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Proceedings of the Combustion Institute 35 (2015) 2691–2698

**Proceedings
of the
Combustion
Institute**

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Upslope spread of a linear flame front over a pine needle fuel bed: The role of convection cooling

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Available online 27 June 2014

Abstract

This paper presents an experimental analysis on the role of convection cooling in upslope spread of a linear flame front over a pine needle fuel bed. The slopes of the fuel bed were varied within 0–30° in experiments. The experimental data of heat flux, gas temperature and gas velocity are used to characterize the significant effect of convection cooling in fire spread. The natural convection (due to the temperature difference between the unburnt fuels and the ambient) and flame-induced convection (caused by the flame-induced inflow which produces pressure difference between the flame and the ambient) are investigated by experimental and computational analyses, in order to understand their respective contributions to pre-heating of unburnt fuels. The results indicate that both kinds of convection have effects of cooling on the unburnt fuels ahead of the flame front, but with different spatial influence ranges. Natural convection takes effect in a region from far field to near field (close to the flame), while flame-induced convection plays an important role within a region close to the flame. The convection cooling is dominated by natural convection under lower slope angles, with comparable intensity as compared to radiation loss, and is controlled by the mixed convection (the combination of natural convection and flame-induced convection) under higher slope angles. Additionally, the fire line contour has marked impact on the convection heating, and compared to a convex flame front, the convection heating induced by a linear flame front has a much shorter spatial range of influence on unburnt fuels.

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Keywords: Wildland fire; Upslope fire; Linear flame front; Heat transfer; Convection cooling

1. Introduction

For fire spread over a forest fuel bed, it is of essential importance to understand the heat

transfer mechanisms which control the pre-heating of fuels. For forward fire spread, basically unignited fuels are heated by radiation and affected by re-radiation and convection. An important point is that there has been much controversy in literature concerning the role of convection cooling in fuel pre-heating. In fire spread modeling efforts, some authors had no

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consideration on the convection cooling (e.g. [1,2]), while some others implied that convection cooling cannot be neglected. For example, Albini [3,4] achieved good agreement between predicted and experimental rates of spread by adding a natural convection cooling term into his model of a linear flame front spreading over a fuel bed with no wind and zero-slope. Mestre et al. [5] also incorporated a convection cooling term into the model they developed, by which good agreement with the observed rate of spread was achieved.

Very limited experimental work has been conducted to examine the convective cooling effect in fire spread. In the experiments with linear flame fronts by Anderson et al. [6], the measured gas temperature was shown to be lower than the fuel temperature within the major region ahead of the flame front, which implied convection cooling. Dupuy and Maréchal [7] conducted upslope fire spread experiments with convex flame fronts, and made heat balance calculations based on measured temperatures and incident radiant heat flux received by a small fuel bed volume, by which they concluded that convection cooling is substantial far from the fire front except at the 30° slope angle. Recently, Silvani et al. [8] used total and radiant heat flux gauges close to the end of the fuel bed to measure the heat fluxes ahead of the convex flame fronts. Unfortunately they failed to obtain the convective heat flux due to the uncertainty in the sensitivities of the heat flux gauges.

The convection cooling effect considered in literature is mainly limited to the general natural convection due to the temperature difference between the unburnt fuels and the ambient. Besides this, another kind of convection may be caused by the flame-induced inflow which produces the pressure difference between the flame and the ambient. This convection is essentially correlated with the buoyancy of the flame, and is thus called “flame-induced convection” in this paper. It seems that only Dupuy and Maréchal [7] presented an effort of modeling to consider the role of this kind of convection in fuel preheating.

In addition, experimental efforts have indicated that the fire line contour has marked effect on fire spread. Especially, linear and curved (concave or convex) flame fronts involve distinct burning mechanisms and behaviors [9–11]. However, there is much lack of knowledge about the convection effect for a spreading linear flame front under slope conditions. In the above cited works, the linear flame front experiments by Anderson et al. [6] only dealt with those under zero-slope conditions, while those by Dupuy and Maréchal [7] and Silvani et al. [8] with different slopes were concerned with convex flame fronts.

In this paper, we present an experimental examination on the convection cooling effect for a linear flame front spreading over a pine needle

fuel bed under slope conditions. The linear flame front mimics a section of a long fire line. The heat flux, temperature and velocity data are used to characterize the marked effect of convection cooling and analyze the respective contributions by natural convection and flame-induced convection. Additionally, the effect of fire line contour on the convection heating is discussed.

2. Experimental

Experiments were conducted in a large enclosed space by using a 6 m-long and 1.8 m-wide experimental bench (Fig. 1), which was motor-driven so that the slope could be varied from zero to 45°. The fuel bed was composed of a 1 m-wide bed of dead pine needles (*Pinus sylvestris* var. *mongolica* Litv., with a density of 583 kg/m³). The surface area to volume ratio of the pine needles was measured to be 4710 m⁻¹, and the heat value was 21.0 kJ/g. In each test the fuel moisture content was measured just before ignition, and the measured data was around 10%, with small variations. The depth and total fuel load of fuel bed were designed to be 4 cm and 0.7 kg/m² respectively. Because of the nearly constant moisture content, this total fuel load corresponds to a consistent fuel load on a dry basis among tests. Two strips of metal sheeting, 10 cm in height, were fixed along each side of the fuel bed to suppress the indrafts into the combustion zone. This means was also used by other authors (e.g. [12,13]). The fuel was ignited by a wooden stick (with the same width of the fuel bed) dipped with a small amount of *n*-heptane.

A total heat flux meter (Captec Entreprise, HS30B series, size: 30 × 30 mm, thickness: 0.4 mm, response time: 300 ms, sensitivity: 2.5 μV/(W/m²)) was used to measure the overall incident heat flux. A radiant heat flux meter (Captec Entreprise, TS30 series, size: 30 × 30 mm,

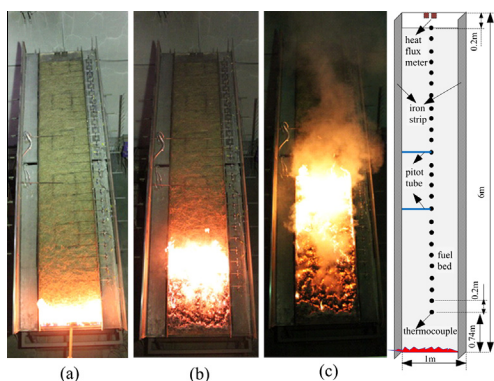


Fig. 1. Experimental photos (slope angle: 29°) and schematic of the fuel bed. (a) Ignition; (b) 62 s after ignition; (c) 96 s after ignition.

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