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Piloted ignition of wildland fuels

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ABSTRACT

Piloted ignition of wildland fuel litters was experimentally studied using the FM Global Fire Propagation Apparatus (FPA) with an applied external radiant heat flux up to 30 kW/m^2. Fuel types (i.e. Maritime Pine needles and Kermes Oak leaves) and loadings are representative of Mediterranean ecosystems. For the fuel beds considered the inverse of the ignition time was found to be linearly dependent on the imposed heat flux, as observed for thermally-thin solids. A systematic study was carried out to determine the critical (minimum) heat flux for piloted ignition. On the other hand, a dimensionless analysis of the energy equation for the homogeneous equivalent medium was carried out based on the assumptions that the solid and gas phases are in thermal equilibrium and that piloted ignition occurs when the average equivalent medium temperature over the radiation penetration depth reaches a critical value. Using experimental data, a correlation was found between dimensionless ignition time and imposed heat flux.

1. Introduction

Ignition marks the onset of flaming combustion. It is generally the combined result of an externally imposed heat flux that causes the gasification of the solid fuel, and the presence of conditions that will lead to the onset of sustained combustion reaction between the vaporized fuel and the oxidizer gas [1]. There are two types of ignition, piloted and spontaneous. Spontaneous ignition occurs without the aid of an external pilot source. The ignition of combustible forest materials is a critical process in the initiation and propagation of wildland fires. Spontaneous ignition of wildland fires is rare and requires very high intensities to occur [2]. Piloted ignition is the most prevalent in wildland fires where the combustible materials are heated by radiative and/or convective heating sources and ignition sources (e.g. flame, firebrand) are present. It occurs at lower temperature and it is the mechanism responsible for fire growth, the flame acting both as a source of heating and as a pilot. The present study focuses on the piloted ignition of wildland fuel litters under external heating. The heterogeneous (two-phase) wildland fuel bed is conceptualized as an equivalent medium with effective properties. The standard test method for determining the flammability characteristics of solids is expected to be applicable to such beds. In the last few decades, extensive systematic collection of data on the ignitability of solid materials generally took place only in two contexts: test under ISO 9773 or similar tests and radiant, piloted ignition of materials in the Cone Calorimeter, Fire Propagation Apparatus (FPA) or in other test apparatuses providing a controlled radiant heat flux. The ISO 9773 test is generally a poor indicator of actual performance under real-life conditions that do not involve attack by a small flame. The results from radiant-heat tests, on the other hand, have wide applicability and validity and can be used directly as inputs into computational schemes [3]. These standard methods are used to determine the time to piloted ignition of a solid, when exposed to a pre-determined well-controlled incident radiant heat flux and also to estimate the critical incident heat flux.

The ignition of a solid can be viewed as a three-step process [1,4]: the solid is heated to a sufficient temperature for pyrolysis to occur. In the second step, the fuel vapor is transported through the fluid boundary layer and mixes with fresh air to form a combustible mixture, and the flammable mixture reaches the pilot to the point where the chemical reaction reaches the 'thermal runaway'. A large number of mathematical models of the piloted ignition problem have been developed with varying degrees of complexity. Some models account for the diffusion and mixing in the gas phase, as well as the conduction and pyrolysis in the solid phase [5–7]. Others consider only the solid phase. There are therefore two main possibilities with regard to ignition: either the solid must be heated to the ignition temperature [8–10] or it must be heated so that it generates the critical pyrolysis mass flux rate. The latter requires taking thermal degradation process into consideration [11,12].

A small amount of research work has been devoted to piloted ignition of wildland fuels [13–15]. Trabaud [14] used an infrared heat unit to evaluate the time to ignition at different moisture contents. Unfortunately, the radiant heat flux incident over a

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Nomenclature

a_b	absorptivity of the fuel layer.
C_p	specific heat (J kg^{-1} K^{-1}).
G	average incident radiation (W m^{-2}).
h	enthalpy (J kg^{-1}).
h_{conv}	heat transfer coefficient (W/m^2 K).
I	radiative intensity (W m^{-2}).
I_b	black body radiative intensity.
KO	Kermes Oak.
m	mass (kg).
MP	Maritime pine.
n	number of repeats for a given test.
q	heat flux (kW).
s	standard deviation.
T	temperature (K).
t	time (s).
u	velocity (m s^{-1}).
x	coordinate (m).

