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Flame Spread through Arrays of Wooden Dowels

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In practical applications, flammable materials are often arranged in arrays of discrete objects whose combustion properties may vary compared to that of a homogeneous material. In this study, the influence of spacing between arrays of wooden dowels on the rate of upward flame spread through arrays has been studied. This configuration adds to previous work on single columns of matchsticks (Gollner et al., 2012), in some ways modeling physics that appears in flame spread through wildland fuels and suspended cable trays. A single dowel was ignited at the base of an array of birch dowels with fixed spacings of 0.75, 1.0 and 1.5 cm and allowed to spread upwards. In the wider-spaced cases (1.0 and 1.5 cm), the flame spread upward mostly along the center column, igniting few dowels to its side. In the 0.5 cm spacing, however, flame spread exhibited a two-dimensional nature, spreading throughout the array in a V-shaped pattern. Comparing results to an existing theory for upward flame spread and burning of single vertical columns of matchsticks, the far-spaced arrays follow the previous theory (Gollner et al., 2012); however rates of upward spread are decreased through the closer-spaced arrays. This may be due both to impedance of the flow through the array, but perhaps more importantly to a lack of available oxygen for burning. In the denser spacing of this configuration, significant unburnt fuel vapors are seen released above the array of this configuration. Results for mass-loss rates and spread horizontally through the array are also presented.

1. Introduction

Arrays of wooden sticks have proved to be a useful surrogate to test discrete fuel behavior in fire (Vogel & Williams, 1970). They have been used extensively in studies on wildland fires (Fons, 1950; Prahl & Tien, 1973), however only one study has previously been conducted on vertical arrays (Gollner, Xie, Lee, Nakamura, & Rangwala, 2012). Unlike propagation through horizontal arrays where a steady state is often reached, flame spread through vertical arrays of sticks is driven by buoyancy developing an accelerating behavior of flame spread.

In Gollner et al., a theory for flame spread rates, burnout times and burning rates was developed for flame spread through a single vertical row of sticks (Gollner et al., 2012). While this study provided important insight into the problem of flame spread through discrete fuels, it did not quantify the influence of whole arrays of discrete objects, where flame spread occurs in 2-D and is sometimes limited by the high density of available fuel. In this study, the previous work is extended by performing experiments on arrays of birch dowels with fixed spacings of 0.75, 1.0 and 1.5 cm. Flame spread occurs both upward through the array and horizontally between columns of sticks as the spacing increases. While rates of upward flame spread are well-predicted through the less-dense arrays, predictions are found to be significantly faster than upward spread rates through the highest density array. This work will attempt to describe these effects, with planned work in the future focused on quantitatively predicting these effects.

Practically, these configurations present similar features to flame spread through cable trays and some wildland fire fuel beds. In fires in cable trays, a small fire started on a lower wire tray will ignite wires above and then spread horizontally through the trays (Alvares & Fernandez-Pello, 2000; Hunter, 1979). This work may assist in the process of designing these trays so that flame spread is limited and predicting the maximum burning rates of cable trays, related to the maximum heat-release rates of the fuel. Effects such as radiation and the complex nature of wire trays may be added to the model in the future. Knowledge is also provided on wildland fire behavior, which has recently been found to be controlled by the ignition of fine fuels (Cohen & Finney, 2010; Finney, Cohen, Grenfell, & Yedinak, 2010),with mechanisms similar in many ways to those in the experiments conducted here.

2. Methods

Wooden dowels made of birch wood0.32 cm in diameter were cut to lengths of 3.18 cm and then sealed in an airtight container until just before experiments where they were exposed to the laboratory environment. Temperature and humidity measurements were taken during the experiments and varied between 73°-74°C and 17-46% relative humidity. In order to prevent the effect of the moisture content of the wood from affecting results, tests were performed at different spacings on different days, multiple times and no variation with differing ambient conditions was found.

