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Ignition behavior of cardboard fuel particles

Justin D. English[a], Nelson K. Akafuah[a], Brittany A. Adam[a], Mark Finney[b], Jason Forthofer[b], Jack Cohen[b], Sarah McAllister[b] and Kozo Saito[a]

[a] *Univ. of Kentucky, Lexington, KY 40506, justin.english@uky.edu, nelson.akafuah@uky.edu, brittany.adam@uky.edu, ksaito@uky.edu*
[b] *USDA Fire Science Laboratory, Missoula, MT 59808, mfinney@fs.fed.us, jaforthofer@fs.fed.us, jcohen@fs.fed.us, smcallister@fs.fed.us*

Abstract
This paper reports infrared thermal-image-based temperature changes on cardboard fuel surfaces during ignition. Two sets of experiments were designed to separately test the effect of convective heating and radiative heating on ignition of cardboard fuel samples. An air torch was used to provide the convective heating, and a crib fire was used for the radiative heating. An infrared thermography technique developed in our laboratory was used to obtain thermal profiles/signature of the heated cardboard sample surface under two different heating rates, from which the surface temperature change was obtained as a function of heating time. We found that radiation effects increased with an increase in the cardboard sample surface area exposed to radiation while the effects from convection dominated the smaller surface area samples. This finding qualitatively explains the United States Department of Agriculture's (USDA) original findings that millimeter diameter pine needles cannot be ignited by radiation only, even under a long duration fire generated radiant heat flux of an average 10.3 kW/m^2. Our experimental results also justify the use of the cardboard fuelbeds to simulate fire behavior of large scale forest fires.

***Keywords**: Ignition, Fuelbed, Fuel Particle, Heat Transfer*

1. Introduction

Wildland fires are unpredictable and destructive events that use enormous amounts of resources to fight and contain, particularly in the wildland-urban interface where numerous amounts of resources are utilized to protect homes and other structures.

Scientific advances in the form of spread rate models have paved the way in providing more effective means for firefighting and containment for large fires. Such fire behavior models form the core for decision support system (Noonan-Wright, et al., 2011).

Given the limitations and empirical nature of current fire behavior models, the question remains of how to enhance physical understanding and someday enhance operational fire spread modeling (Gollner, 2012). As surmised by Finney *et al*. (2012), 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 theory behind ignition on forest fuels (including live fuels) is needed to develop a coherent theory on the heat transfer mechanisms affecting it. The flame is the source to provide sufficient heat to pyrolyze (solid) forest fuel, and the pyrolyzed gas phase products will then mix with air. When this fuel-air mixture satisfies flammability limit under the ignition temperature, ignition occurs creating flammable combustion. 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 (Fernandez-Pello & Hirano, 1983).

Radiation has been thought as the primary mechanism in wildland fire spread, similar to upward flame spread along vertical walls under natural convection (Brehob & Kulkarni, 1998; Brehob, Kim, & Kulkarni, 2001) and flame spread across a continuous horizontal fuel bed under a very high horizontal wind velocity (Steward, 1971). These laboratory experiments use 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. Emori and Iguchi *et al*. (1988) mimicked forest fuel with excelsior and vertically oriented paper strips coated with candle wax, whose geometry is similar to the cardboard fuelbeds, and showed that flame spread over inclined fuel beds for the paper strip fuels and horizontal and inclined excelsior fuel beds is controlled by convection (Emori, *et al*., 1988). Adam *et al* (2013) 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.

2. Experimental Methods

To ensure homogenous properties and physical attributes among the fuel samples being used, we engineered cardboard particles 1.27 mm thick with approximately 60% recycled content using a laser engraver. We measured the transient temperature history of the fuel particles when subjected to various heat sources using a FLIR SC4000™ infrared camera (spectral range of 3-5 µm, fitted with a broadband flame filter with spectral range of 3.7 - 4.2 µm, with spatial resolution of 320 x 256 pixels). To reduce the amount of noise and saturation captured in each video image, we employed a super-framing algorithm which takes a set of four images (subframes) of the scene at progressively shorter exposure times, in rapid succession, and then repeats this cycle. The sub-frames from each cycle are then merged into a single super-frame to combine the best features of the four sub-frames. This process, called collapsing, can provide thermal images both high in contrast and wide in temperature range.
The following section provides results from two sets of experiments: convective dominated heating from an air torch and radiative dominated heating from a crib fire.

2.1. 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 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 is 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.