Greek symbols

α	volume fraction.
δ	mean free path of radiation (m).
φ	dimensionless incident heat flux.
κ_a	absorption coefficient (m^{-1}).
λ	thermal conductivity (W m^{-1} K^{-1}).
ρ	density (kg m^{-3}).
σ	Stefan–Boltzmann constant (W m^{-2} K^{-4}).
σ_k	surface–volume ratio of a solid fuel element (m^{-1}).
τ	dimensionless time.
υ	uncertainty.
θ	dimensionless temperature.

Subscripts

0	initial.
cr	critical.
eq	equivalent medium.
g	gas phase.
ig	ignition.
inc	incident.
k	solid fuel.
∞	ambient.

Superscripts

$()''$	per unit area.
$(\cdot)$	per unit time.
$()^*$	dimensionless quantity.

variety of vegetation types was not indicated and apparently only the spontaneous ignition was tested because no pilot was specified. Dimitrakopoulos and Papaioannou [15] used the standard cone colorimeter methods to determine the ignition time and the moisture of extinction of dominant Mediterranean forest fuels in order to develop a relative flammability classification. A calorimetric study of wildland fuels was also carried out recently by Schemel et al. [16] and Bartoli et al. [17]. Although, these works were focused on the burning rate of pine needle beds varying the porosities and the air entrainment, the time to piloted ignition was also measured. In this paper, we report experimental data on the time for piloted ignition of Mediterranean wildland fuel layers exposed to varying external radiant flux intensities using a bench-scaled apparatus (FPA). A dimensionless ignition analysis is also conducted to correlate these data.

2. Experimental apparatus and procedure

Piloted ignition experiments were conducted in the FM Global Fire Propagation Apparatus (FPA) [18]. This calorimeter comprises two sections. The combustion arrangement is constituted basically of four external infrared heaters, pilot igniter, sample holder, load cell, and a data acquisition system. Fig. 1 presents a schematic of the experimental set-up of the FPA. In the other part, a hood system topped the combustion zone. It has been dimensioned so that all the combustion gases are sucked up. From the hood, the system narrows to an exhaust duct to ensure gases mixing. Further down, volumetric flow rate is measured by a Pitot tube. Gases pass through a soot filter and a cold trap. They are continuously distributed to a set of different analyzers to measure O_2, CO/CO_2 concentrations. Finally, the extinction method is used, with a laser beam at λ=632 nm, along the exhaust duct in order to evaluate the soot volume fraction.

The ignition pilot consists of an ethylene/air premixed flame. The visible region of the pilot flame was adjusted to approximately 1 cm in length, with a diameter of 0.5 cm. The pilot flame was located 1 cm above the center of the fuel bed as shown in Fig. 1.

Each infrared heater contains six tungsten filament tubular quartz lamps in a compact reflector body that would be capable of providing heat fluxes to the specimen in the range 10–100 kW/m^2. In agreement with previous ignition studies for solids and composite materials [19,20] the maximum of radiant heat flux was fixed at 30 kW/m^2.

Prior to each test the total incident heat flux was calibrated using a Gardon type fluxmeter. This gauge has an accuracy of within $\pm$3% and repeatability within 0.5% between calibrations [18]. Calibration of the total heat flux as a function of the voltage supply to the lamp was performed. Under steady irradiance the total voltage lamp is proportional to the incident heat flux. However, this relationship changes with time and therefore the abovementioned procedure was repeated before each test and was adjusted if necessary. The homogeneity of irradiance over the sample was verified using theoretical computations perform with the Monte Carlo procedure [21].

The moment of ignition was determined visually from the appearance of flaming combustion and the time to ignition was recorded using a timer installed in a digital data collection system triggered by the operator. The timer is able to recording elapsed time to the nearest tenth of 1 s and has an accuracy of better than 1 s in 1 h. A video verification of the time to ignition was obtained from frames recorded by a scan monochrome CCD camera with a narrow-band filter centered at 430 nm with a bandwidth at one half the transmissivity maximum of 20 nm. This was particularly useful for detecting the onset of flaming combustion because the CCD was not hidden from view within the fuel bed. The concentration of gases and mass loss were also automatically recorded in the digital data collection system, with a frequency of 1 Hz.

Experiments were performed following the standard FPA protocols [18]. No external air flow was imposed during these measurements. The only air flow was generated by the FPA hood