A diagram showing the experimental apparatus used is shown in Figure 1 along with the configuration for three different spacings, with parameters tested shown in **Error! Reference source not found.**. The array of dowels was inserted into one of three pre-drilled aluminum plates which provided clear spaces both below the array of dowels and on the sides in order to reduce the effects of the flow rate at the edges of the plate from influencing test results. The aluminum plate was mounted atop a drip pan used to collect any material that may drop during burning. Both were placed atop a load cell to measure the mass loss of the experiment over time. The apparatus was placed below a fume hood to vent the products of combustion and curtains placed around the far outer edge of the setup were used to reduce flow effects from the laboratory from influencing the experiment.

Experiments were begun by igniting one dowel placed below the center column of the bottom-most row. This dowel was ignited with a standard lighter while a metal place was held in place above it to prevent ignition or preheating of sticks above. The experimental time began once the metal plate was removed.

The spread of flames through the matchstick array was observed by a front-facing Sony, high-definition camcorder recording at 60 frames per second (fps). While in experiments on single rows of matchsticks (Gollner et al., 2012), ignition was observed with a side-facing camera, this was not possible in the present experiments because the dense columns of wooden dowels obstructing the view. To overcome this, a high speed camcorder (Casio EFX-1) was used to record the experiments at 300 fps. Through trial and error, it was found that observing the array from the front at an angle slightly off center allowed the best observation of igniting dowels between flames. The high speed video was tediously analyzed after experiments and ignition was defined as the point where 50% of the observable region of the wood dowel had blackened. Burnout was defined as the point when flames adjacent to burning dowels ceased to be observed in the video. In the densely-spaced configuration, for instance, 529 dowels had to analyzed frame by frame (with frame rates of 300 fps), constituting a very time consuming process. Infrared video recordings were also attempted, but found to be unsatisfactory due to excessive soot in the flames between wooden dowels.