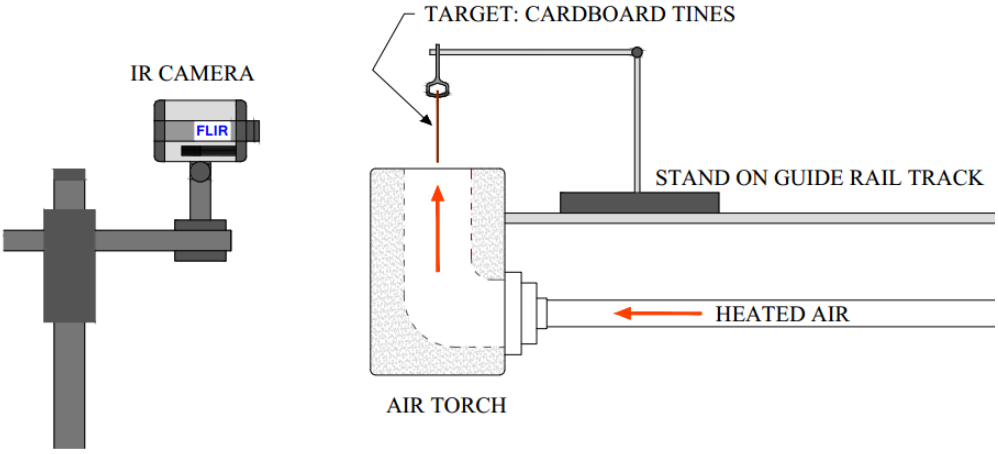

Figure 1. Experimental setup: Air torch - Side view

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 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.

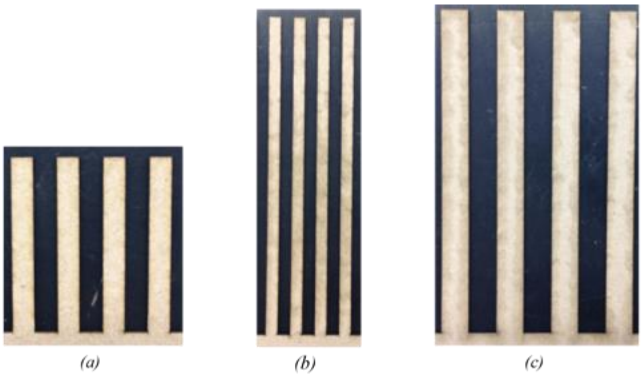

Figure 2 - Tine geometries (a) 0.635 cm wide x 5.08 cm high (b) 0.635 cm wide x 15.24 cm high (c) 1.27 cm wide x 15.24 cm high

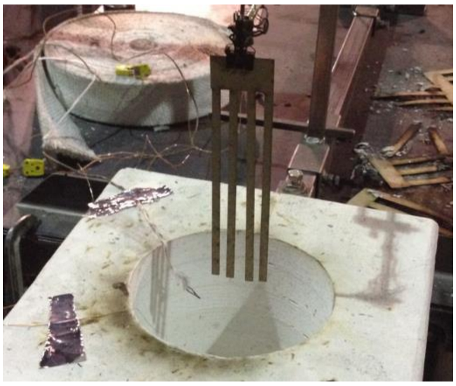

Figure 3 – Tine orientation

2.2. 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. 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, such 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

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

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.

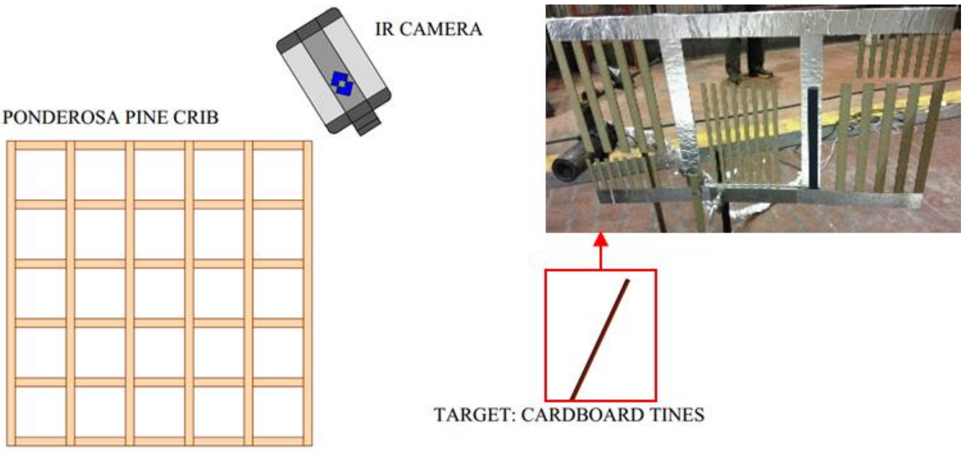

Figure 4 - Crib schematic: Plan view

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 as 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 ($\varepsilon = 0.95$) 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.

