Critical mass flux for flaming ignition of dead, dry wood as a function of external radiant heat flux

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ABSTRACT

Extreme weather often contributes to crown fires, where the fire spreads from one tree crown to the next as a series of piloted ignitions. An important aspect in predicting crown fires is understanding the ignition of fuel particles. The ignition criterion considered in this work is the critical mass flux criterion – that a sufficient amount of pyrolysis gases must be generated for a diffusion flame to be established above the surface. An apparatus was built to measure the critical mass flux for sustained flaming ignition of woody materials for varying environmental conditions (heat flux and external oxidizer flow velocity). This paper reports the results of measured critical mass fluxes for dead, dry poplar under a constant flow velocity of 1 m/s under a range of radiant heat flux levels from 20 kW/m^2 to 50 kW/m^2. The critical mass flux is seen to agree qualitatively with those in the literature (around 1-2 g/m^{2}s) and to increase with increasing levels of heat flux. Future work will explore the changes in critical mass flux with flow velocity, fuel moisture content, species, and live fuels.

INTRODUCTION

Wildfires are a costly and deadly problem. Extreme weather often contributes to crown fires, where the fire spreads from one tree crown to the next as a series of piloted ignitions. An important aspect in predicting crown fires is understanding the ignition of fuel particles. Many theories for ignition criteria exist in the literature [1], such as ignition temperature and flux-time product [2], but most are empirically derived and can only be applied in the conditions in which they were measured (see [3]). The "critical mass flux" criterion, however, can potentially be derived from fuel properties, scale from the smallest fuel particles to much larger slabs of fuel, and is the most physically correct [4]. This approach was primarily developed with polymeric materials [4,5,6], but has not been explored in the context of wildland fuels.

When a solid material is heated to a sufficiently high temperature, thermal degradation, or pyrolysis, occurs. In flaming combustion, it is these gaseous products of pyrolysis that ignite and burn as a diffusion flame over the surface. As a material is heated, these pyrolysis gases will escape from the surface and mix with the ambient air. If the fuel and air mixture is within the flammability limits, a premixed flame will form near the ignition source (pilot). In order for a sustained flame to exist, enough pyrolysis gases must be generated such that the heat losses from the premixed flame don't extinguish the flame. Because the temperature and heat release rate of a premixed flame increases with fuel concentration, there is a critical production rate of pyrolysis gases per surface area of fuel, or critical mass flux, in order to initiate sustained flaming. Note that the critical mass flux ignition criteria is equivalent to two other ignition criteria used in the literature – the critical flame temperature [7,8] and critical heat release rate criteria [9,10].

Though the idea of there being a critical mass flux for ignition was first proposed in regard to wood by Bamford, Crank, and Malan [11], it has primarily been measured with polymers. Perhaps the first carefully performed experiments to measure the critical mass flux were performed by Rasbash *et al*. [4]. For PMMA they found that the critical mass flux slightly increased as the heat flux increased from 12 to 20 kW/m^2 but indicated that it may level out for higher heat fluxes. In contrast, Rich et al. [6] saw the critical mass flux continues to increase at least to 25 kW/m^2 for both polymethylmethacrylate (PMMA) and a polypropylene/glass fiber composite. Though PMMA and polypropylene are not char forming, Staggs [12] suggests that a non-charring polymer with inert fillers, such as the composite tested by Rich *et al*., do behave as a charring material like wood. Drysdale and Thomson [5] also found that the critical mass flux generally increases up to 35 kW/m^2 for many non-charring polymers including PMMA, fire-retarded PMMA, polypropylene, fire-retarded polypropylene, polystyrene, and fire-retarded polystyrene. For a charring polymer (ethylene vinyl acetate copolymer – EVA), Staggs developed an ignition model that predicts the measured increase in critical mass flux with heat flux up to 70 kW/m^2. In one of the few works found that actually measured the critical mass flux of a wood product, Delichatsios [13] saw an increase with heat flux between 25, 35, and 50 kW/m^2 for both plywood and fire retarded plywood. The goal of the current research effort is to determine whether the trends in the critical mass flux for ignition that were observed for other materials hold for the solid fuels more likely to be found in a wildfire. As a first step, the research presented here will explore the effect of the radiant heat flux on dry poplar.