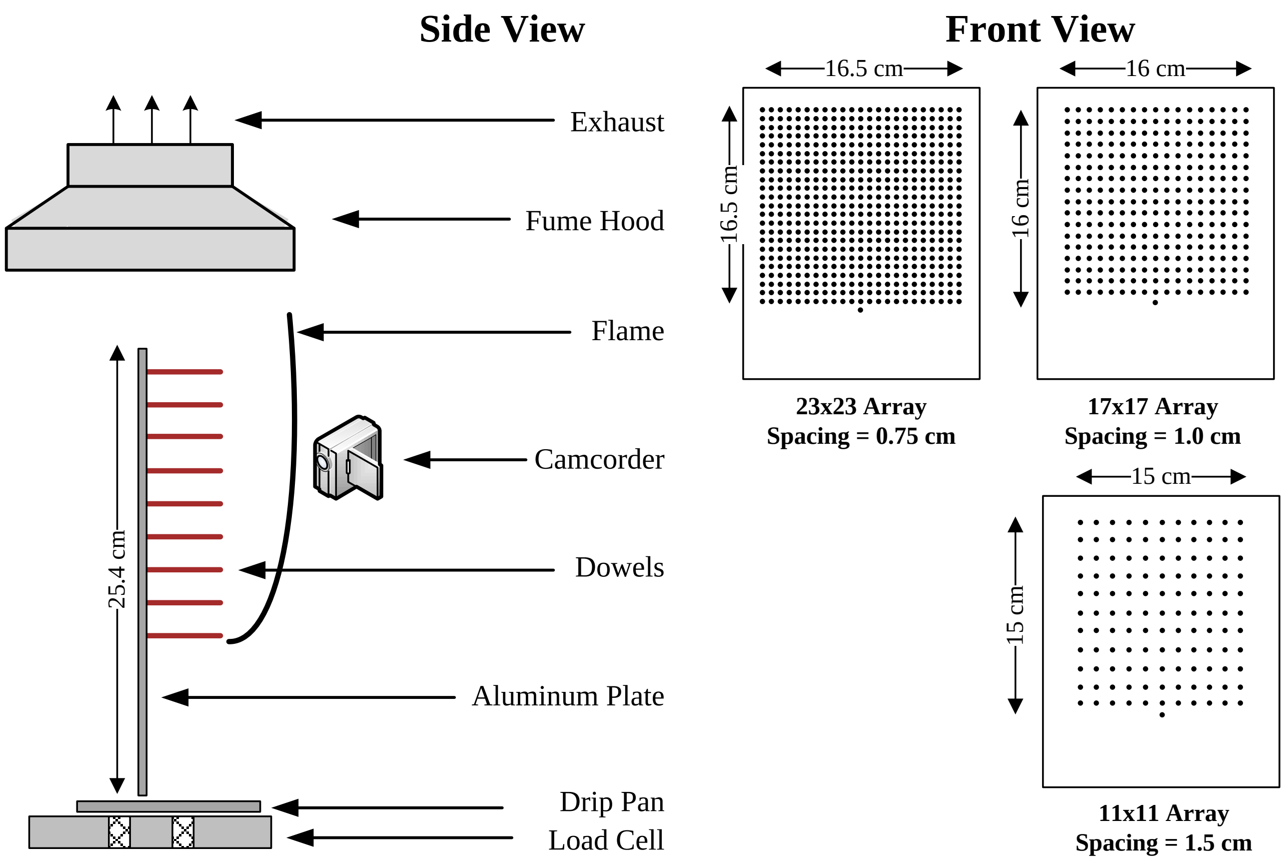

Figure 1: Experimental setup (left) and aluminum plates used to hold array of wooden dowels (right).

3. Results and Discussion

Figures 2, 3 and 4 show the flame spread process through the array of wooden dowels. In the widest spacing, 1.5 cm, the flame spreads just along the center column of dowels without igniting sticks to either side, similar to previous experiments by Gollner et al. (Gollner et al., 2012). As the spacing decreases, up to 1.0 cm, the flame primarily spreads up the center column, however towards the top row some horizontal spread occurs, and igniting matchsticks in adjacent vertical columns. In the densest array, with 0.75 cm spacing, flame spread occurs simultaneously both upwards and outwards. The rate of upward spread was noticeably slower than in the less-spaced arrays. White smoke was also observed above the array along with intermittent flames present, suggesting burning occurred within at least some parts ofthe array in an under-ventilated condition.

Table 1: Experimental configurations tested, where S/d is the ratio of the spacing to diameter of wooden dowels.

Spacing	Dowel Diameter	S/d Ratio
1.5 cm	0.32 cm	4.72
1.0 cm	0.32 cm	3.15
0.75 cm	0.32 cm	2.36

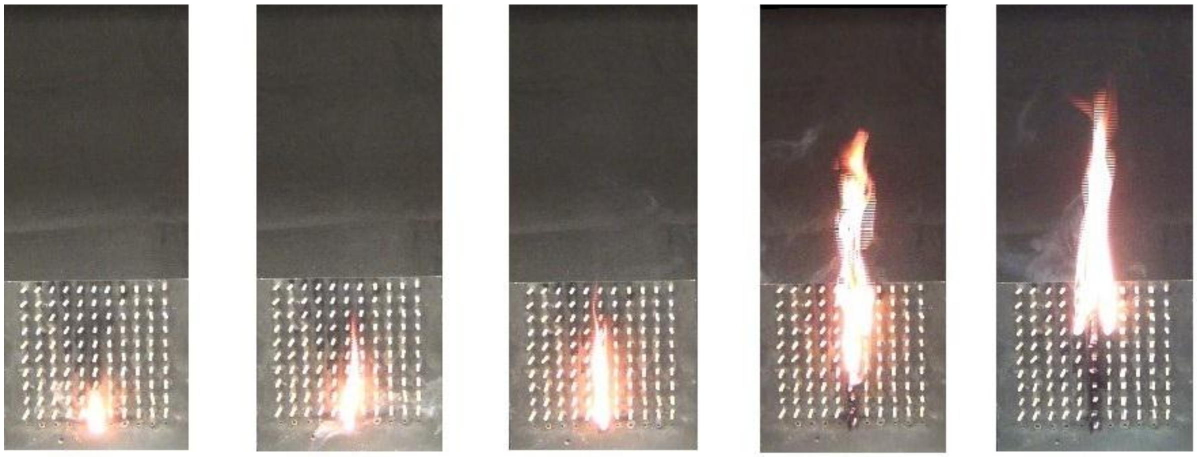

Figure 2: Front video showing a time-lapse of the behavior of experiments with a spacing of 1.5 cm.