3. Results

3.1. Convection Dominated Heating: Air Torch

The recorded infrared video images provided a rich database for all 30 fuel samples, but this paper only reports the results for the 0.635 cm wide x 5.08 cm high cardboard elements due to space limitations. It should be noted 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™ (FLIR Systems, Inc., 2014) 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 5).

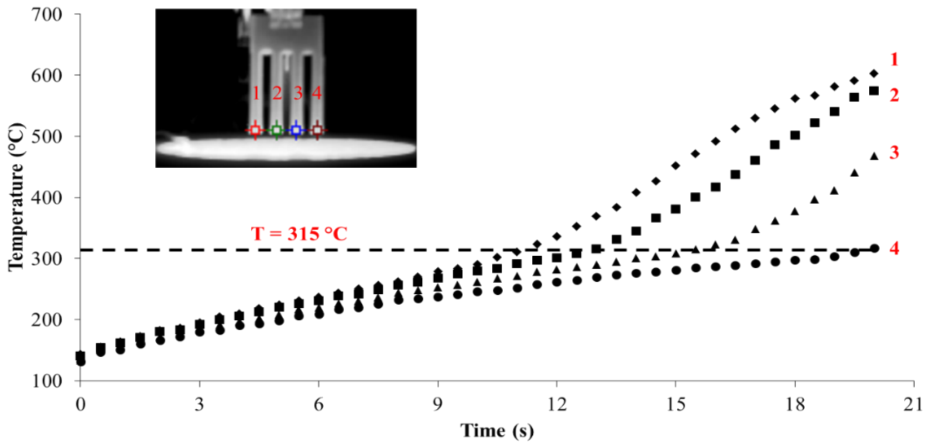

Figure 5. Temperature history for the 0.635 cm wide x 5.08 cm high fuel element subjected to an outlet temperature of 500 °C

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 6.

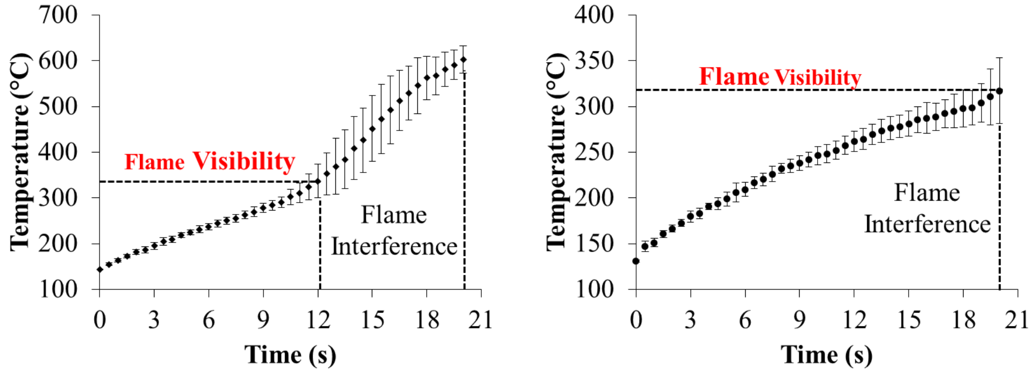

Figure 6. Temperature history showing standard deviations as a result of flame movement and CO2 interference for an outlet temperature of 500 °C for Cursor 1 and Cursor 4

For the case of an outlet temperature of 750 °C (Figure 7), the results show a decrease in flame visibility temperature (307 °C) with an increase in heat flux, as expected (Atreya & Abu-Zaid, 1991). Additionally, more fluctuations in the temperature progression are present as a result of increased turbulence in the airflow (Figure 8). 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 increases convective heat transfer rate to the unburned fuel element and consequently increasing the rate of flame spread.

