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HEAT TRANSFER CHARACTERISTICS IN WILDLAND FUELBEDS

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THESIS

A thesis submitted in partial fulfillment of
the requirements for the degree of Master
of Science in the College of Engineering
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By

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ABSTRACT OF THESIS

HEAT TRANSFER CHARACTERISTICS IN WILDLAND FUELBEDS

The fundamental physics governing wildland fire spread are still largely misunderstood. This thesis was motivated by the need to better understand the role of radiative and convective heat transfer in the ignition and spread of wildland fires. The focus of this work incorporated the use of infrared thermographic imaging techniques to investigate fuel particle response from three different heating sources: convective dominated heating from an air torch, radiative dominated heating from a crib fire, and an advancing flame front in a laboratory wind tunnel test. The series of experiments demonstrated the uniqueness and valuable characteristics of infrared thermography to reveal the hidden nature of heat transfer and combustion aspects which are taking place in the condensed phase of wildland fuelbeds. In addition, infrared thermal image-based temperature history and ignition behavior of engineered cardboard fuel elements subjected to convective and radiative heating supported experimental findings that millimeter diameter pine needles cannot be ignited by radiation alone even under long duration fire generated radiant heating. Finally, fuel characterization using infrared thermography provided a better understanding of the condensed phase fuel pyrolysis and heat transfer mechanisms governing the response of wildland fuel particles to an advancing flame front.

KEYWORDS: Ignition, Fuelbed, Fuel Particle, Radiative Heat Transfer, Convective Heat Transfer

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NOMENCLATURE

A preheated areas of interest

c specific heat

d thickness

E product of Stefan-Boltzmann constant, integrated emissivity, and a geometrical view factor

h convection coefficient

q heat rate

Q heat transferred

t time

T temperature

v spread rate of pyrolysis

w width

Δ change in parameters

ε emissivity

ρ density

Subscripts

0 intial

∞ fluid

pre preheated

s surface

sur surroundings

Superscripts

$''$ identifies per unit area

CHAPTER 1: LITERATURE REVIEW

1.1 *Introduction*

Wildfires are extremely destructive events, resulting in considerable social and economic costs. This ongoing battle presses on as expenses continue to grow, particularly in the wildland-urban interface where numerous amounts of resources are utilized to protect homes and other structures. Fire suppression represents the most publicized cost associated with wildfires, as average annual expenditures of the U.S. Forest Service totaled $580 million dollars from 1991 to 2000 and then more than doubled to $1.2 billion from 2001 to 2010. Additionally, state expenditures related to fighting wildland fires have also increased. In 2008, the National Association of State Foresters (NASF) reported more than $1.6 billion in annual expenses by State forestry agencies on wildfire protection, prevention, and suppression (including Federal funding exhausted by State agencies) [1].

However, the costs associated with fire suppression represent only a small part of a much larger picture. Numerous other expenses are consumed in restoring and reviving the damages and losses accrued from wildfires, specifically, the cost to human health, life and well-being. The lives lost or injured due to a wildfire are a real and tragic consequence of one of nature's most fierce and powerful forces that cannot be represented by dollar signs. One such example includes the 2013 Yarnell Hill wildfire, which claimed the lives of 19 members of an elite firefighting crew known as the Granite Mountain Hotshots in Yarnell, Arizona. Such events provide the necessary drive and motivation to better understand wildfires, in hopes of preventing such tragedies from happening in the future.

The unpredictability and raw, cataclysmic power of wildfires presents an inherent difficulty in terms of understanding fire spread mechanisms. As such, predicting the path of wildfires is extremely important in the efforts of forestry services and fire managers. Scientific advances in the form of spread rate models have paved the way in providing more effective means for firefighting and containment. Such fire behavior models form the core for decision support systems [2].

Given the limitations and empirical nature of current fire behavior models, the question remains of how to enhance physical understanding and someday improve operational fire spread modeling [3]. To answer this question, it is imperative to expand upon our understanding of the heat transfer mechanisms that govern the ignition process and flame spread rate, specifically radiation and convection [4].

1.2 *Radiation Driven Spread Models*

As surmised by Finney et al. [4], correct application of the heat transfer mechanisms contributing to ignition have yet to be reliably applied to fire spread models. Therefore, a more thorough understanding of the underlying physics and ignition theory of forest fuels (including live fuels) is needed to develop a coherent theory on the heat transfer mechanism.

In the past, radiative heat transfer has typically been noted as the primary mechanism governing wildland fire spread [5-15] similar to upward flame spread along vertical walls under natural convection [16, 17] and flame spread across a continuous horizontal fuel bed under a very high horizontal wind velocity [18]. These laboratory experiments used PMMA and wood samples under well controlled laboratory boundary conditions, while flame spread over forest fuel beds involves many other additional parameters. These parameters include complex mixtures of different types of live and dead fuels, non-uniform porous fuel structure, different terrain, and changing wind speed among others.

Furthermore, Morvan and Dupuy [19] developed a multiphase formulation model used to simulate the decomposition of solid fuel constituting a wildland fuelbed. This approach consisted of solving the governing equations for mass, momentum and energy conservation for a surface fire in a pine needle fuel bed with a scaled control volume sufficient enough to contain several solid fuel particles in a surrounding gas mixture. The numerical results were then compared to experimental data obtained from laboratory tests. The results showed that the primary controlling mechanism driving fire spread along flat ground with no imposed flow was radiative heat transfer.

Rothermel [20] developed a mathematical model for predicting rate of spread for a variety of wildland fuels. This particular model utilized a set of mathematical equations to physically and chemically represent a wildland fire burning uniform, small, dead fuel particles on a forest floor. The model input parameters were independent of fuel species but instead included fuel loading, fuel depth, fuel particle surface-area-to-volume ratio, fuel particle heat content, fuel particle moisture and mineral content, and the moisture content required for extinction. Unfortunately, as the uniformity of the fuel elements diminishes, the accuracy of the model is also decreased. More significantly, the spatial inconsistency present in a forest cannot properly be accounted for in this particular model. As such, there is no way for the model to suitably predict fire spread rates through intermittent fuel elements.

1.3 *Infrared Thermography as a Method to Observe the Heating and Ignition Processes of Fuel Particles*

Albini [5] articulated that a well-developed flame zone would block ambient winds thus preventing the ignition of adjacent fuel from convective heating. Others however, have questioned whether radiative heat transfer is a sufficient means of driving wildland fire spread [21-26]. Fire spread models developed by Sullivan [27] and Weber [28] incorporated both radiative and convective heat transfer. Unfortunately, the process of ignition at the fuel particle scales has been assumed without any experimental data. Emori and Iguchi et al. [29] mimicked forest fuel with excelsior and vertically oriented paper strips coated with candle wax. The results from the experiment showed that flame spread over inclined fuel beds for the paper strip fuels and horizontal and inclined excelsior fuel beds was controlled by convection [29]. Adam et al. [30] further studied scaling laws on flame spread by bringing a Strouhal-Froude number flow instability to convection heat transfer, predicting that flame spread through forest fuelbeds would satisfy these convection-controlled scaling law conditions.

