7th US National Technical Meeting
of the Combustion Institute
Hosted by the Georgia Institute of Technology, Atlanta, GA
March 20-23, 2011

Critical mass flux for flaming ignition of wood as a function of external radiant heat flux and moisture content

S. McAllister, M. Finney, and J. Cohen

RMRS Missoula Fire Sciences Laboratory, USDA Forest Service, 5775 W US Highway 10, Missoula, MT 59808, USA

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 variation of measured critical mass fluxes for poplar with externally applied radiant heat flux and moisture content. The critical mass flux is seen to agree qualitatively with those in the literature (around 1-3 g/m^2s) and to increase with increasing levels of heat flux and moisture content. Future work will explore the changes in critical mass flux with species, thickness, and live fuels.

1. 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" (CMF) 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 lean premixed flame increases with fuel concentration, there is a critical production rate of pyrolysis gases per surface area of fuel, or critical mass flux (CMF), in order to initiate sustained flaming. Note that the critical mass flux ignition criteria is related 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. In general, the critical mass flux for ignition is seen to increase with heat flux for both non-charring [4, 5, 6] and charring [12] polymers. 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 and 50 kW/m^2 for both plywood and fire retarded plywood. The critical mass flux for ignition of non-charring polymers also appears to increase with oxidizer flow velocity [4, 6]. 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. The research presented here will explore the effect of the radiant heat flux and moisture content with poplar slabs.

2. 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 (corresponding to Reynold's numbers of $3\text{-}6\cdot10^4$, well under the transition to turbulent flow). 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, a position which covers the entire fuel concentration boundary layer. 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 combined effect of moisture content and 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 and moisture contents from 0-18.5% (dry basis). All tests are repeated three times to provide an estimate of the experimental variability.

The material used was 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]. Experiments were performed with moisture contents of approximately 0%, 8%, and 18.5% on a dry weight basis. All samples were weighed and then conditioned in an oven at 80°C for at least 48 hours. Upon removing the samples from the oven, they were immediately reweighed to assess the dry weight. The dry (0% moisture content) samples were then placed in an air-tight container with silica gel packets to cool. The dry samples were left in these containers for up to a few days before use. Prior to a test, the dry sample used was reweighed to asses any changes in moisture content. On average, the samples gained approximately 0.21% moisture content before use. To obtain moisture contents of 8% and 18.5%, freshly dried samples were placed in a conditioning chamber at 24°C and 55% relative humidity, and 30°C and 90% relative humidity, respectively. The samples were left in the conditioning chamber until the change in moisture content was minimal (0.01%) which took about ten days. All "wet" samples were burned within ten minutes of being removed from the conditioning chamber.

All samples were darkened with powdered graphite to increase absorptivity. The sample holder was a thin, lightweight aluminum box with a 1.27 cm thick Cotronics board on the inside. The edges of the samples were insulated with Cotronics 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 (not shown in the picture). Care is also taken to maintain a constant balance temperature to prevent drifts in the readings from elevated temperature.