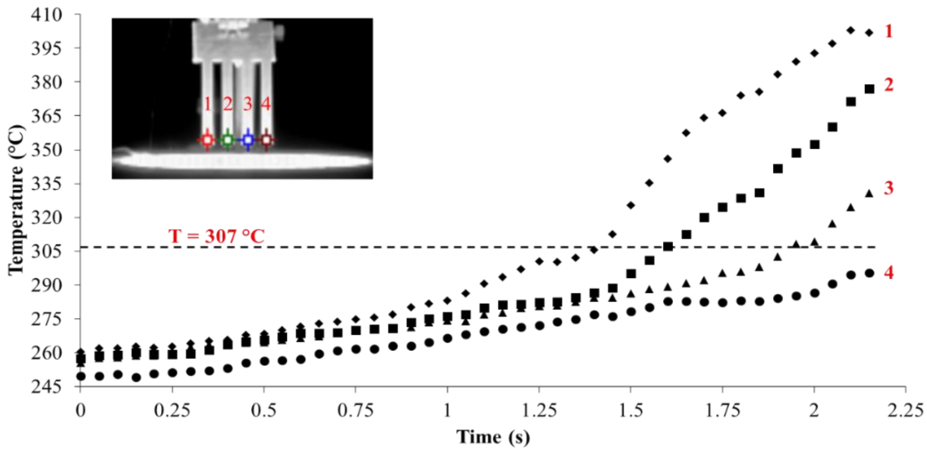

Figure 7. Temperature history for the 0.635 cm wide x 5.08 cm high fuel element subjected to an outlet temperature of 750 °C

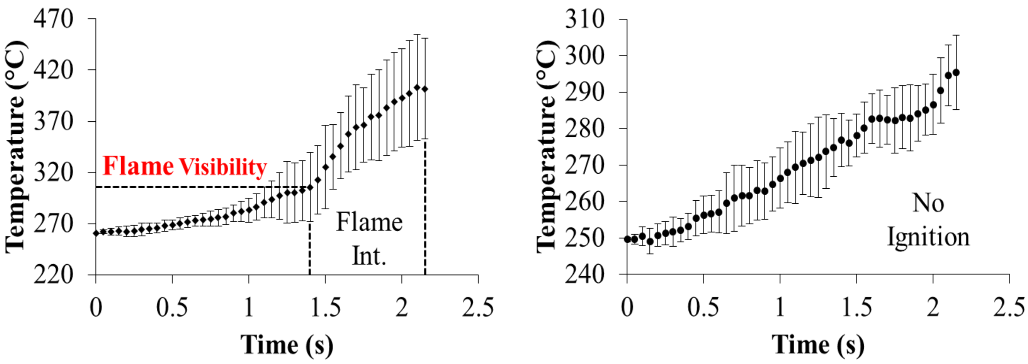

Figure 8. Temperature history showing standard deviations as a result of flame movement and CO2 interference for an outlet temperature of 750 °C for Cursor 1 and Cursor 4

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 primarily radiative heating. 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 9(c).

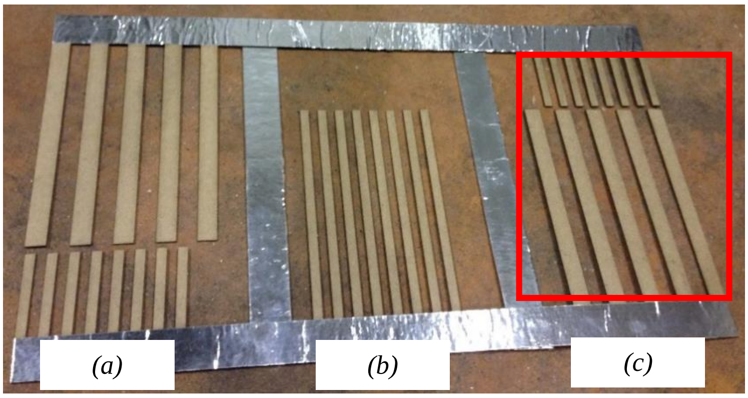

Figure 9 – Tine geometries: (a) 0.635 cm wide x 5.08 cm high (b) 0.635 cm wide x 15.24 cm high (c) 1.27 cm wide x 15.24 cm high

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, we realized that the potential for receiving radiant heat as opposed to losing energy to the surroundings from natural convective cooling was greater for the larger fuel particles. This explains the results of Figure 10 where the larger tines (1.27 cm wide x 15.24 cm high) were able to ignite at the tip.