Lamentably, little wildland fire research has been devoted to investigating the role of convection in wildland fire spread [4]. Within the visible spectrum, there appears to be a gap between the observed fuel particle response to an advancing flame front and the mechanisms driving the heating process. Therefore, it is suggested that in order to better understand the heating and ignition processes of fuel particles, a new visualization technique must be employed.

Infrared thermography has gained wide popularity within fluid mechanics and heat transfer research due to its non-contact capabilities for measuring temperature [31]. This imagining technique allows infrared radiation emitted by an object to be converted into a visual image. This emitted energy is dependent upon the surface characteristics of the object as well the temperature of the object [32]. In the case of wildland fires, infrared thermography techniques are particularly useful in obtaining thermal/heat transfer processes taking place on and in the condensed fuelbeds during flame spread [33]. This practice was successfully applied to measure the transient pyrolysis location for upwardly spreading fire over wood and PMMA samples [34], [35] and sub-surface layer defects [36].

1.4 *Ignition Theory*

In order to ignite unburned fuel particles and initiate a pyrolysis reaction, enough heat must be transferred to the surrounding fuel bed to produce a satisfactory amount of pyrolysis gases. When the pyrolysis gases are combined with the surrounding air, a combustible mixture is formed that ignites and burns with a heat release rate greater than the rate of heat loss to the environment [3], [4]. This cycle is repeated until the fire is extinguished either by natural means or by force (e.g. wildland fire fighters). According to Fernandez-Pello and Hirano [37], this repeating pattern is the mechanism which allows the flame front to spread, where heat transfer from the front to the unburned fuel particles and gas phase kinetics play an important role.

Grishin et al. [38] indicated that ignitability of combustible forest materials is a critical component in initiating and sustaining wildland fires. There are two ways in which the ignition process can occur: piloted or spontaneous. Spontaneous ignition occurs without the aid of an external pilot heating source and requires intense heat fluxes to sustain burning. As such, the occurrence of this type of ignition is rare. According to Mindykowski et al. [39], piloted ignition represents the most prevalent means of ignition for combustible materials in wildland fires due to the presences of radiative and/or convective heating and ignition sources (e.g. flame, firebrand). With the flame acting as the pilot source and the heating source, this form of ignition can occur at lower temperatures and thus is the mechanism responsible for fire growth in wildland fuelbeds.

Within the wildland fire community, a common practice is to assume that ignition occurs at some fixed ignition temperature [4]. While this assumption may be satisfactory for some conditions, it is more difficult to accurately apply an ignition temperature to most wildland fires due to the variety in environmental conditions, spatial configuration, heating method and rate, and non-uniformity throughout the fuelbed [40], [41]. Therefore, due to the inherent difficulty in making accurate predictions based off ignition temperature, a more comprehensive understanding of the physical processes governing ignition must be better established.

1.5 *Research Objective*

The work resulting in this thesis was motivated by the need to better understand the role of radiative and convective heat transfer in the ignition and spread of wildland fires. Therefore, the focus of this work incorporated the use of infrared thermographic imaging techniques to investigate fuel particle response from three different heating sources: convective dominated heating from an air torch, radiative dominated heating from a crib fire, and an advancing flame front in a laboratory wind tunnel test.

CHAPTER 2: EXPERIMENTAL METHODS

2.1 *Fuel Particle Development*

In order for a wildland fire to be sustained, three elements must be present: heat, oxygen, and fuel. Noted by Keane et al. [42], one of the core elements in many wildland fire planning and management activities is wildland fuels. Fuels constitute the biological matter required for ignition. Additionally, they offer the best opportunity for humans to interact with the fire and change the fire behavior [20], [43], [44].

The spread, intensity, and severity of a wildland fire can be partially attributed to the physical characteristics of fuels, such as loading (weight per unit area), size (particle diameter), and bulk density (weight per unit volume) [45], [46]. Unfortunately, it becomes quite difficult to encompass the physical characteristics for all fuels in any given area, due to the large variations in environmental conditions such as moisture and soil content, altitude, topography, etc. Hence, it is critical to utilize fuel particles that compare well to actual wildland fuelbeds but maintain homogenous properties and physical attributes. Cardboard and paper strips have been used in previous experiments [47] and offer the freedom to customize in any configuration desired. Therefore, engineered cardboard fuel particles (1.27 mm thick with approximately 60% recycled content) were fabricated at the Missoula Fire Sciences Laboratory using a Universal Laser Systems Inc. ILS12.150D model CO_2 laser engraver equipped with two 60W laser cartridges. The cardboard samples were connected along a common spine and cut at regular spacing. The width and height of the cardboard elements varied according the desired fuel particle/fuelbed properties.

2.2 *IR Camera*

The transient temperature history of the cardboard fuel particles heated under various sources was measured using a FLIR SC4000™ infrared camera. The IR camera has a spatial resolution of 320 x 256 pixels and a spectral range of 3-5 μm. Additionally, the camera was fitted with a broadband flame filter with a spectral range of 3.7 - 4.2 μm to eliminate flame interference and obtain thermal images at the condensed phase.

To reduce the amount of noise and saturation captured in each video image, a super-framing algorithm was employed. This algorithm takes a set of four images (subframes) of the scene at progressively shorter exposure times, in rapid succession, and then repeats this cycle. The subframes from each cycle were then merged into a single superframe to combine the best features of the four subframes. This process, called collapsing, provided thermal images both high in contrast and wide in temperature range.

The following sections provide methodology from three sets of experiments: convective dominated heating from an air torch, radiative dominated heating from a crib fire, and infrared thermographic analysis from a wind tunnel test.

2.3 *Convection Dominated Heating: Air Torch Experiment*

The cardboard fuel elements were heated from ambient temperature by a convective heater to achieve ignition (recognized by the establishment of a visible flame). Figure 1 depicts a schematic of the convection heating experiment. A vertically oriented convection heater provided forced convective heat flow parallel to the cardboard elements suspended approximately 0.5 cm above the exit of the air torch, where two different temperature settings (500 °C and 750 °C) were used. The mass flow rate of air was controlled and held constant, so the airflow velocity at the exit of the torch varied from 1.3 to 1.5 m/s for the two temperatures tested.

