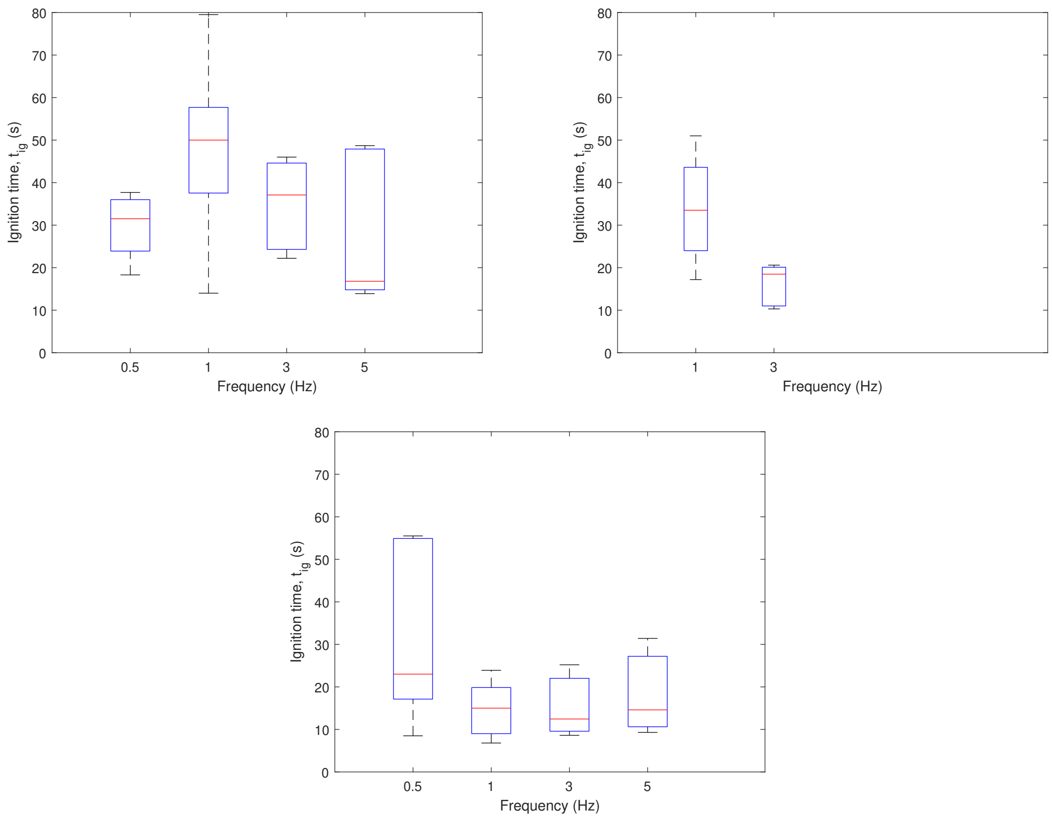

Figure 5.5: Box plots showing the distribution of the ignition times of fuels tested at various moisture contents and frequencies for ambient (top-left), mid-dried (top-right), and dried (bottom) moisture contents.

plateau is likely conforming to the ignition time that would be found through constant convective heating. Tests of time to ignition for Ponderosa pine needles at these moisture contents was not conducted, but would provide necessary validity to this observation.