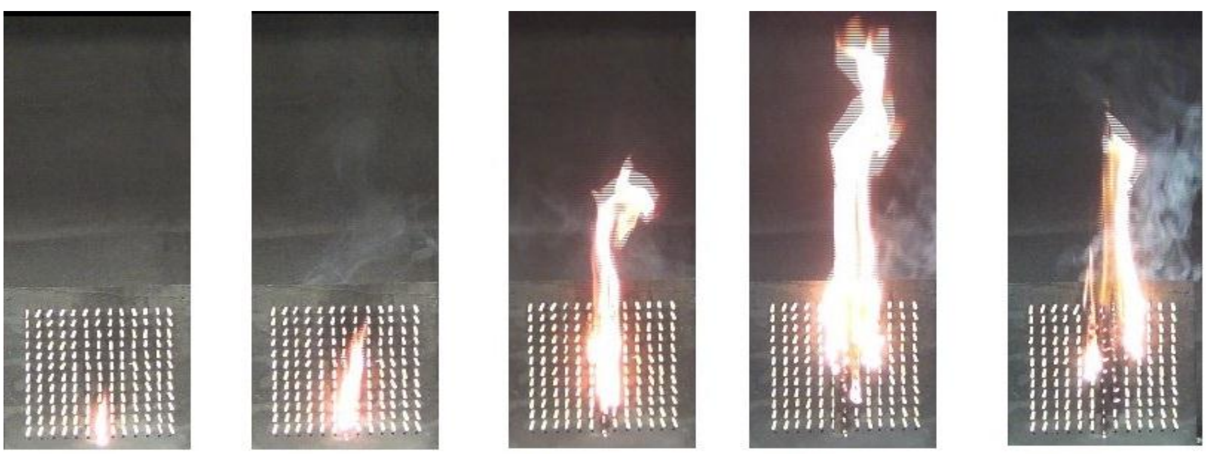

Figure 3: Front video showing a time-lapse of the behavior of experiments with a spacing of 1.0 cm.