EXPERIMENT DESIGN

An apparatus was built to measure the critical mass flux for sustained flaming ignition of woody materials for varying environmental conditions such as heat flux and airflow velocity. This apparatus, based on the Forced Ignition and Flamespread Test [14], consists of a small-scale wind tunnel, infrared heater, coiled wire igniter, and a high precision mass balance (see Figure 1). The tunnel is 9 cm tall, 25 cm wide, and 60 cm long. A fan at the entrance produces a laminar forced airflow through the tunnel with a velocity ranging from 0.8 to 1.6 m/s. The sample, measuring 9 cm by 9 cm with a depth of 1.2 cm, is placed on top of the mass balance with the upper surface of the sample flush with the bottom of the tunnel. The sample is heated from above using an infrared heater capable of producing a uniform heat flux of 0 to 50 kW/m^2 over the sample surface. As the sample is heated, pyrolysis begins. The forced flow pushes the pyrolysis gases into the coiled Kanthal wire igniter that initiates ignition. To remove the igniter location as a potential variable in the experiments, the 3.5 mm diameter igniter is fixed 1.2 cm downstream of the sample, centered 4.25 mm off the bottom. Additionally, the igniter consisted of a fixed number of coils and the supplied current was calibrated to keep the igniter above 1000°C. The time to ignition is recorded visually and confirmed with a 3 mil (.003 inch/.076 mm) K-type thermocouple located near the middle of the top surface of the sample. The temperatures of the top and bottom surfaces of the sample, along with the instantaneous mass reading are logged at a rate of 5 Hz. To explore the effect of external heat flux on the critical mass flux for ignition, tests were performed with a fixed airflow velocity of 1 m/s with irradiances from 20 to 50 kW/m^2. All tests are repeated three times to provide an estimate of the experimental variability.

The material used was dry (approximately 0% moisture content) poplar (*Liriodendron tulipifera*). Poplar was chosen because of its consistent grain, lack of knots, and contains a higher proportion of cellulose than other common woods [15]. The samples were weighed and then conditioned in an oven at 80°C for 48 hours. Upon removing the samples from the oven, they were immediately reweighed before being placed in an air-tight container with silica gel packets to cool. The samples were left in these containers for up to a few days before use. Prior to a test, the sample used was reweighed to asses any changes in moisture content. On average, the samples gained approximately 0.21% moisture content before use. Each sample was darkened with powdered graphite to increase its absorptivity. The sample holder was a thin, lightweight aluminum box with a 1.27 cm thick Cotronix board on the inside. The edges of the samples were insulated with Cotronix paper to minimize heat losses and edge effects. In every test the sample was mounted in the tunnel with the grain perpendicular to the airflow direction. The balance used has a precision of 0.1 mg. To minimize errors in the balance readings due to vibrations, the entire apparatus is mounted on a granite weighing table with the balance on an isolated marble block. A temporary wind screen is also placed around the balance to reduce the effect of any ambient air currents. Care is also taken to maintain a constant balance temperature to prevent drifts in the readings from elevated temperature.