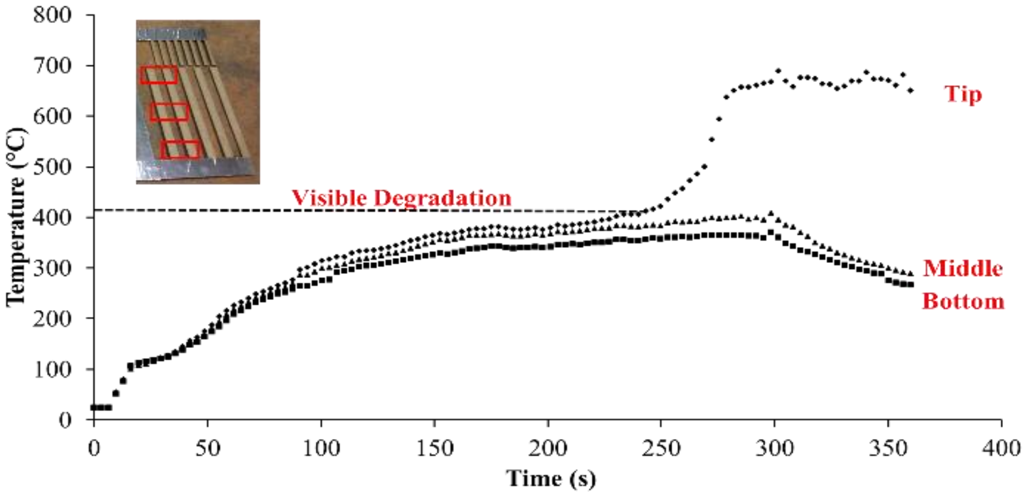

Figure 10 - Temperature history of the 1.27 cm wide x 15.24 cm high fuel element subjected to predominately radiative heating

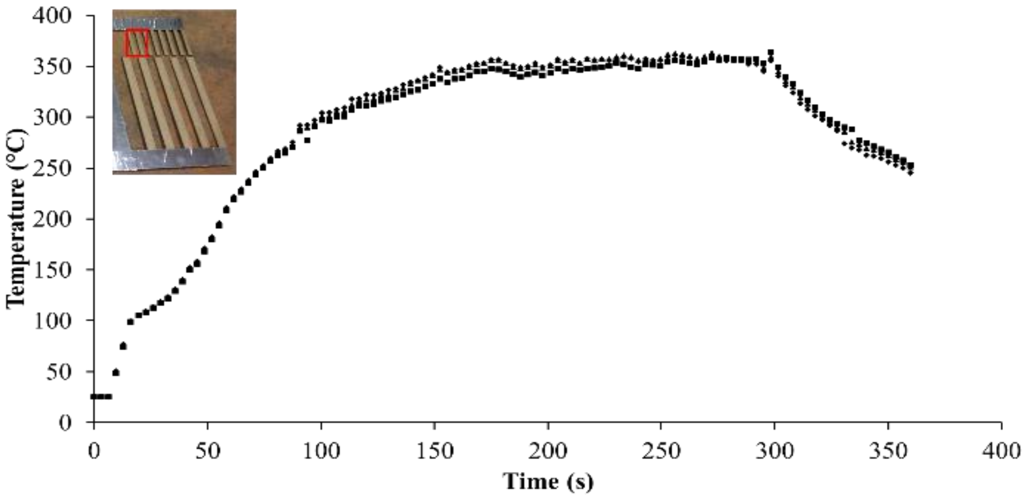

Figure 11 - Temperature history of the 0.635 cm wide x 5.08 cm high fuel element subjected to predominately radiative heating

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, perhaps based on previous studies by Adam *et al*. (2013), Emori and Saito (1983), and Emori and Iguchi *et al* (1988), 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 (McAllister & Finney, 2014) and therefore, a fundamental study to reveal ignition behaviour of live fuels is certainly needed.

4. Summary

This paper reports IR thermal image-based temperature history and ignition behavior of engineered cardboard fuel elements subjected to convective and radiative heating. Our results support the USDA's original findings that millimeter diameter pine needles cannot be ignited by radiation only even under a long duration fire generated radiant heat flux of an average 10.3 kW/m^2.

The objective of the air torch experiment was to examine convective heating of fuel particles. The tines above the torch represented the unburned fuel particles that are receiving flame contact near a spreading fire. This layout, however, does not exactly represent forest fire conditions, where fuel particles receive heat from a cross-flow as opposed to a parallel flow. We are planning to perform an additional experiment using a heat gun to simulate forced convection due to an imposed flow along and around cardboard fuel elements in cross-flow.

5. Acknowledgements

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