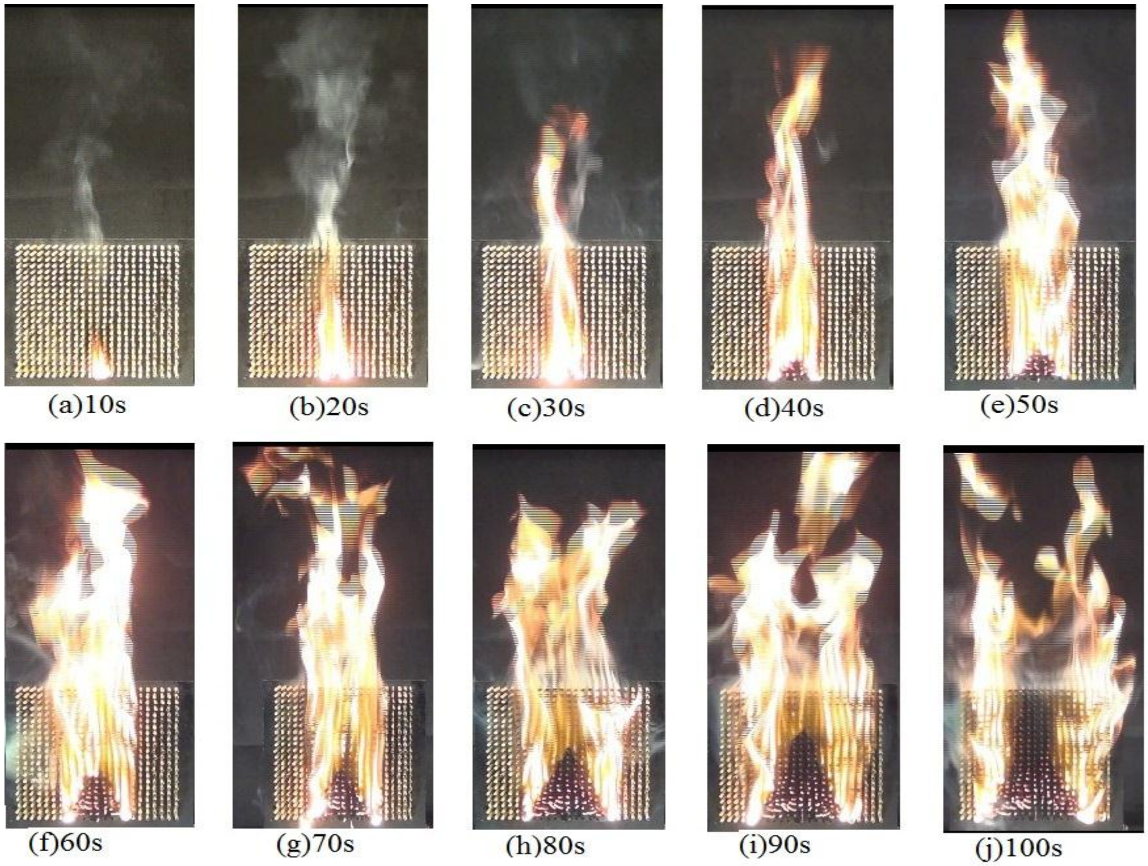

Figure 4: Front video showing a time-lapse of the behavior of experiments with a spacing of 0.75 cm.

Measurements of the ignition times up the array of wooden dowels, here defined as the flame spread rateare shown in Figure 5. The rate of flame spread is shown to decrease with decreasing spacings. Horizontal error bars in the figure represent the standard deviation of variations between repeated tests. While there are some expected variationsbetween tests, it appears that the repeated tests performed have no noticeable effect on the outcome.

Predications for the ignition of dowels in the center column are also shown in Figure 5 as dashed lines. These predictions are based on the work of Gollner et al. (Gollner et al., 2012), where predictions of the ignition time of matchsticks was based upon convective heating. The wooden dowels in this study are assumed to ignite when enough heat flux is imparted to pyrolyze combustible vapors in the wood, estimating a time to ignition fron the time to pryolysis,

$$t_{ig} = \rho_s c_{p,s} d(T_p - T_\infty)/\overline{\dot{q}''}, \tag{1}$$

where t_{ig} is the time to ignition, $\rho_s c_{p,s} d$ the produce of the density, specific heat and diameter of the solid fuel, T_p the pyrolysis temperature of the fuel, T_∞ the ambient temperature and $\overline{\dot{q}''}$ the average heat flux over the area of the wooden dowel (Fernandez-Pello, 1995). For a transient ignition process, the average heat flux in Equation 1 can be estimated from correlations for cross flow over a cylinder, found to be the best estimate for heat flux to a stick immersed in fire (Albini & Reinhardt, 1995). The correlation used to describe the heat transfer from flames to individual sticksis

$$\overline{Nu_d} = 0.344 Re_d^{0.56}, \tag{2}$$

where $\overline{Nu_d} = \bar{h}d/k_g$ is the average Nusselt number of the flow, $\bar{h}$ the heat transfer coefficient and $k_g$the thermal conductivity of the gas evaluated at $T_g = (T_p + T_\infty)/2$. A Reynolds number must be used in order to use a forced-flow correlation, $Re_d = \rho u_g d/\mu_g$, where ρ and μ_g are the density and viscosity of the gas evaluated at T_g, respectively. u_g is a buoyant velocity, $u_g \approx \sqrt{gx}$estimated from the height of the stick,x.

Equation 2 is then used with the definition for the average heat flux to a wooden dowel, $\overline{\dot{q}''} = \bar{h}(T_s - T_\infty)$ to assess correlations at the height of each stick, using Equation 1 to calculate the ignition time for each stick.

