Fire Safety Journal 61 (2013) 200–206

Contents lists available at ScienceDirect

Fire Safety Journal

journal homepage: www.elsevier.com/locate/firesaf

Critical mass flux for flaming ignition of wet wood

S. McAllister *

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

ARTICLE INFO

Article history:
Received 17 September 2012
Received in revised form
29 April 2013
Accepted 3 September 2013
Available online 27 September 2013

Keywords:
Piloted ignition
Critical mass flux
Moisture content

ABSTRACT

Wood is a common building material and can constitute the bulk of the fuel load in structures. Cellulosic, woody material is also the fuel in a wildland fire. Wood and forest fuels are porous and hygroscopic so their moisture content varies with the ambient temperature and relative humidity. A complete understanding of both structural and wildland fire thus involves understanding the effect of moisture content on ignition. The ignition criterion considered in this work is critical mass flux – that a sufficient amount of pyrolysis gases must be generated for a diffusion flame to establish above the surface. An apparatus was built to measure the critical mass flux for sustained flaming ignition of woody materials for varying environmental conditions (incident heat flux and airflow (oxidizer) velocity). This paper reports the variation of measured critical mass fluxes for poplar with externally applied incident radiant heat flux, airflow velocity, and moisture content. The critical mass flux is seen to increase with increasing levels of moisture content, incident heat flux, and airflow velocity. Future work will focus on modeling these experiments and exploring the changes in critical mass flux with species, thickness, and live fuels.

Published by Elsevier Ltd.

1. Introduction

Wood is a common building material and can constitute the bulk of the fuel load in structures. Cellulosic, woody material is also the fuel in a wildland fire. Wood and forest fuels are porous and hygroscopic so their moisture content (MC) varies with the ambient temperature and relative humidity. Live forest fuels can even have such a high MC (over 200% by weight) that the physically thin needles and leaves may actually behave as thermally intermediate or even thermally thick solids [1,2]. A complete understanding of both structural and wildland fire thus involves understanding the effect of moisture content on fire behavior. Fire spread, one of the main descriptors of fire behavior, is commonly viewed as a series of piloted ignitions [3,4]. Crown fires, an especially unmanageable and unpredictable form of wildfire are no different – they spread from one tree crown to the next as piloted ignitions. Piloted ignition is affected by both fuel and ambient conditions. Both incident heat flux and airflow (oxidizer) velocity change ignition temperature and ignition delay time [5]. Logically then, a fire in calm, humid locations will behave differently than one in very dry and windy locations. Thus, predicting structural and wildland fires requires understanding of ignition in a variety of conditions, including incident radiant heat flux, airflow velocity, and fuel moisture content.

Many theories for ignition criteria exist in the literature [6], such as ignition temperature and flux-time product [7], but most are empirically derived and can only be applied to the range of conditions in which they were measured (see [8]). Alternatively the “critical mass flux” (CMF) criterion is more physically consistent [9], can potentially be derived from fuel properties, and scale from the smallest fuel particles to much larger slabs of fuel. However, this approach was primarily developed with polymeric materials [9–11] and has not been explored in the context of cellulosic or wildland fuels.

Solid ignition is a coupled solid–gas phase phenomenon. When a solid material is heated to a sufficiently high temperature, thermal degradation, or pyrolysis, occurs. In flaming combustion, it is these gaseous pyrolysis products 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). When the mixture is right at the lean flammability limit, there is often too much heat loss to sustain the premixed flame, so it merely “flashes” before extinguishing (flashing ignition). In order for a sustained flame to exist, enough pyrolysis gases must be generated to offset the heat losses. 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), for sustained flaming. Note that the CMF criterion is related to two other ignition criteria used in the literature – the critical flame temperature [12,13] and critical heat release rate criteria [18,19].

* Tel.: +1 406 329 4907; fax: +1 406 329 4877.
E-mail address: smcallister@fs.fed.us

0379-7112/$ - see front matter Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.firesaf.2013.09.002

Moisture content affects the ignition process in both the solid and gas phases. If all of the water within the fuel does not evaporate prior to ignition, then the water vapor will dilute the gaseous pyrolyzates making it more difficult to generate a flammable mixture [6]. In fact, Janssens showed in [14] that the ignition temperature increased by about 2 °C for each percent increase in moisture. Atreya and Abu-Zaid found a similar result in [15] for moisture contents up to about 30%. As detailed in [16], water has three effects on the solid: it changes the thermal properties of the material (density, thermal conductivity, and specific heat increase), it transfers heat by molecular diffusion, and its evaporation is strongly endothermic. There seems to be some disagreement in the literature about whether moisture content has a stronger effect on the solid phase or the gas phase. In [6], Babrauskas claims the gas phase effect to be a minor in comparison to the solid phase effects. However, in [17] Abu-Zaid claims that the increase in ignition temperature with moisture content is more important than the change in the solid thermal properties.