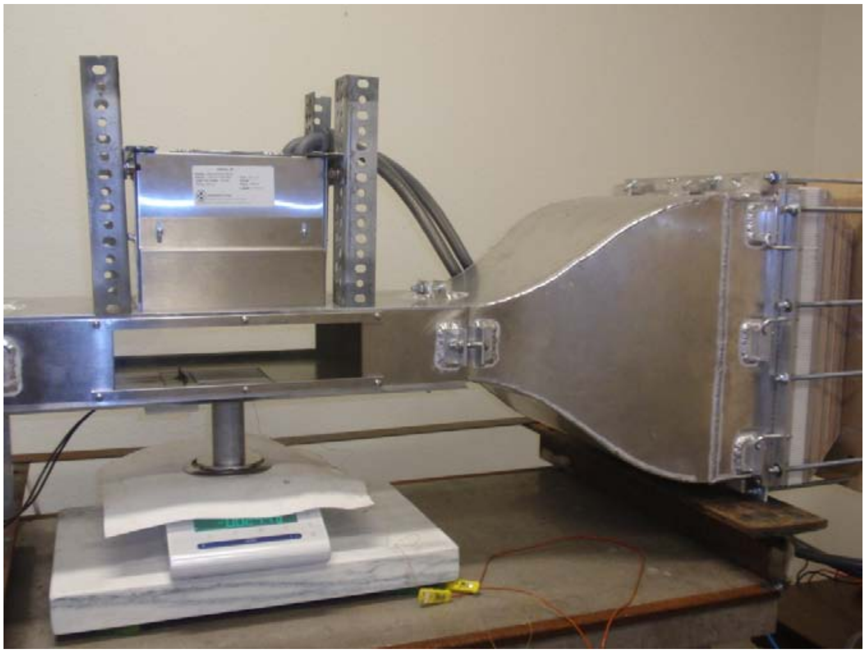
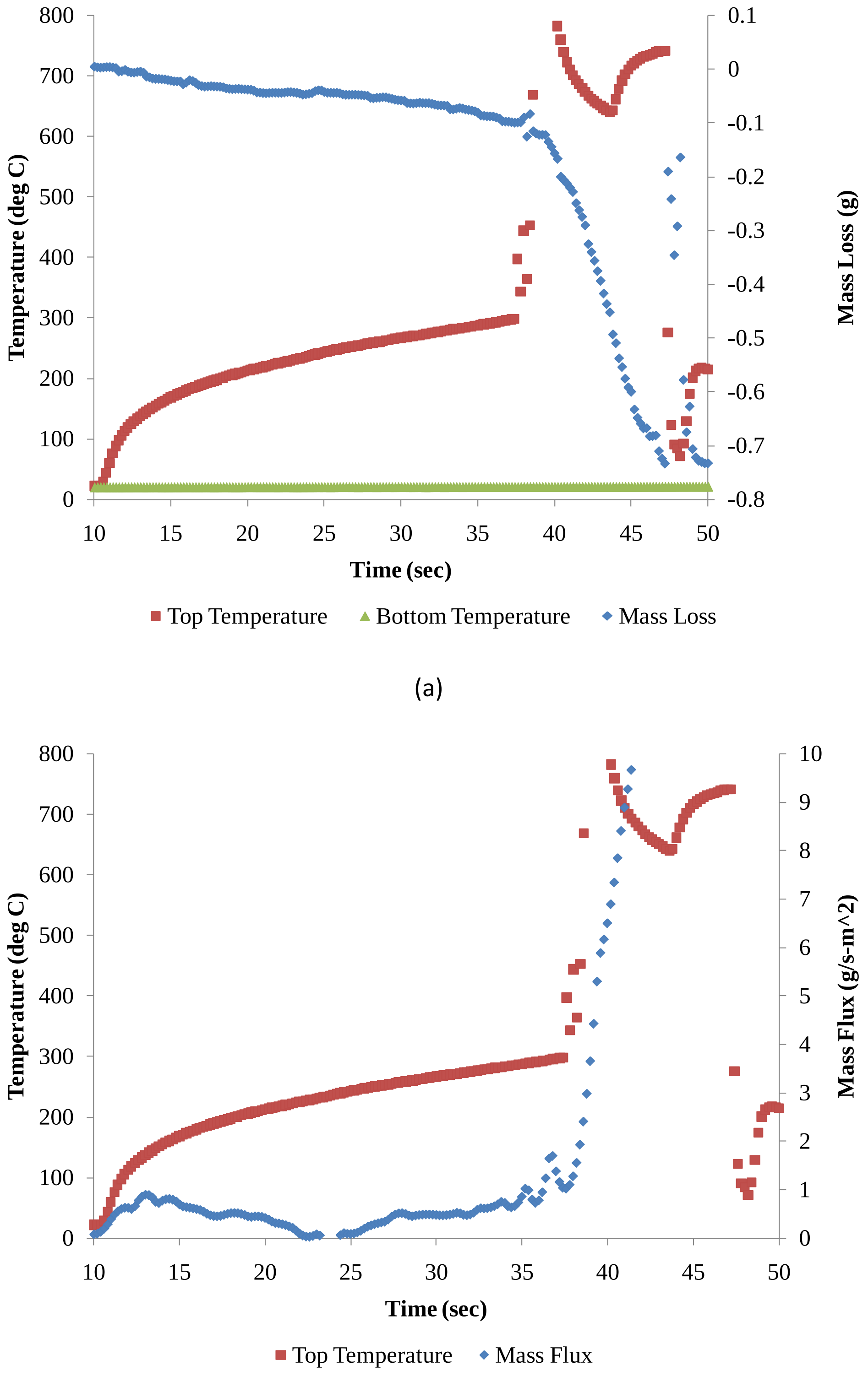


Figure 1 – Experiment apparatus: small-scale wind tunnel with high precision balance