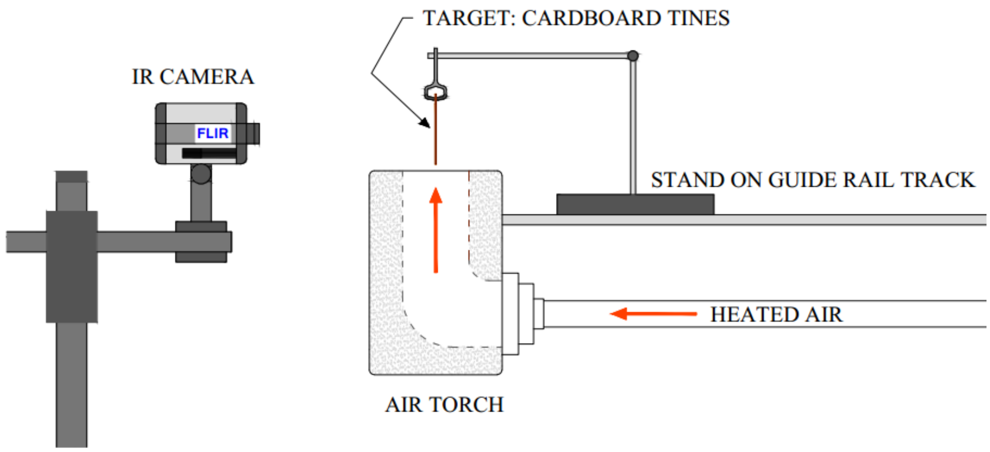

Figure 1 - Air torch schematic: Side view.

Three common tine geometries, shown in Figure 2, were used and each experiment was repeated ten times per geometry. Every effort was made to ensure all experimental conditions remained the same and that the results were repeatable, since the temperature distribution at the circular exit of the torch was not symmetric which could lead to an uneven temperature distribution across the hot exiting air stream.

The cardboard tine samples were suspended in a downward facing manner, as shown in Figure 3, throughout the duration of the experiment to mimic the condition of heated vertical plates subjected to forced convection from an imposed parallel flow.

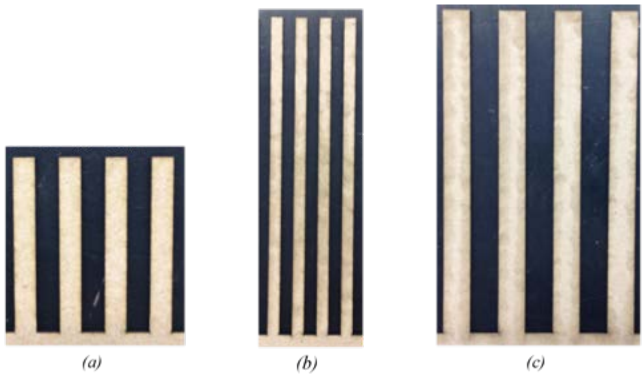

Figure 2 - Tine geometries (a) 0.635 cm wide x 5.08 cm high (b) 0.635 cm wide x 15.24 cm high (c) 1.27 cm wide x 15.24 cm high.

Figure 3 – Tine orientation.

2.4 *Radiation Dominated Heating: Crib Fire*

A wood crib (91.44 cm wide x 76.2 cm tall x 91.44 cm long) constructed of Ponderosa pine (*Pinus ponderosa*) sticks was used to provide radiative heating to the cardboard samples under circumstances as close to wildland fires conditions as possible. The crib was conditioned at 30 °C and 3% RH for approximately 2 weeks to adjust the moisture content, which was identified as roughly 1%. A schematic of the experimental set up is shown in Figure 4. The crib was constructed with 2.54 cm square sticks with six sticks per layer and 30 layers so that it burned in the loosely-packed regime. The crib was placed on cinder blocks providing 19.5 cm of space between the crib and the support platform. The crib was housed within a large (12.4 m x 12.4 m x 19.6 m) sealed burn chamber with no imposed flow. This allowed minimal incoming and outgoing drafts, thus limiting convective heating and cooling effects and maximizing the radiative heating effects. Equation (1) can describe the above heat balance

$$\frac{dq''}{dt} = E(T_s^4 - T_{sur}^4) + h(T_s - T_\infty) \quad (1)$$

where E represents the product of the Stefan-Boltzmann constant (5.67 x 10^{-8} W/m^2-K^4), the integrated emissivity of the cardboard elements, and a geometrical view factor and the $h(T_s - T_\infty)$ term is used to define the convective cooling effects.

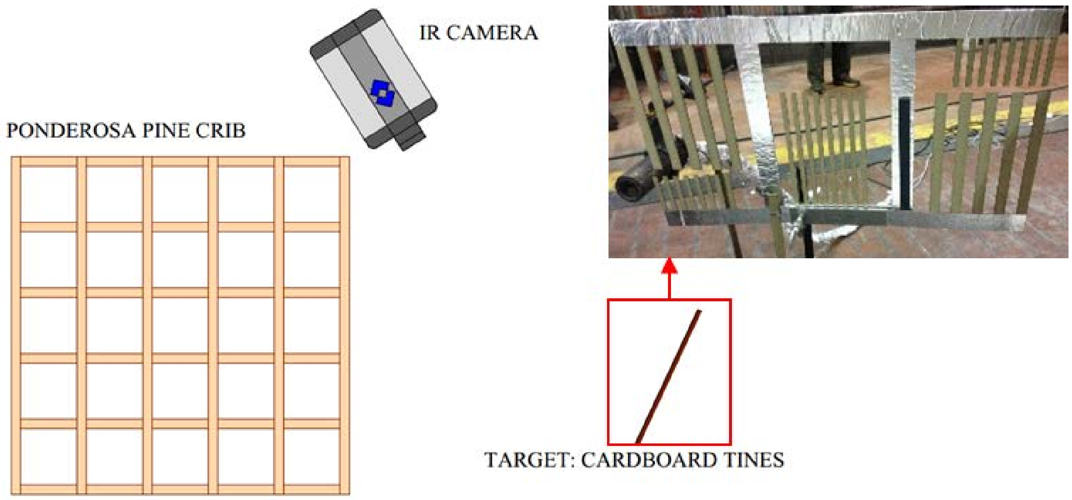

Figure 4 - Crib schematic: Plan view.

Three cardboard tine geometries were used for this experiment: 0.635 cm wide x 5.08 cm high, 0.635 cm wide x 15.24 cm high, and 1.27 cm wide x 15.24 cm high. The tines were originally constructed into two foot sections, but cut into smaller segments and taped together using reflective aluminum adhesive tape. To achieve the best viewing angle possible between the IR camera and the fuel, the tines were positioned at an angle of 25° with respect to the crib with the closest end measuring 91.44 cm away from the edge of the crib and the furthest measuring 109.22 cm away.

A separate cardboard tine was coated with high carbon content black paint (ε = 0.95) to serve as a black body for the IR camera. Additionally, a 1 mm K-type thermocouple was taped to the bottom of the cardboard sample to measure the surrounding air temperature during the heating experiment.