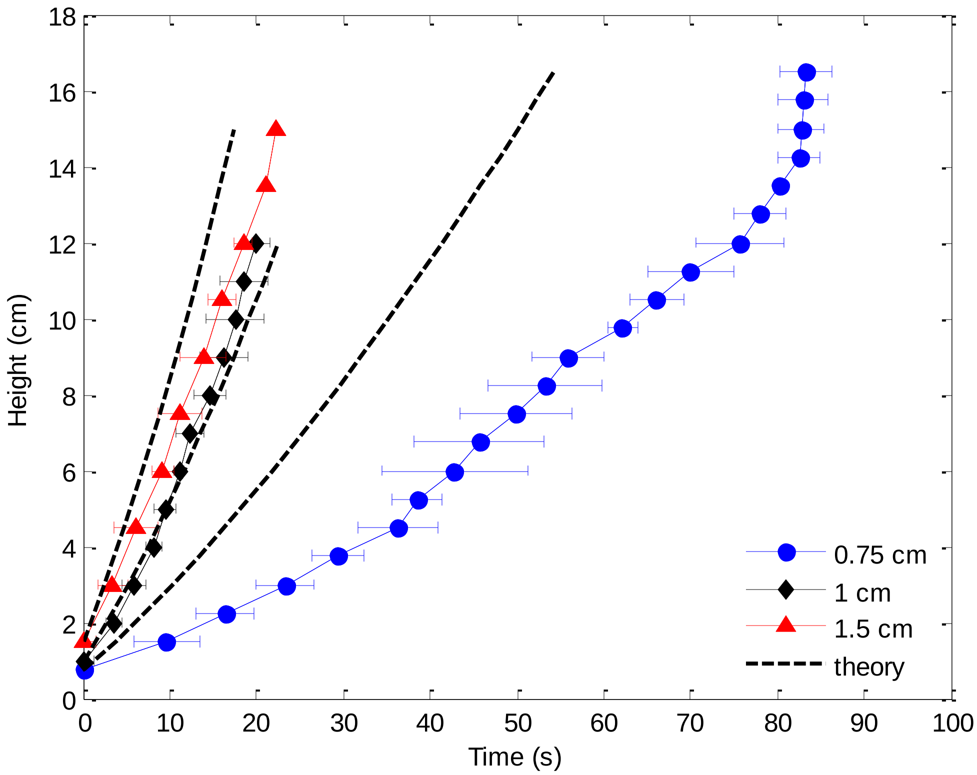

Figure 5: The spread of ignitions along the center column of wooden dowels is shown, with horizontal error bars indicating the standard deviation of ignition times between multiple tests. Dashed lines indicate theoretical predictions for the three spacings of dowels used in this study, based on the theory of Gollner et al. (Gollner et al., 2012). The results have all been shifted so that ignition of the first matchstick above the igniter corresponds to *t* = 0, removing effects of the ignition source that are most variable at the bottom row of the experiment.

Maximum spread rates horizontally through the array, shown in Figure 6 appear to be fairly constant over time for the two spacings in which data was available. By maximum rates, it is meant that the rate is calculated by finding the furthest dowel ignited to either side of the center column at every time step. Similarly constant rates are observed when calculating the horizontal spread rate for each row in which this spread occurs, pointing towards a similar mechanism for horizontal spread that is independent of spacing or height. Such spread may therefore be dominated by a simple conductive process from flames to unignited sticks, similar to the theory provided for horizontal spread by (Vogel & Williams, 1970), in contrary to an alternatively-theorized plume model. Further development of a theory for spread horizontally through the array is under way.