RESULTS AND DISCUSSION

Figures 2a and 2b show the temperature and mass measurements for a representative test. This particular test was performed with a heat flux of 30 kW/m^2 and flow velocity of 1 m/s. As shown in Figure 2a, once the infrared heater is turned on, the temperature of the sample begins to increase. The sharp spike in temperature at about 37 seconds indicates ignition. Notice, however, that the temperature "stalls" at about 450°C. This means that the first increase in temperature was due to flashing ignition. Flashing ignition was seen visually at this approximate time as well. Sustained ignition occurred about a second later when the temperature continued its rise to above 800°C, in agreement with visual observations. Figure 2a also shows the change in mass with time. As the sample is heated, it loses mass due to pyrolysis. At the moment of ignition, however, the rate of mass loss dramatically increases. Looking closely at the mass loss curve at the moment of ignition, also noticeable are fluctuations in the readings possibly due to a pressure wave from the ignition event. In evaluating the mass flux, these erratic data points were excluded. Due to this and other noise in the data, a locally weighted scatterplot smoothing, or LOESS, was applied to the data. The mass flux is then slope of the LOESS fit to the mass loss curve divided by the sample surface area and is shown in Figure 2b. Note that the mass flux is shown as a positive quantity for clarity. The value of the critical mass flux for ignition was then determined as the value of the mass flux at the moment of ignition. The moment of ignition was evaluated using both the visual ignition times and the thermocouple data. In the example presented in Figure 2, the ignition time was assumed to be 38.2 sec with a corresponding critical mass flux of 1.554 g/sm^2.

Though this procedure seems straightforward, some difficulties arose, particularly in determining the exact moment of ignition in both the lower heat flux (20 kW/m^2) and the highest heat flux (50 kW/m^2) tests. In the cases of high heat flux, the rate of change of the temperature and mass flux data is very quick (see Figure 3). Thus there are fewer data and very small errors in ignition time correspond to very large changes in mass flux values. For the test in Figure 3, a one second difference in ignition time corresponds to a change in mass flux from 1.052 to 1.816 g/s-m^2, a 73% difference.



(a)

(b)

Figure 2 – Typical temperature, mass loss (top), and mass flux (bottom) measurements