2.5 *Wind Tunnel Experiment: Composite Fuelbed*

Composite fuelbeds constructed of 0.635 cm wide x 5.08 cm high and 0.635 cm wide x 15.24 cm high cardboard fuel elements were burned in the Missoula Fire Sciences Laboratory wind tunnel with a 3.048 m x 3.048 m cross section. The wind speed was held constant at 0.89 m/s. The combs were supported and arranged on a foundation of cement-board strips (Hardy Board) 0.635 cm wide x 5.08 cm high each separated by a steel spacer 0.158 cm wide x 2.54 cm high. The steel spacers rested on the floor to preserve a slot at the upper surface which pinched the spine of the fuel combs such that only the vertical tines were exposed. The cardboard comb spacing was held constant at 7.62 cm. Figure 5 shows schematics of the experimental setup.

The transient temperature history of the cardboard fuel particles when subjected to primarily convective and radiative heating from an advancing flame front was measured using the IR camera shown in Figure 5. The camera was fixed approximately 93 cm away from the fire, looking down at the fuelbed with a view angle of approximately 30 degrees from the horizontal. The camera was stored in an air purged aluminum container 33.02 cm in diameter. Additionally, ice packs were placed inside the housing to regulate the internal temperature of the camera during the burns due to the intense radiative heat of the advancing flame front.

This particular fuelbed arrangement aided in observing a regular series of peaks-and-troughs in the span-wise direction from which the convective and radiative heating were separately obtained. The collected IR images were also used to determine the gradual preheating process taken over the entire length of the 0.635 cm wide x 15.24 cm high fuel particle surface since the rows contained within the region of interest were staggered

(Figure 6). From the results of this dynamic heating process, the heat flux being experienced by the preheated areas of the 0.635 cm wide x 15.24 cm high cardboard fuel particles was estimated. Finally, the downward spread rate was estimated by examining the increase in burning area between IR images of the 0.635 cm wide x 15.24 cm high fuel elements.

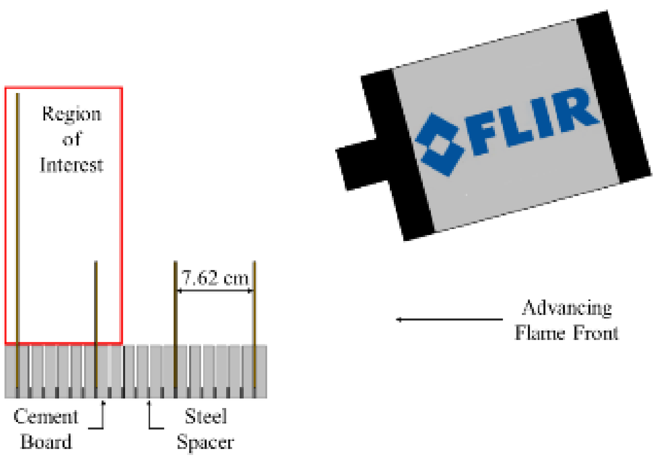

Figure 5 - Composite fuelbed schematic: Side view.

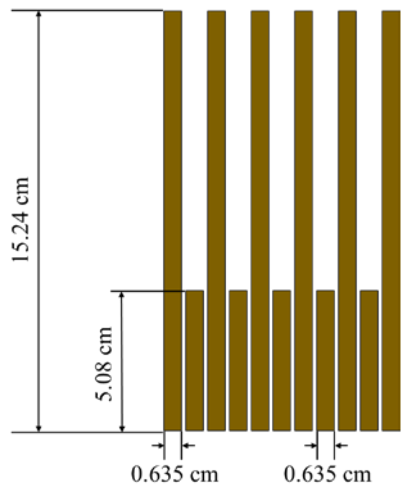

Figure 6 - Region of interest: Front view.

CHAPTER 3: RESULTS AND DISCUSSION

3.1 *Convection Dominated Heating: Air Torch*

The recorded infrared video images provided a rich database for all 30 fuel samples, but here, only the results for the 0.635 cm wide x 5.08 cm high cardboard elements were presented due to their significance. Note that the results presented are not representative of a single test but rather depict the average of all ten trials for the 0.635 cm wide x 5.08 cm high fuel element.

The software ExaminIR™ [48] was used to evaluate the IR video image data. Specific regions of interests (ROI's) located at the tip of each tine were used to determine a temperature history of the cardboard fuel elements. These ROI's were labelled from left to right as Cursor one through four. In the grayscale image, white is representative of hotter temperatures, while dark is indicative of colder temperatures. The results for the air torch outlet temperature of 500 °C show a steady progression in temperature up to the point of flame visibility at approximately 315 °C where temperature rises sharply (Figure 7).

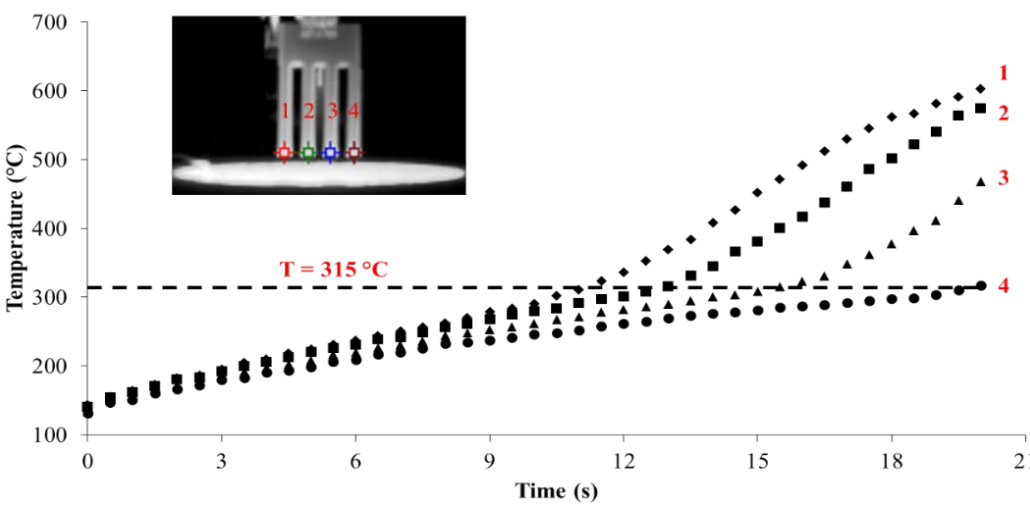

Figure 7 - Temperature history for the 0.635 cm wide x 5.08 cm high fuel element subjected to an outlet temperature of 500 °C.

Once a stable flame was established, the tines were pulled away from the outlet of the torch to prevent burning fuel elements from falling into the air torch and possibly damaging the equipment. In evaluating each cursor, fluctuations due to flame movements and CO_2 interference, which are visible in the spectral range of the filter, are represented by a larger standard deviation. These fluctuations are shown for Cursor one and Cursor four in Figure 8.