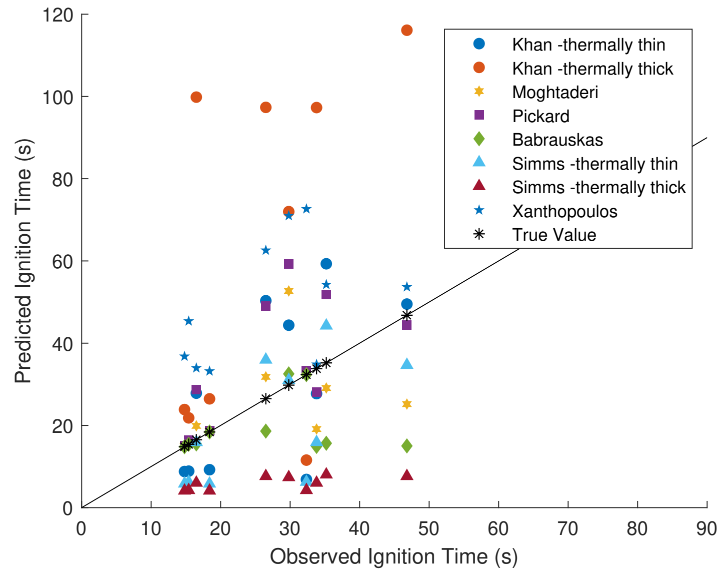

Figure 5.6: Regression model for time to ignition predictions from literature [51, 52, 53, 41, 43, 44]

5.4 Regression Models

As part of their work studying the piloted ignition of live fuels, McAllister used a small wind tunnel to run piloted ignition tests of live Lodgepole and Douglas fir pine needles [22]. The ignition results were then compared to a number of models that accounted for fuel moisture content in their calculations. Some of the models were empirical, while others relied on knowledge of species-specific thermal properties. A linear regression model was then used to compare the predictions of these models to the experimental values found by McAllister [22]. None of the models evaluated were created specifically for either of these species of fuel, so the applicability of each of these models across various live fuels is an important consideration moving forward in the pursuit of a more sound theory of wildland fire ignition and spread.

The same models used by McAllister have been applied in this study using species-specific properties found experimentally and in literature, as listed in Table 4.1-1, to estimate the time to ignition for Ponderosa pine needles with various moisture contents [23]. In these comparisons, the ignition time is predicted through fuel moisture content on a dry mass basis instead of the wet mass basis used elsewhere in this study. The models were originally developed using this descriptor for moisture content, therefore it is used in these calculations.

The model proposed by Moghtaderi included moisture content as a variable within a quadratic expression for the time to ignition along with the dry ignition time for the same conditions [52].

$$t_{ig,MC}(s) = t_{ig,dry}(1 + 0.35MC)^2 \tag{5.1}$$

Although Moghtaderi's model as seen in eqn. 5.1 is less complex in the variables it requires than other models in comparison, more agreement was found between these results and Moghtaderi's predictions than was found by McAllister in their piloted ignition tests [22]. A summary of predicted ignition times from Moghtaderi's model and others can be seen in Figure 5.6 in comparison to the experimental ignition times found using the Rubens' tube. For most experimental ignition times, Moghtaderi under-predicted the ignition times overall, but the predictions were more accurate with lower moisture contents.

As stated previously, pine needles are considered to be thermally intermediate in terms of heat transfer dynamics, and so in the case of Simms et al. and Khan et al., both thermally thin and thermally thick calculations were performed [40]. The Simms et al. model used fundamental equations for heat transfer and adjusted the thermal properties of density, specific heat, and thermal conductivity to account for the moisture content and species of fuel [43]. Additionally, work done by Janssen was integrated into the model to calculate the ignition temperature of the fuel in terms of moisture content and was included as a part of Simms' calculations in order to account for gas-phase effects [54]. Even with thermal properties and the ignition temperature being changed to match the specifications of moisture content, the Simms' model consistently under-predicted the ignition times. Predictions using the thermally thin equations were closer than the thermally thick equations in the case of Simms et al. and Khan et al. as well. Khan et al. used a similar approach to Simms et al. and accounted for the moisture content by calculating the ignition delay for the fuel [51]. This is seen in equations 5.2 and 5.3

$$t_{ig,thin} = \frac{\rho_o c_o [1 + \gamma(MC/100)] d(T_{ig} - T_o)}{\alpha_s \dot{q}"_e - \dot{q}"_{loss}} \tag{5.2}$$