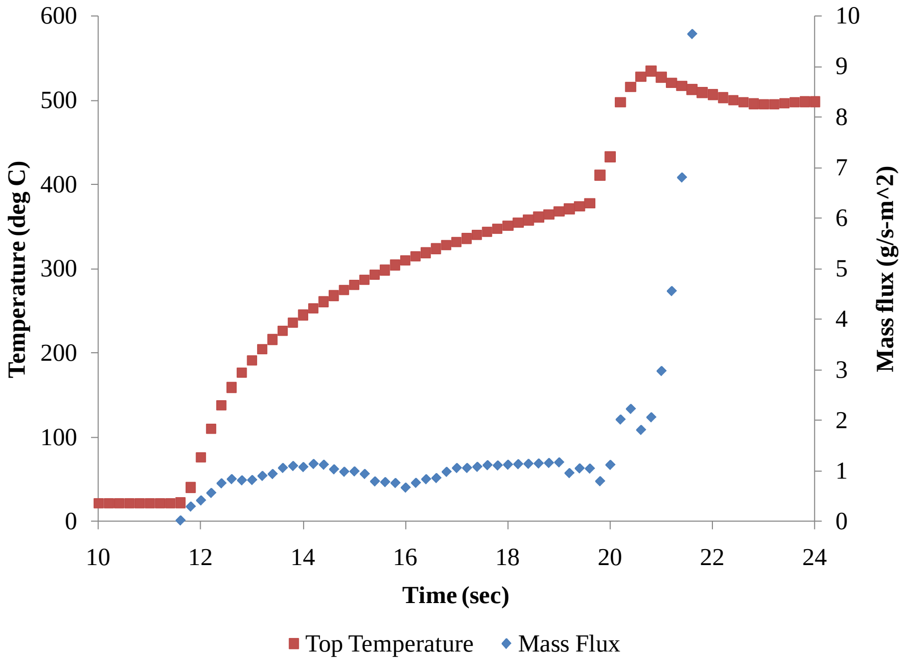


Figure 3 – Temperature and mass flux for test at 50 kW/m^2

For the lowest heat flux tested (20 kW/m^2), another difficulty was encountered. Figure 4 shows the mass flux and temperature for a test at 20 kW/m^2. The time scale has been adjusted to more clearly see the data near ignition. Based on the temperature data, flashing ignition occurs at 80 seconds and sustained ignition at about 80.8 seconds. However, the mass flux clearly starts to spike at around 78 seconds. This "preignition" spike in mass flux occurred in all tests performed at 20 kW/m^2 so it is not thought to be remaining noise in the data. It is likely that at this low heat flux smoldering ignition is occurring prior to flaming ignition. In their ignition experiments, Bilbao et al. [16] also found smoldering to be significant for heat fluxes lower than 30 kW/m^2. It is possible that the small jump in mass flux seen in Figure 2 for 30 kW/m^2 may also be due to smoldering ignition occurring before the flaming event. In fact, Fangrat *et al*. [3] saw solid ignition before flaming ignition for heat fluxes up to 50 kW/m^2. In this experiment design, the igniter is providing a slightly higher radiant heat flux to the nearest portions of the sample which could start a local smoldering reaction. Because the thermocouple is located near the middle of the sample, the temperature rise due to the smoldering won't necessarily be seen on the thermocouple trace. However, the balance is sensitive enough to pick up the associated small change in mass thus increasing the mass flux without a corresponding increase in temperature. Without the smoldering providing an additional source of heat and pilot, ignition may occur later or not at all [17]. In a fire scenario, this pathway to ignition is still probable and must be considered. For the purposes of this paper, the mass flux at this initial increase was taken as the critical mass flux for ignition even though this may not truly represent the critical mass flux for sustained *flaming* ignition for the lowest heat flux.

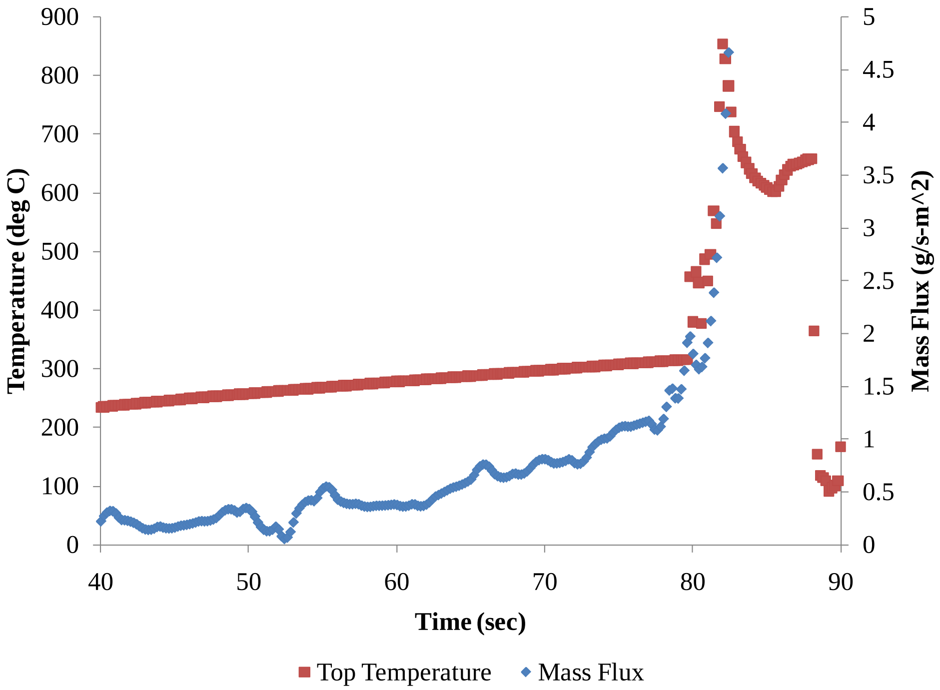


Figure 4 – Temperature and mass flux for test at 20 kW/m^2 illustrating probable smoldering ignition.

Table 1 – Critical mass flux and ignition time results with heat flux.

Heat flux (kW/m^2)	Flow velocity (m/s)	Average ignition time (sec)	Average critical mass flux (g/s-m^2)	St. dev. (% of mean)
20	1	75.3	1.061	10.50
30	1	31.0	1.564	1.00
40	1	16.7	1.656	6.98
50	1	9.7	2.000	12.30

The results of the critical mass flux for ignition measurements with varying heat flux are shown in Table 1 and Figure 5. The results represent an average of three tests. In Table 1, it is clear that the variation of the data is greater with both the high and low extremes of heat flux tested here due to the reasons discussed above. The average standard deviation for all heat flux levels (7.7%) was used to generate the error bars in Figure 5.