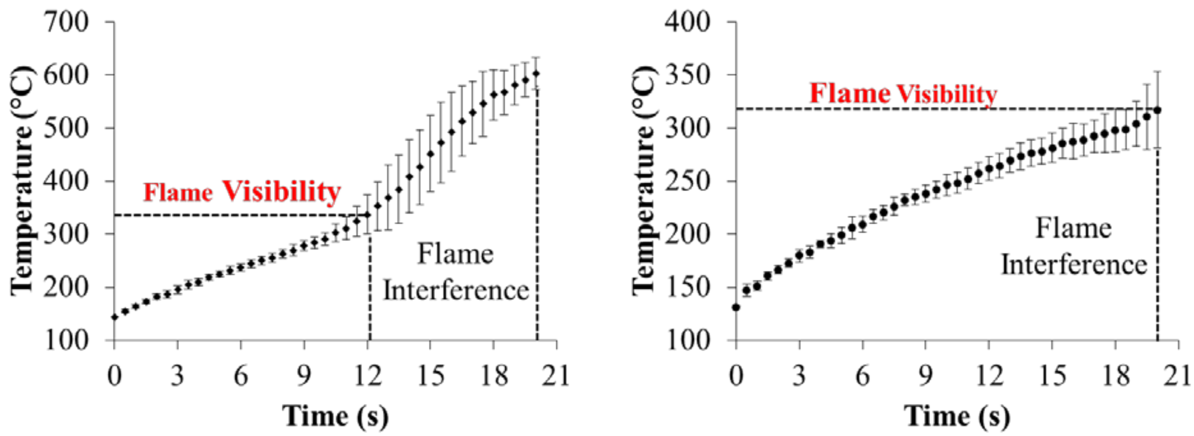

Figure 8 - Temperature history showing standard deviations as a result of flame movement and CO_2 interference for an outlet temperature of 500 °C for Cursor 1 and Cursor 4.

For the case of an outlet temperature of 750 °C (Figure 9), the results show a decrease in flame visibility temperature (307 °C) with an increase in heat flux, as expected [49]. Additionally, more fluctuations in the temperature progression are present as a result of increased turbulence in the airflow (Figure 10). Note that for an outlet temperature of 500°C, it took approximately 12 seconds to reach ignition, while for an outlet temperature of 750 °C it took roughly 1.5 seconds, indicating that an increase in the heat flux enhances the heat transfer rate by convection to the unburned fuel element and consequently increasing the rate of flame spread.

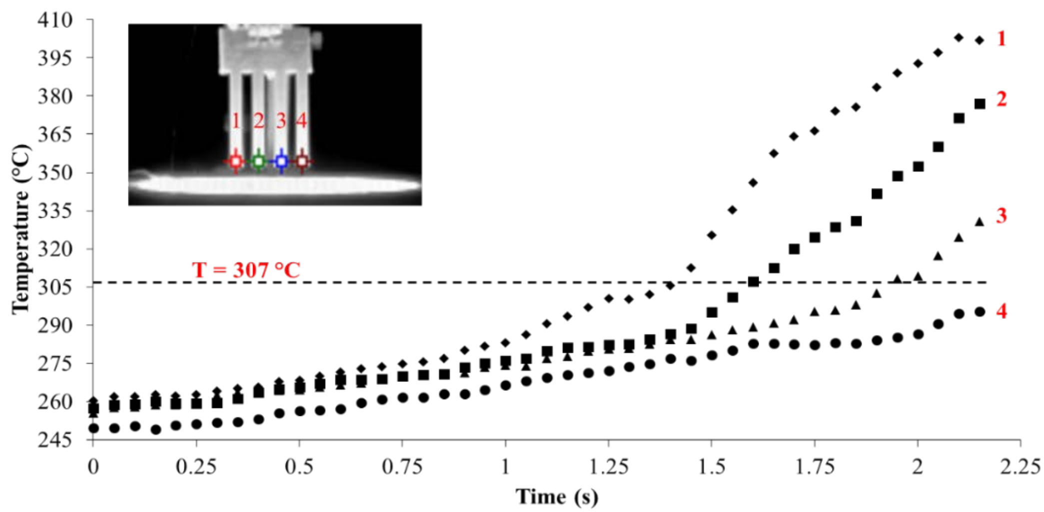

Figure 9 - Temperature history for the 0.635 cm wide x 5.08 cm high fuel element subjected to an outlet temperature of 750 °C.

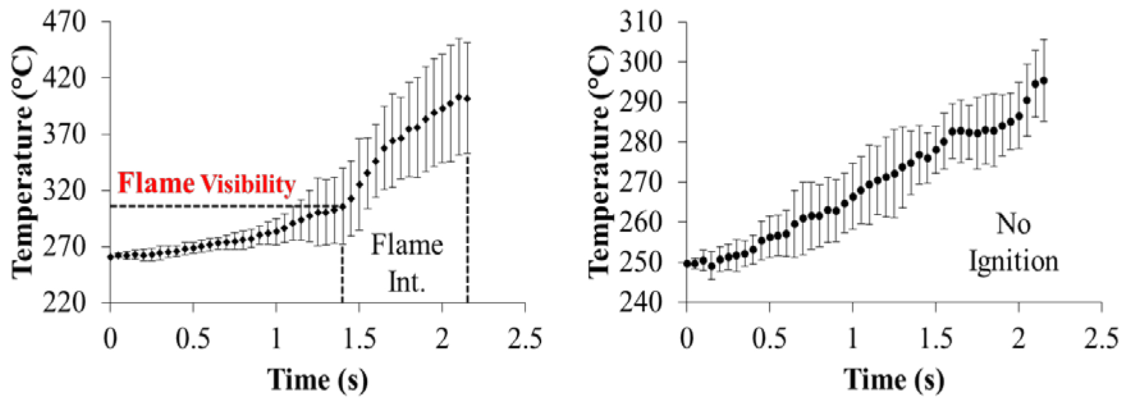

Figure 10 - Temperature history showing standard deviations as a result of flame movement and CO_2 interference for an outlet temperature of 750 °C for Cursor 1 and Cursor 4.

3.2 *Radiation Dominated Heating: Crib Fire*

A similar procedure was used to determine the temperature history of the cardboard fuel elements when subjected to a predominantly radiative heating source. The average radiative heat flux of the crib fire was approximately 10.3 kW/m^2. Within ExaminIR™, specific areas of interest were placed at the tip, middle, and bottom of the cardboard fuel elements closest to the burning crib, as these tines were exposed to the largest amount of radiative heat. These fuel particles included the 0.635 cm wide x 5.08 cm high tines and the 1.27 cm wide x 15.24 cm high cardboard elements shown in Figure 11(c).