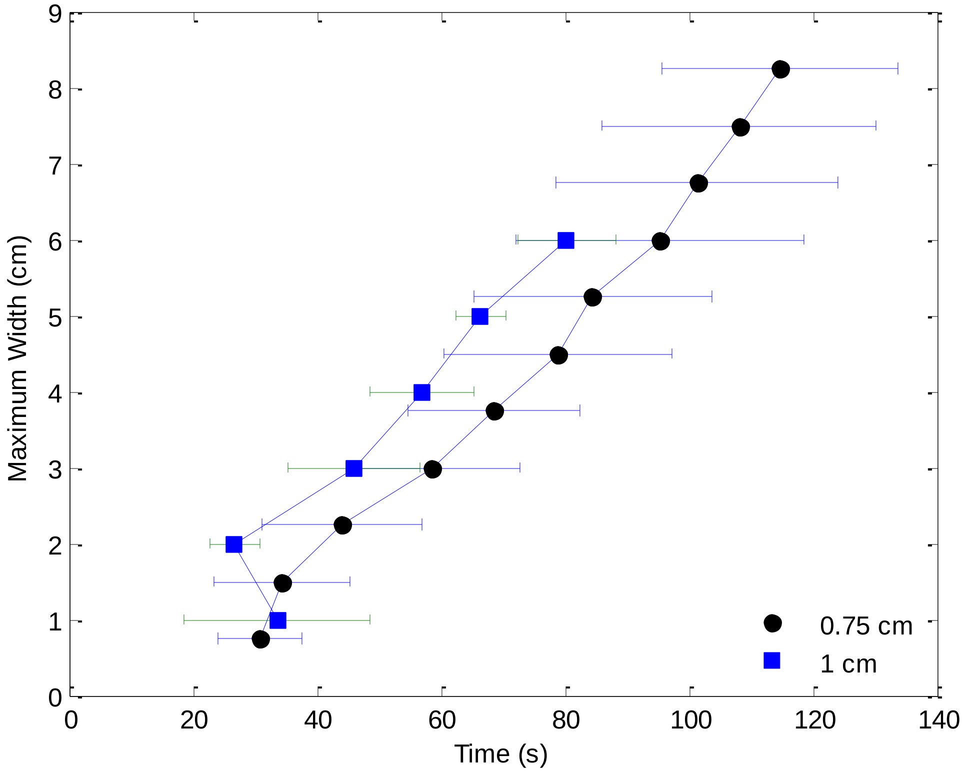

Figure 6: The maximum width that ignition has spread horizontallythrough the array is shown. The furthest-spaced array, 1.5cm is not shown because flames did not spread horizontally more than one column. Horizontal error bars indicate the standard deviation of ignition times between multiple tests.

Burnout times through the array were also observed using high-speed video, and the results of center column burnout times are shown in Figure 7. The burnout data, perhaps more subjective to errors in observations as well as inconsistent processes during the burning of individual matchsticks, is not as clear as the ignition data. Trends however are still observed similar to those seen in Figure 5.

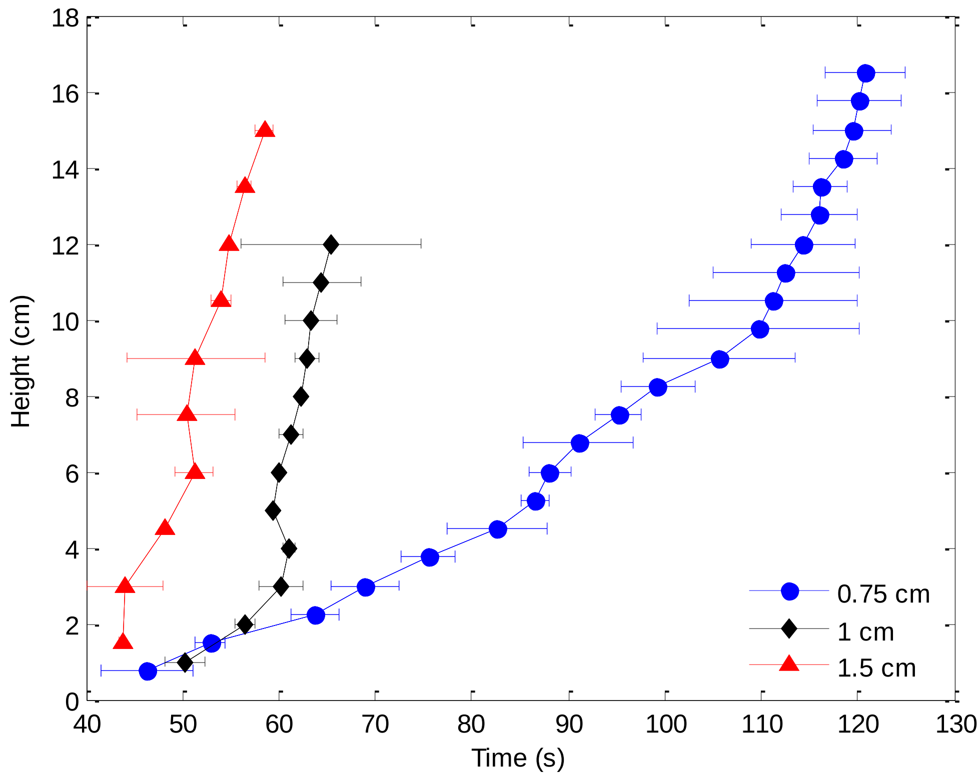

Figure 7: Burnout through the center column of the array, observed by high-speed front video recording. Horizontal error bars indicate the standard deviation of burnout times between multiple tests.