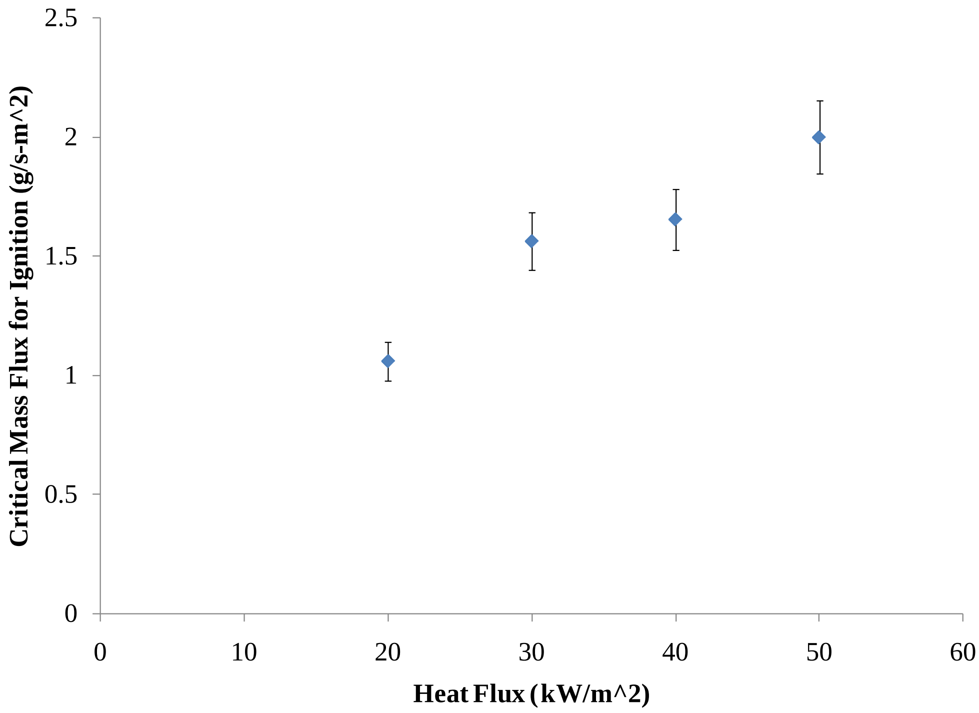


Figure 5 – Critical mass flux for ignition as a function of external heat flux.

The critical mass flux for ignition ranges from about 1 to 2 g/s-m^2. Values reported in the literature range from about 0.5 to 5.5 g/s-m^2 for a range of materials [4-13]. Thus, the values measured here are within the range of those measured by others. As indicated in Figure 5 and Table 1, the critical mass flux for ignition increases as the heat flux increases. This agrees with the trends found by Rich *et al*. for PMMA and a polypropylene/glass composite [6], Staggs for a charring polymer (EVA) [12], and Delichatsios for plywood [13]. Interestingly, Boonmee and Quintiere in [17,18] examined the onset of glowing autoignition for wood. In their experiments and model, smoldering autoignition was seen for before flaming autoignition for heat fluxes up to 40 kW/m^2. For smoldering autoignition from 10 to 40 kW/m^2, the critical mass loss for glowing autoignition also followed the trends for flaming piloted ignition noticed here and elsewhere.

SUMMARY AND FUTURE WORK

The critical mass flux for ignition is quite possibly the most physically correct ignition criterion. For this reason, a series of experiments will be performed to measure the critical mass flux for fuels more likely found in a wildfire. The work presented here is envisioned as the first step toward understanding ignition of complex wildland fuel structures with the ultimate goal of better understanding and predicting how wildfires spread. As a first step, the critical mass flux was measured for dry poplar under a varying external radiant heat flux. The values measured here were within the range of those reported in the literature for a wide variety of materials. The critical mass flux was seen to increase with heat flux, a trend also seen in the literature for several polymers.

In performing these experiments, several issues were encountered and discussed. Before moving forward with the work, these issues presented here need to be addressed. One possible solution to the uncertainty in the results at high heat flux values is to take data at a higher sampling rate. This, however, may add additional noise to the data. A high speed and infrared camera will be used to examine the ignition of all tests, but in particular the low heat flux tests to perhaps see if smoldering is in fact preceding flaming ignition. Also, more thermocouples could be added to the surface to help clarify the smoldering versus flaming question. Once these questions are resolved, the next phase in this set of experiments will explore the effect of airflow velocity on the critical mass flux for ignition. Future work will explore the changes in critical mass flux with thickness, grain direction, fuel moisture content, species, and live fuels.

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