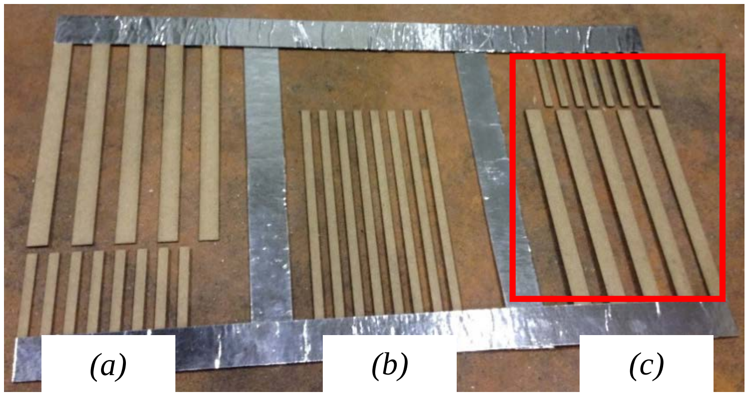

Figure 11 - Tine geometries: (a) 0.635 cm wide x 5.08 cm high (b) 0.635 cm wide x 15.24 cm high (c) 1.27 cm wide x 15.24 cm high.

During radiative heating, a natural convection thermal boundary layer will be developed over the heated fuel surface bringing two different benefits for ignition: reducing the heat loss from its heated surface to the surrounding air and promoting a fuel-air mixture layer within the boundary layer, both are favourable for ignition.

Examining the ratio of exposed heating area to total fuel surface area, the potential for receiving radiant heat as opposed to losing energy to the surroundings from natural convective cooling was recognized to be greater for the larger fuel particles. This explains the results of Figure 12 where the larger tines (1.27 cm wide x 15.24 cm high) were able to ignite at the tip.

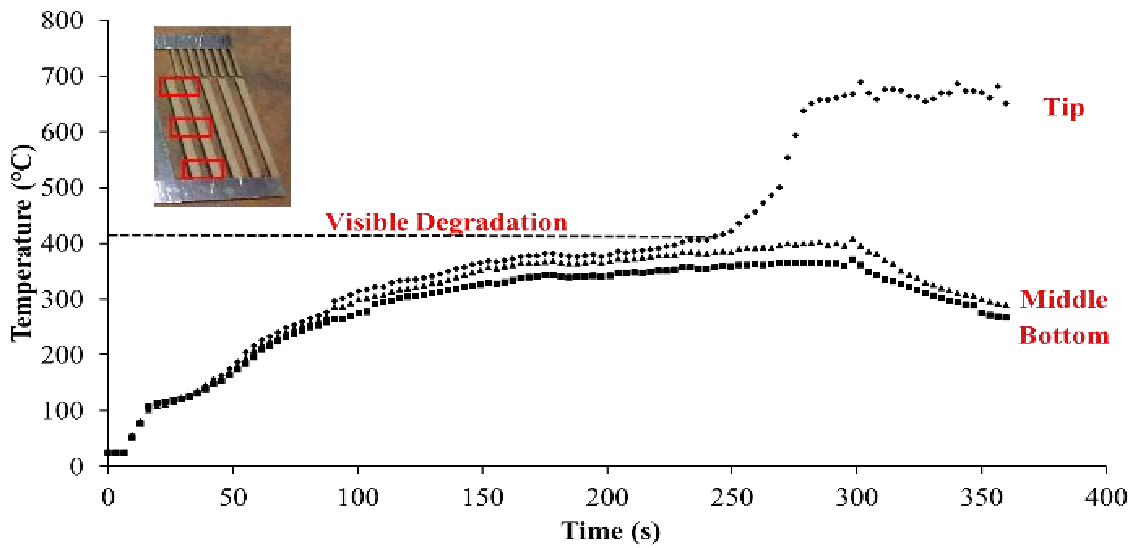

Figure 12 - Temperature history of the 1.27 cm wide x 15.24 cm high fuel element subjected to predominately radiative heating.

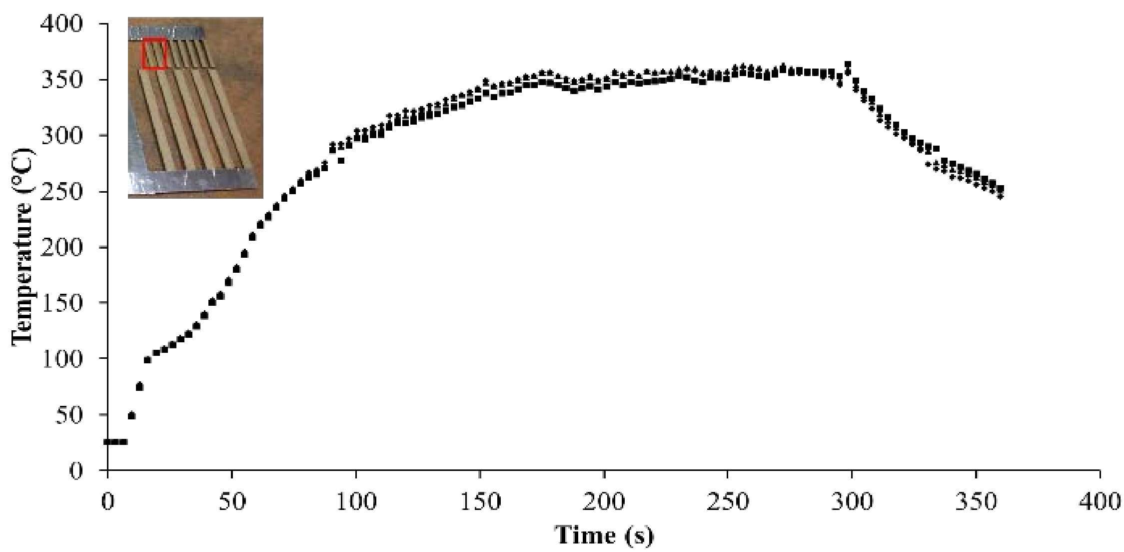

Figure 13 - Temperature history of the 0.635 cm wide x 5.08 cm high fuel element subjected to predominately radiative heating.

It should be noted that the ratio of the exposed heating area to the total fuel surface area is an important indicator to assess the effect of radiation on ignition not only for cardboard fuel samples but possibly for actual dead forest fuels, since the underlining governing physics can be also applied. But a more thorough scaling study, based on the studies conducted by Adam et al. [30], Emori and Saito [50], and Emori and Iguchi et al. [29], is required to justify whether or not this ratio can be an important scaling factor. As for live forest fuels, however, the above finding may not be directly applicable due to its complex fuel structure [51] and therefore, a fundamental study to reveal ignition behaviour of live fuels is certainly needed.

In summary, IR thermal image-based temperature history and ignition behaviour of engineered cardboard fuel elements subjected to convective and radiative heating support the USDA's original findings that millimeter diameter pine needles cannot be ignited by radiation alone [4] even under a long duration fire generated radiant heat flux of an average 10.3 kW/m^2.