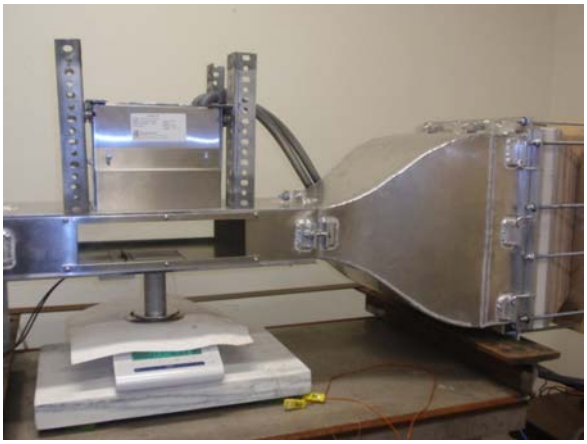
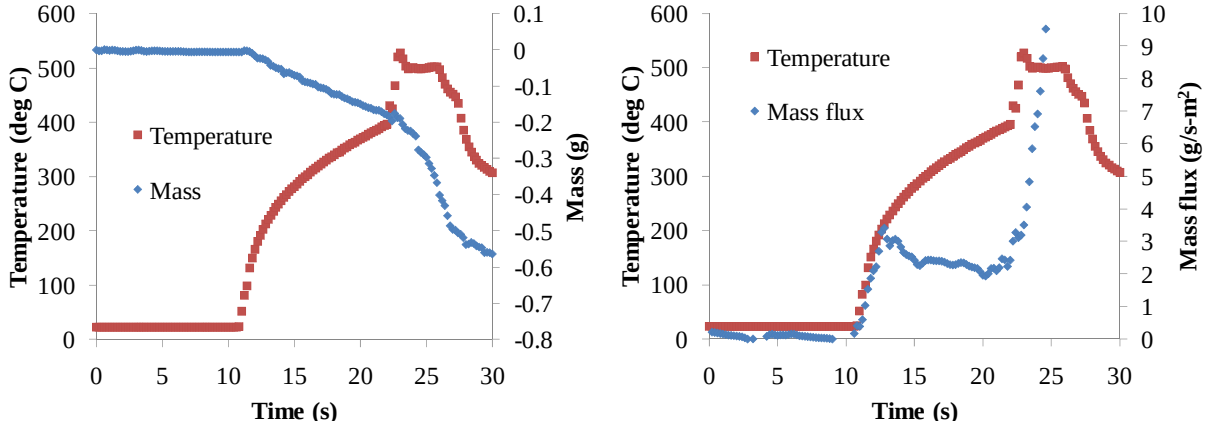


Figure 1 – Experiment apparatus: small-scale wind tunnel with high precision balance

3. 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 50 kW/m^2, flow velocity of 1 m/s, and a moisture content of 18.5%. As shown in Figure 2a, once the infrared heater is turned on at about 12 seconds, the temperature of the sample begins to increase. The sharp spike in temperature at about 22 seconds indicates ignition. Notice, however, that the temperature "stalls" at about 450°C. It is believed that this 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 half second later when the temperature continued its rise, 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 drying and 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. The LOESS is taken over a subset of 30 data points. The mass flux is then slope of the LOESS fit to the mass loss curve divided by the burned 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 times of flashing and flaming ignition were assumed to be 22 sec and 22.6 sec, respectively, with corresponding critical mass fluxes of 2.831 g/sm^2 (flash point) and 3.1179 g/sm^2 (fire point). Note that the initial mass flux from the sample due to evaporation is actually higher that the flux required for ignition. This will have consequences when incorporating these findings into a theoretical model.