$$t_{ig,thick} = \frac{\pi k_o \rho_o c_o [1 + 8.1(MC/100)](T_{ig} - T_o)^2}{(\alpha_s \dot{q}"_e - \dot{q}"_{loss})^2} \tag{5.3}$$

where

$$\gamma = \frac{c_w(T_b - T_o) + \Delta h_{vap}}{c_o(T_{ig} - T_o)} \tag{5.4}$$

Here ρ, k, and c represent the fuel density, thermal conductivity, and the specific heat capacity of the fuel respectively. The fuel absorptivity, α, and thickness, d, are used in this calculation along with the fuel moisture content, ignition and ambient temperatures and the applied and net heat flux. Khan's predictions for thermally thick fuels greatly over-predicted the ignition times, while the predictions for thin fuels were slightly under-predicted, but still some of the closest out of all the models.

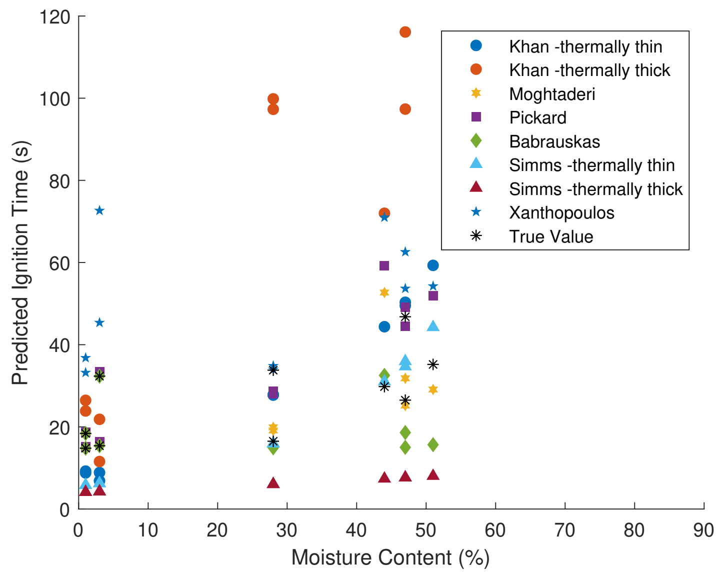

Figure 5.7: Model ignition time predictions for each fuel moisture content tested

Pickard assumed that ignition and evaporation occur as separate events and are modeled using separate terms for each, as seen in equation 5.5.

$$t_{ig,MC} = t_{ig,dry} + \frac{\Delta h_{vap} d\rho_o MC}{\alpha_s \dot{q}"_e} \tag{5.5}$$

Here Δh_{vap} represents the latent heat of vaporization of water. This approach works only with lower moisture content and loses accuracy when used to evaluate higher moisture contents [53]. In equation 5.6, Babrauskas proposed a slight change to the calculation of Pickard that assumed only a fraction of the fuel moisture evaporated prior to ignition [41].

$$t_{ig,MC} = t_{ig,dry} + \frac{[33,200(\dot{q}"_e)^{-2} - 8.7]d\rho_o MC}{\alpha_s \dot{q}"_e} \tag{5.6}$$

Xanthopoulus developed empirical models for the prediction of ignition time by looking at the time to ignition, temperature, and moisture content relationship of three coniferous species including Ponderosa pine [44]. Their calculations are seen to only slightly over-predict the ignition time for all moisture contents except for the mid-dried conditions, with moisture contents of 28%, where its predicted ignition times for the 1 Hz condition and 3Hz condition are over-estimated by 1 second and 17 second respectively. Despite being an empirical formula developed specifically for Ponderosa pine, this model fails to calculate the ignition times at both low and high moisture contents.

While many of these models are accurate for some moisture contents, no individual model proves reliable across all moisture contents tested. This is likely due to the fact that these models were developed either for different fuel types, or for situations that didn't correctly account for intermittent convective heating of the fuels. As discussed previously, most models rely on radiation or constant convection as the main form of heat transfer, while these experiments sought to investigate the effect of intermittent convective heating. The needles in these experiments experienced short periods of convective heating followed by a period of convective cooling. It is likely that this extended the time to ignition of the fuel past that which has been seen in constant convective heating.