3.3 *Post Processing of Wind Tunnel IR Images: Heat Flux Analysis*

Once more, the software ExaminIR™ was used to capture several infrared thermographic images of the cardboard fuel elements. Thermal bounds (300 °C – 1,000 °C) were set in ExaminIR™ to enhance image details as well as better understand the mechanism affecting the preheating of the unburned fuel particles in relation to the flame spread. Figure 14 shows three different IR images, labelled from left to right as Phase one to Phase three, captured at three different times (t = 133.1 s, 144.5 s, 150.2 s). In the color images of Figure 14, white is representative of the upper temperature bound (1,000 °C) and black is indicative of temperatures below the lower bound (300 °C). Furthermore, temperature changes from high to low in the order of yellow, orange, red, green, light blue, dark blue, and purple.

These IR images revealed a higher surface temperature at the corners and edges in comparison to the flat face. This behavior is an agreement with a thicker boundary layer on the flat surfaces of the fuel particles signifying an important role of convective heating from an advancing flame front.

Using the processing software ImageJ [52] in conjunction with Adobe® Photoshop®, we extracted high pixel information from the collected IR images without sacrificing too much detail. Figure 15 shows an increase in the preheated areas of interest for the 0.635 cm wide x 15.24 cm high cardboard fuel elements from t = 133.1 s to t = 150.2 s.

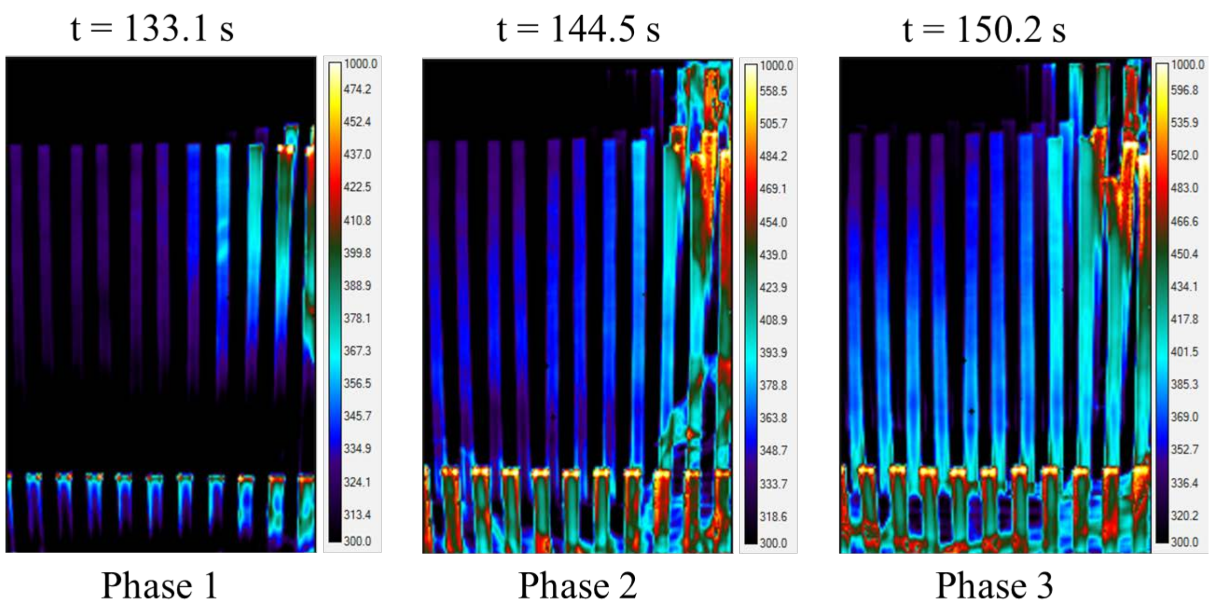

Figure 14 - Infrared thermographic images of the cardboard fuel elements. The 0.635 cm wide x 5.08 cm high fuel particles reveal a higher surface temperature at the corners and edges in comparison to the flat face. Additionally, preheating of the 0.635 cm wide x 15.24 cm high fuel particle is visible over the time interval shown.

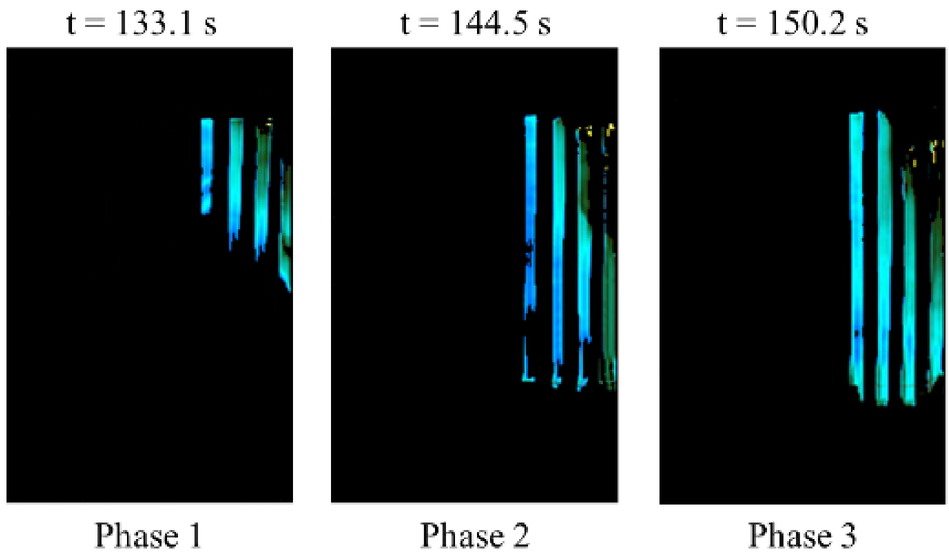

Figure 15 - Preheated areas of interest for the 0.635 cm wide x 15.24 cm high cardboard fuel elements.

In calculating the preheated areas, it was necessary to compensate for the downward facing angle (approximately 30 degrees from horizontal) of the camera using the CAD software SolidWorks® to adjust for the geometrical complexities associated with the viewing angle. The heat transferred to each area of interest was then roughly estimated using Equation (2)

$$Q = c\rho A d(T_{pre} - T_0) \quad (2)$$

where c represents the specific heat of the fuel particles, ρ represents the density of the cardboard fuel elements, A is the calculated preheated areas of interest, d is the thickness of the cardboard samples, and T_{pre} is the average temperature of the preheated areas which was determined from the IR images. Note that due to the limited information available on the material properties of the cardboard being used, the specific heat of paper (1.255 kJ/kg-K) [53] at room temperature was used. The cardboard fuel elements were also assumed thermally thin allowing for a constant thickness d. The heat rate was then determined using Equation (3).

$$q = \frac{\Delta Q}{\Delta t} \tag{3}$$

where Δt is the time interval between images. Finally, the total heat flux was calculated through the use of Equation (4)

$$q'' = \frac{q}{\Delta A} \tag{4}$$

where ΔA represents the increased area of preheating between the IR images. The calculated results are shown in Table 1.