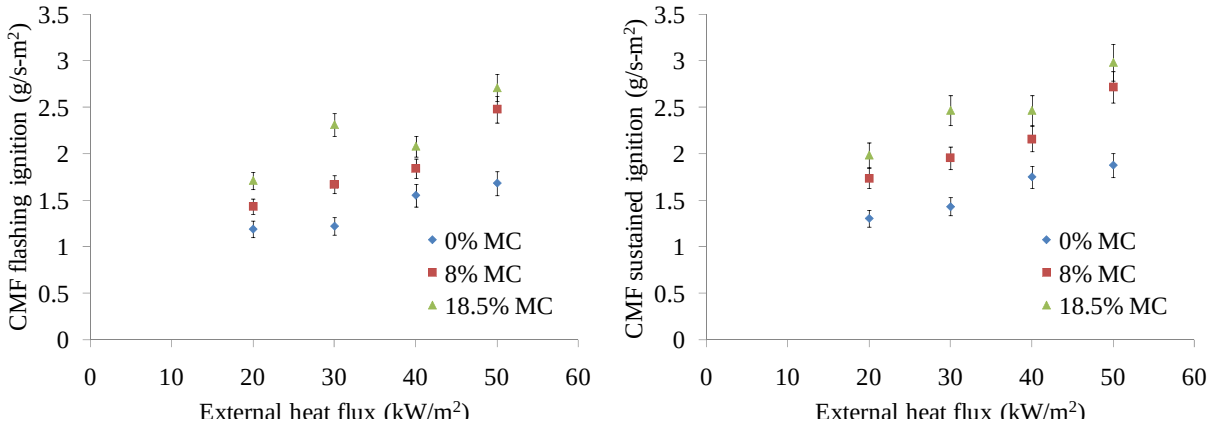


(a) (b)

Figure 2 – Typical temperature, mass loss (a), and mass flux (b) measurements (50 kW/m^2, 1 m/s, and 18.5% MC)

Table 1 – Critical mass flux for flashing and flaming ignition (flash and fire point)

Moisture content (% of dry mass)	Heat flux (kW/m^2)	Average ignition time (s)	Average CMF for flashing ignition (g/s-m^2)	Standard deviation of CMF (flash) (% of mean)	Average CMF for sustained ignition (g/s-m^2)	Standard deviation of CMF (fire) (% of mean)
0.2	20	75.3	1.189	10.8	1.305	6.4
	30	28.0	1.220	8.3	1.430	5.9
	40	16.7	1.551	10.1	1.749	5.0
	50	9.7	1.682	4.7	1.875	9.9
8	20	90.7	1.434	5.3	1.735	3.7
	30	38.7	1.670	5.4	1.953	4.8
	40	20.7	1.840	4.2	2.160	11.6
	50	12.7	2.477	7.9	2.716	4.7
18.5	20	106.3	1.712	4.4	1.985	11.6
	30	48.3	2.311	3.8	2.465	1.2
	40	22.7	2.079	7.6	2.464	7.6
	50	13.3	2.706	5.6	2.978	6.2



(a) (b)

Figure 3 – Critical mass flux for (a) flashing and (b) sustained flaming ignition

The results of the measurements of the critical mass flux for both flashing and sustained flaming ignition are shown in Table 1. Figures 3a and 3b illustrate the variation with external heat flux and moisture content. All results represent the average of three tests. The error bars in Figure 3 represent one standard deviation.

The critical mass flux for both flashing and sustained ignition ranges from about 1 to 3 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 3 and Table 1, the critical mass flux for both flashing and sustained ignition increases as the heat flux increases for all levels of moisture content. 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]. Rich *et al*. suggest that this increase with heat flux is due to the fact that the temperature gradient inside the material becomes much steeper with only the thin region near the surface at a high enough temperature to pyrolyze. Because oxygen can penetrate this region, more oxidative pyrolysis will occur. Due to being partially oxidized, the products of oxidative pyrolysis have a lower heat of combustion. Thus, more pyrolysis products are required to generate a hot enough flame and the critical mass flux for ignition increases.

The critical mass flux for both flashing and sustained ignition increases with moisture content as well. Near ignition, the temperature gradient inside a thermally-thick solid will form such that there are three regions within the solid. By definition, the region furthest from the surface experiences no temperature change. The region nearest the surface can be defined as the region with sufficiently high temperature for pyrolysis (greater than roughly 250°C). In between these two regions is one where the temperature is sufficient for water evaporation but not pyrolysis (roughly 60 - 250°C). Water is thus still being evolved from the solid near ignition. This water dilutes the pyrolysis products and cools the forming flame, therefore increasing the critical mass flux for sustained ignition. It also is possible that at the heating rates tested here, there is still evaporation occurring in the region nearest the surface so that evaporation and pyrolysis are occurring simultaneously in the same region. Note that changing the moisture content of the material will alter the thermal properties, shifting the temperature gradient inside the material.