The inaccuracy of predicted ignition times of these models when compared to experimental ignition times of fuels when exposed to convective heating highlights the need for a better physical understanding of wildland fires. Convective heating has been seen to play a significant role in the spread of wildland fires, yet current models are unable to satisfactorily consider this in their predictions.

5.5 Impacts of Study on Theory

The inability of current models to accurately account for the ignition times and temperatures determined experimentally point to the need for a further understanding behind the heat transfer and ignition processes during wildland fires. Most models account solely for radiation, and those that factor in the effects of convection do so minimally. Intermittent convection creates further complexity within this process by alternatively heating and cooling the fuel in the process of heating to ignition. Lack of understanding of this process and its interaction with live fuels is evident in the disparities of predictions by current models. While this study does not propose a new empirical model or method for these predictions, it provides much needed insight and information on the basics of the intermittent convective heating of live fuels to the point of ignition. Hopefully, this will lay the foundation for further work and insight that will pave the way for future models.

Chapter 6

Conclusion

This study sought to expand on the information known about the ignition behaviour of fine wildland fuels. While no new model is suggested for the analysis of Ponderosa pine or any other fuels ignition characteristics, new insight has been provided through the experiments performed. Other work has evaluated this fuel when exposed to radiation and constant convection as live or dead fuels. This work is the first to evaluate numerous fuel moisture contents when exposed to a method of intermittent convective heating. The alternating heating and cooling caused by the Rubens' tube mimics the spread and bursting phenomena of a wildland fire in an effort to provide a more accurate picture of expected behavior.

Trends seen in the experimental ignitions indicate that the ignition temperature of live fuels is a function not only of the moisture content of the fuel, as proposed by Xanthopoulos, but also is dependent on the method of heating [44]. Constant heating through radiation, convection, or both, can cause a higher fuel surface temperature by the time of ignition than a fuel that undergoes intermittent heating leading to ignition. Additionally, comparison to work on dead needles done by Benny demonstrated the differences in ignition times between dead needles and dried needles with the same moisture content. This further established the need for natural moisture content in testing instead of traditional conditioned moisture content. Across all heating frequencies, stair step heating to ignition was observed. Fuel with lower moisture contents had a sharper incline to ignition temperature resulting in less time to ignition. This pattern of increasing time to ignition with increasing moisture content was observed in all heating frequencies, while the ignition temperatures did not vary as predictably or drastically.

6.1 Future Work

These experiments were limited by time, and therefore trends identified should be reinforced through further experiments with the same conditions. Unlike previous work by Benny, variation existed between the test conditions, and trials and comparisons across heat fluxes at the same height for all fuels should be conducted. Once this point is reached, the way forward is clear and three-fold. First, more experiments must be conducted on this same fuel at more intermediate moisture content levels and throughout the growing season of Ponderosa pine to determine how big of an impact seasonal changes have on this fine fuel. The scope of this study originally included more tests, to further confirm results as well as investigate additional intermediate moisture contents. However, unprecedented events prevented further lab work from being complete. Once the ignition behavior under convective heating is better understood, the next step involves moving from the scale of individual fascicles of needles to exploring the spreading behavior along entire branches of live foliage when exposed to intermittent convective heating. Thirdly, the use of a surrogate material such as steel or copper rods should be tested to further understand the heating dynamics of a small stick shaped object when exposed to intermittent convective heating. These tests would provide data necessary for the creation of a model that incorporates the heating dynamics of a fuel of this size and shape through Nusselt correlations. This study was one small piece in a vast and dynamic puzzle that is the behavior of wildland fires. Future work on the convective intermittent heating of fine wildland fuels will further aid in the creation of models that are more accurate, more theoretically sound, and more versatile for the future.

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