Though the idea of a critical mass flux for ignition was first proposed in regard to wood by Bamford, Crank, and Malan [20], it has primarily been measured with polymers. In general, the CMF for ignition is seen to increase with incident heat flux for both non-charring [9–11] and charring [21] polymers. In one of the few known works that actually measured the CMF of a wood product, Delichatsios [22] saw an increase with incident heat flux between 25 and 50 kW/m^2 for both plywood and retardant-treated plywood. The CMF for ignition of non-charring polymers also appears to increase with oxidizer flow velocity [9,11]. This paper seeks to show that the trends in the CMF for ignition that were observed for other materials hold for the solid fuels more likely to be found in a structural or wildland fire, and to explore the effect of moisture content combined with incident radiant heat flux and airflow velocity.

2. Experiment design

An apparatus was built to measure the critical mass flux for flashing and 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 Flame-spread Test [5], consists of a small-scale wind tunnel, radiant heater, coiled wire igniter, and a high precision mass balance (see Fig. 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 free-stream velocity above the sample ranging from 0.8 to 1.6 ($\pm$0.01) m/s (corresponding to Reynolds numbers of 1–3 $\times$ 10^4 at the sample).

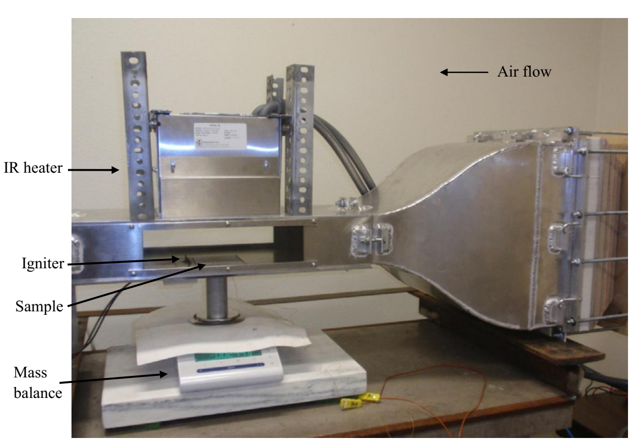

Fig. 1. Experiment apparatus: small-scale wind tunnel with high precision balance.

The sample, measuring 9 cm $\times$ 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 0–50 kW/m^2 ($\pm$1%) over the sample surface.

As the sample is heated, pyrolysis begins. The forced flow pushes the pyrolysis gases into the coiled Kanthal[1] 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 fuel concentration boundary layer. Additionally, the igniter consists of a fixed number of coils and the supplied current is calibrated to keep the igniter above 1000 °C to minimize the gas-phase induction time. The time to ignition is recorded visually and confirmed with a 5 mil (0.005 in./0.127 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 gain some insight into the temperature gradient within the solid, the temperatures at the surface, middle (6 mm below the surface), and bottom of the sample were measured for several tests using a similar method to [23].

To explore the combined effect of MC and incident heat flux on the CMF for ignition, tests were performed with a fixed airflow velocity of 1 m/s and irradiances from 20 to 50 kW/m^2 and MCs from 0 to 18% (dry weight basis). An additional set of tests to explore the combined effect of MC and airflow velocity were performed at a fixed incident heat flux of 30 kW/m^2 and airflow velocities from 0.8 to 1.3 m/s and MCs from 0% to 18% (dry weight basis). All tests were repeated three to four times to provide an estimate of the experimental variability.

The material used was wood from "yellow poplar" (*Liriodendron tulipifera*) that was cut cross-grain. Poplar was chosen because of its consistent grain, lack of knots, and contains a higher proportion of cellulose than other common woods [24]. Experiments were performed with MCs of approximately 0%, 4%, 8%, and 18% on a dry weight basis. All samples were weighed and then conditioned in an oven at 80 °C for at least 48 h. Upon removing the samples from the oven, they were immediately reweighed to assess the dry weight. The dry (0% MC) 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 MC. On average, the samples gained approximately 0.1% MC before use. To obtain MCs of 4%, 8% and 18%, freshly dried samples were placed in a conditioning chamber at 24 °C and 25% relative humidity, 24 °C and 55% RH, and 29 °C and 92% RH, respectively. The samples were left in the conditioning chamber until the change in MC was minimal (0.01%) which took about ten days. All "wet" samples were burned within ten minutes of removal from the conditioning chamber.

The IR heater used emits "short" wavelength radiation (1.03–1.30 μm) compared to typical fire situations (1.97–2.28 μm assuming temperatures of about 1000–1200 °C). Because wood is not perfectly gray and its absorptivity varies with wavelength [25], all samples were darkened with powdered graphite to increase absorptivity (particularly during the initial heating) and to decrease the effects of this difference in IR wavelength. Though this coating can act as an insulative layer and slightly decrease the thermal inertia of the sample [6,26], this practice is considered

[1] Business and trade names used for reference and do not constitute official endorsement.