Interestingly, the increase in the critical mass flux for sustained ignition increased by 34.5% and 56.1% as the moisture content went from 0% to 8% and from 0% to 18.5%, respectively. This increase with moisture content was seemingly not related to the external heat flux. Though only a few moisture contents were tested thus far, there is an indication that this increase of the critical mass flux with moisture content may be non-linear.

4. Summary

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 a step toward understanding ignition of complex wildland fuel structures with the ultimate goal of better understanding and predicting how wildfires spread. In this work, the critical mass flux was measured for poplar under a varying external radiant heat flux and moisture content. 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 and moisture content. In order to fully understand the trends in the data seen here, more experiments with different moisture contents should be coupled with theoretical modeling.

5. Acknowledgements

This project was funded by the National Fire Decision Support Center. The authors would like to thank Jack Kautz, Randy Pryhorocki, and Mike Chandler for the fabrication of the apparatus; Cyle Wold and Jim Reardon for help with data acquisition and wiring; Isaac Grenfell for help with data processing; Jake Gerstenberger for help running experiments; and Ian Grob for running the high-speed camera.

6. References

[1] V. Babrauskas, 2003. *Ignition Handbook*, Fire Science Publishers, Issaquah, WA.

[2] J.D. Cohen, 2004. "Relating flame radiation to home ignition using modeling and experimental crown fires," *Canadian Journal of Forest Research* **34**: 1616-1626.

[3] J. Fangrat, Y. Hasemi, M. Yoshida, and T. Hirata, 1996. "Surface temperature at ignition of wooden based slabs," *Fire Safety Journal* **27**: 249-259.

[4] D.J. Rasbash, D.D. Drysdale, and D. Deepak, 1986. "Critical heat and mass transfer at piloted ignition and extinction of a material," *Fire Safety Journal* **10**: 1-10.

[5] D.D. Drysdale and H.E. Thomson, 1989. "Flammability of plastics II: critical mass flux at the firepoint," *Fire Safety Journal* **14**: 179-188.

[6] D. Rich, C. Lautenberger, J.L Torero, J.G. Quintiere, C. Fernandez-Pello, 2007. "Mass flux of combustible solids at piloted ignition," *Proceedings of the Combustion Institute* **31:** 2653-2660.

[7] A.F. Roberts, and B.W. Quince, 1973. "A limiting condition for the burning of flammable liquids," *Combustion and Flame* **20**: 245-252.

[8] J.G. Quintiere, and A.S. Rangwala, 2004. "A theory for flame extinction based on flame temperature," *Fire and Materials* **28**: 387-402.

[9] A.N. Koohyar, J.R. Welker, and C.M. Sliepcevich, 1968. "The irradiation and ignition of wood by flame," *Fire Technology* **4** (4): 284-291.

[10] R.E. Lyon, and J.G. Quintiere, 2007. "Criteria for piloted ignition of combustible solids," *Combustion and Flame* **151**: 551-559.

[11] C.H. Bamford, J. Crank, and D.H. Malan, 1946. "The combustion of wood. Part I." *Mathematical Proceedings of the Cambridge Philosophical Society* **42**(2): 166-182.

[12] J.E.J. Staggs, 2001. "Ignition of char-forming polymers at a critical mass flux," *Polymer Degradation and Stability* **74**: 433-439.

[13] M.A. Delichatsios, 2005. "Piloted ignition times, critical heat fluxes and mass loss rates at reduced oxygen atmospheres," *Fire Safety Journal* **40**: 197-212.

[14] J.L. Cordova, D.C. Walther, J.L. Torero, and A.C. Fernandez-Pello, 2001. "Oxidizer flow effects on the flammability of solid combustibles," *Combustion Science and Technology* **164**: 253-278.

[15] J.S. Han, and J.S. Rowell, 1997. "Chemical Composition of Fibers," Paper and Composites from Agro-Based Resources, Chapter 5, edited by R.M. Rowell, R.A. Young, and J.K. Rowell, CRC Press, Boca Raton, FL, pg. 83-134.