Figure 8 gives us a clearer picture of the burnout behavior of the center column, subtracting the ignition times of each dowel from its burnout time. This total time of burning gives a qualitative estimate of the burning rate for each matchstick, with longer times corresponding with lower overall burning rates. Errors are not shown in Figure 8 in order to more clearly see the experimental data, but can be inferred from Figures5 and 7.

The burning duration for arrays seem to have a slight trend of shorter burning times with height, indicating higher burning rates at higher elevations. This seems reasonable, as higher-velocity flows result in increased convective heating at higher elevations, not to mention more availability of oxygen for burning, especially in the densest-space array. Still, these results are contrary to previous results (Gollner et al., 2012) and the associated theory.

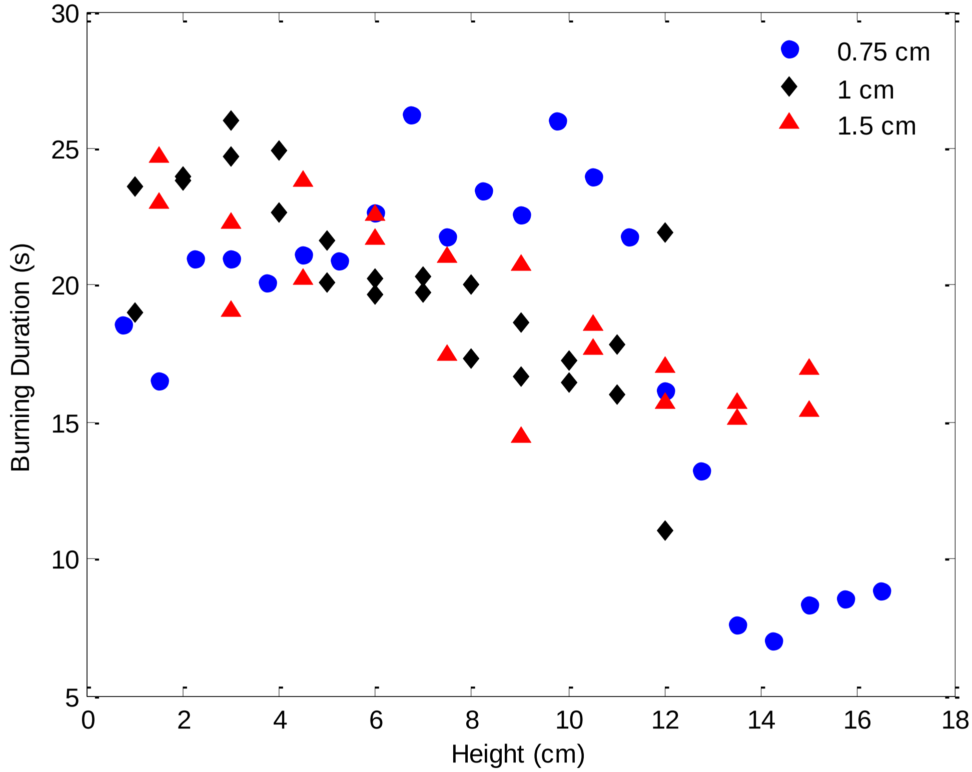

Figure 8: The burning duration of the center column of dowels is shown, calculated from subtracting the ignition time (Figure 5) from the burnout time (Figure 7). While results are not perfectly clear, especially for the smallest spacing, it appears there is at least a slight tendency for burning duration to decrease with height.

4. Conclusions

The study of arrays of wooden dowels has provided a useful surrogate to study the flammability of discrete fuels, including convective heating processes often found in wildfires and flame spread through cable trays. The results point toward a limit to the theory developed for flame spread through single columns of matchsticks once dowels are spaced close enough together to encourage flame interaction between adjacent dowels. This in turn decreases the fire spread rate due to a lack of available oxygen. Future work will further investigate this effect and find appropriate methods to describe it in spread through these arrays as well as wildland fuel beds.

Acknowledgements

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