Table 1 - Thermal analysis of IR images.

Image	**Preheated Area (cm^2)**	**Q (kJ)**	**q (W)**	**q'' (kW/m^2)**
1 (t = 133.1 s)	18.17	0.61	47.65	34.46
2 (t = 144.5 s)	32	1.15	66.7	68.51
3 (t = 150.2 s)	41.74	1.53		

These results show a 98.82% increase in heat flux over the 17 second time interval between image one and image three. Additionally, the thermal analysis of the IR images provided an interesting insight into the mechanisms driving the heating of the cardboard fuel elements since the heat flux values provided in Table 1 encompass all three modes of heat transfer affecting this system: radiative heating from the flame front, convective heating due to an imposed flow, and conductive heating through the cardboard fuel particles.

3.4 *Post Processing of Wind Tunnel IR Images: Spread Rate Analysis*

A similar process was used to determine the increased area of burning between images. Figure 16 shows the change in the burning areas of interest for the 0.635 cm wide x 15.24 cm high cardboard fuel elements from 133.1 s to 150.2 s. Note that for the downward spread rate, the cardboard fuel elements were examined individually rather than as a collective region, the same as with the preheated areas in the Heat Flux Analysis section. In addition, the cardboard particles are labelled from right to left as one, two, and three.

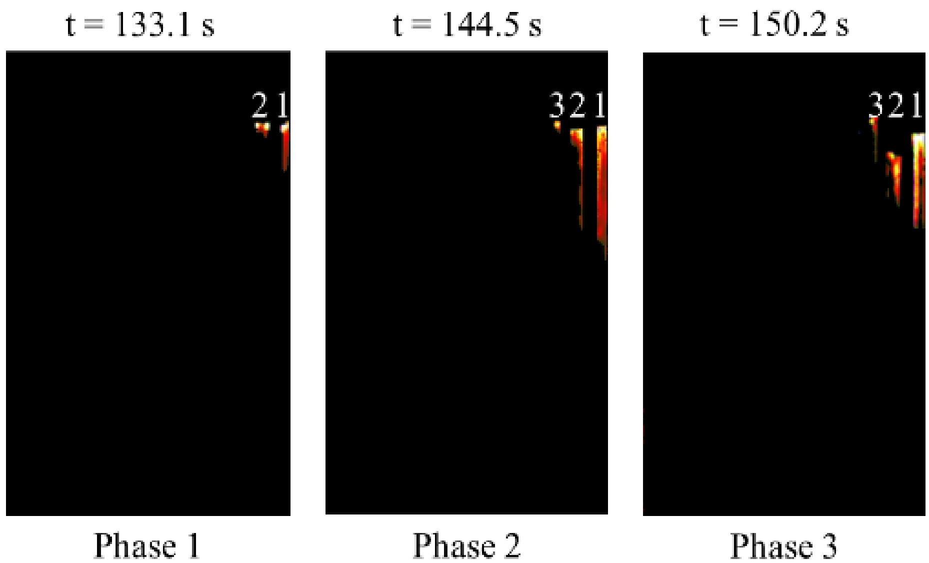

Figure 16 - Burning areas of interest for the 0.635 cm wide x 15.24 cm high cardboard fuel elements.

The spread rate of the pyrolysis front was estimated for fuel particles one, two, and three using Equation (5)

$$v = \frac{\Delta A}{\Delta t \cdot w} \tag{5}$$

where ΔA represents the increased area of burning between the IR images and w is the width of the cardboard fuel particle. The individual heating rates were also determined for the preheated areas of fuel particles one, two, and three based upon the image processing results discussed in the Heat Flux Analysis section. This step was useful in determining whether or not a simple correlation between the increases in preheated areas to downward spread rate exists. The calculated results are shown in Table 2. The IR-based thermal analysis and application can be found in ref. [33] and the use of infrared imaging to obtain spread rate are provided in refs. [36, 54].

Table 2 - Calculated spread rates, increases in preheated area, and heating rates for fuel particles one, two, and three between images.

Particle	**Image**	***v* (cm/s)**	**Δ Preheated Area (cm^2)**	***q* (W)**
1	1 (t = 133.1 s) 2 (t = 144.5 s)	0.352	6.37	9.84
1	2 (t = 144.5 s) 3 (t = 150.2 s)	0.029	1.41	9.87
2	1 (t = 133.1 s) 2 (t = 144.5 s)	0.125	3.28	11.61
2	2 (t = 144.5 s) 3 (t = 150.2 s)	0.119	0.73	5.87
3	1 (t = 133.1 s) 2 (t = 144.5 s)	0.006	4.39	15.02
3	2 (t = 144.5 s) 3 (t = 150.2 s)	0.183	2.63	18.18

The preliminary results do not yield a simple relationship between the increases in preheating area and downward spreading pyrolysis front, therefore, a more in-depth analysis is suggested for future work. Importantly, it was demonstrated that the current study using IR image-based thermal analysis was capable of obtaining the detailed heat transfer process taking place at the condensed phase of the fuel particles, providing a powerful tool for thermal analysis on both full scale and laboratory scale fires.

CHAPTER 4: CONCLUSION

4.1 *Summary*

Wildland fires from unforeseen ignitions are devastating forces of nature that are still largely misunderstood. The knowledge of basic combustion and heat transfer principles governing the ignition and spread of these destructive events is needed in order to improve the predictive capabilities of the currently existing models.

The following specific contributions were made from the present studies:

(1) The present series of experiments demonstrated the uniqueness and valuable characteristics of infrared thermography to reveal the hidden nature of heat transfer and combustion aspects which are taking place in the condensed phase of wildland fuelbeds.

(2) IR thermal image-based temperature history and ignition behavior of engineered cardboard fuel elements subjected to convective and radiative heating supported the USDA's original findings that millimeter diameter pine needles cannot be ignited by radiation alone even under long duration fire generated radiant heating.

(3) These findings not only helped summarize some of the past contributions of the USDA but they also contributed to the extensive and ever growing database used in understanding the complexity of wildland fires spread.

(4) Fuel characterization using infrared thermography provided a better understanding of the condensed phase fuel pyrolysis and heat transfer mechanisms governing the response of wildland fuel particles to an advancing flame front.

4.2 *Future Recommendation*

Finally, it is recommended that the understanding of wildland fire be pushed to new bounds. Questions should continue to be asked and answers continued to be sought after in this ongoing struggle. The health, safety, and well-being of thousands, possibly millions of people are at stake with each passing fire season and it is the responsibility of scientists and engineers to use this growing database and wealth of knowledge to solve the problem of how and why wildland fires spread.

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