ARTICLE IN PRESS

Fire Safety Journal xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Fire Safety Journal

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

Determination of smoldering time and thermal characteristics of firebrands under laboratory conditions

Vladimir Fateev[a], Mikhail Agafontsev[a], Sergey Volkov[b], Alexander Filkov[a,c,*]

[a] National Research Tomsk State University, Department of Physical and Computational Mechanics, 36 Lenin av, Tomsk 634050, Russia
[b] National Research Tomsk State University, Department of Applied Gas Dynamics and Combustion, 36 Lenin av, Tomsk 634050, Russia
[c] University of Melbourne, School of Ecosystem and Forest Sciences, 4 Water St, Creswick, VIC 3363, Australia

ARTICLE INFO

Keywords:
Wildfires
Ignition
Firebrands
Smouldering time
Thermal characteristics

ABSTRACT

The laboratory experiment was conducted to simulate the transfer of smouldering particles produced in forest wildfires by a heated gas flow. The pine bark pieces with the linear dimensions L=(15; 20; 30) mm and a thickness of h=(4–5) mm were selected as model particles. The rate and temperature of the incident flow varied in the range of 1–3 m/s and 80–85 °C, respectively. The temperature of the samples was recorded using a thermal imager. To determine the minimum smouldering temperature of pine bark, the thermal analysis was conducted. The minimum smouldering temperature of pine bark was found to be 190 °C. This temperature will cause thermal decomposition of bark only at the first stage (oxidation of resinous components). In the study the smouldering time, the temperature and the weight of samples were obtained and analyzed under various experimental conditions. The data analysis shows that the increase in the particle size leads to the decrease in their mass loss, and the rate change of the incident flow does not practically influence the mass change. For particles with the linear dimensions of 10 mm and 20 mm, the mass varies from 6% to 25%. The maximum mass loss is observed for the flows with a rate of 1 and 2 m/s. The results have shown that the increase in the particle size leads to the increase in the smouldering time. The position of the particle plays an important role, the effect of which increases with increasing the particle size. The calculations showed that the smouldering time of bark samples is long enough for the particles to serve as new sources of spot fires. The particles were found to be transported to a distance of 218 m from the fire line which can certainly influence the propagation of the fire front.

1. Introduction

During wildfires a huge amount of smouldering particles is produced and transported by the convection column and the wind [1–3] which leads to the formation of new spot fires and the change in the fire behavior. According to [4], spotting can be classified into three categories, depending on the distance and the distribution density: short distance spot fires (up to 750 m) initiated by smouldering firebrands produced by the fire front, average distance spot fires (1000–1500 m) and large distance spot fires (> 5000 m) initiated by smouldering firebrands involved in the convection column. Earlier, physical models of the fire front propagation only considered convection and radiation. In the last decade new models looked at the medium and large distance spotting [5,6]. However, physical models that would consider the effect of smouldering particles on short distance spotting are still lacking. The latest results of field experiments have shown that this mechanism is an integral part of wildfire propagation [7–9]. Therefore, in order to refine mathematical models, it is reasonable to study in detail the process of smouldering and combustion of these particles under the laboratory conditions and evaluate their energy characteristics.

The review of experimental studies has shown that many are devoted to studying the aerodynamic characteristics of particles, with only a few devoted to the specifics of smouldering in the air flow [10–13]. These studies are focused on the determination of flight paths and lifetimes of burning particles. There is no assessment of temperature characteristics for the particles, and smouldering time is determined visually. In order to address these issues, a laboratory experiment was conducted to simulate the transfer of particles by a gas flow where infrared diagnostic methods and thermal analysis were used for the first time to determine the particles temperature, time and characteristics of smouldering in the air flow.

* Corresponding author at: University of Melbourne, School of Ecosystem and Forest Sciences, 4 Water St, Creswick, VIC 3363, Australia.

http://dx.doi.org/10.1016/j.firesaf.2017.03.080
Received 15 February 2017; Accepted 15 March 2017

2. Methods

2.1. Samples and general equipment

The results of field experiments [8,9] studying short distance spotting, have shown that firebrands mainly consist of bark fibres. The maximum mass of the particles reached 7 gr, the cross section area was up to 140×10^{-5} m^2 and the velocity of the particles was in the 0.1–10.5 m/s range with an average value of 2.5 m/s, and the majority of the particles were smouldering. Based on these results pieces of pine bark with the linear dimensions L=(15; 20; 30) mm and a thickness h=(4–5) mm were selected as model particles being the most typical ones for boreal forests. The initial mass of the samples was m_{av}=0.47 ± 0.03 g for L=15 mm; m_{av}=0.8 ± 0.02 g for L=20 mm; and m_{av}=1.86 ± 0.03 g for L=30·mm. Parallelepipeds were cut from the raw material, weighed and their sizes were determined using a caliper with an accuracy of ± 0.1 mm.

The temperature of the samples was recorded using a thermal imager JADE J530SB. The measurements were carried out in the spectral range of 3.1–3.3 µm with the horizontal field of view 10.97°, which allowed the temperature of an object to be measured in the range of 200–800 °C with an accuracy of 1%. The pictures were taken at a frequency of 50 Hz. The matrix of thermal imager has resolution of 320x240 pixels. At this resolution and considering that the distance to the sample was 1 m, 1 pixel equals 0.6 mm. The data of the thermal imager were analyzed using a software Altair 5.60.027 (Cedip Infrared Systems). Using the measurement tools available in the Altair software, the temperature was determined at a point in a smouldering part of the sample during recording. If there were several smouldering centers, the temperature was determined in each of them.

The moisture content and the initial and final mass of the samples were determined using the moisture content analyzer AND MX-50. The mass measurement error was ± 0.001 g, and the moisture content measurement error was ± 0.01%.

Modeling of the heated air flow was conducted using an electric gas heater whose air duct was heated by a nichrome coil. The air flow was supplied from the receiver and controlled by a rotameter. The rate V and the temperature T_{in} of the incident flow were recorded at the point where the sample was located using the electronic anemometer AZ-8901 with a measurement error of ± 0.1 m/s and ± 1 °C. The incident flow rate varied in the range of 1–3 m/s. The flow temperature was 80 ± 3 °C according to the technical characteristics of the laboratory setup, and the relative air humidity was 60% at the air temperature of 22 °C and standard pressure.

2.2. Thermal decomposition

To determine the minimum smouldering temperature of wood and pine bark during heating, thermal analysis was conducted during the experiment using a simultaneous thermal analysis instrument STA 409 PC Luxx (NETZSCH-Geraetebau GmbH, Germany).

The instrument was operated in the following way: the sample and the reference element 40×10^{-6} m^3 were placed in the furnace using a holder (Fig. 1); the sample was a crucible containing a test material; the reference element was an empty crucible and aluminum crucibles were used as the maximum heating temperature did not exceed 500 °C; the holder was mounted in a highly sensitive balance; the furnace was sealed and the air was pumped with a small flow rate (3.2×10^{-6} m^3/s); for the balance protection argon gas was pumped through it (flow rate was 0.2×10^{-6} m^3/s) and then entered the inner part of the furnace. Both gases had the initial temperature of 22 °C and a pressure of 101 325 kPa.

As a result, the furnace atmosphere consisted of air (94%) and argon (6%). When heating a furnace at a certain rate (heating rate was 10 K/min), the test material was exposed to oxidative effects of atmospheric oxygen.

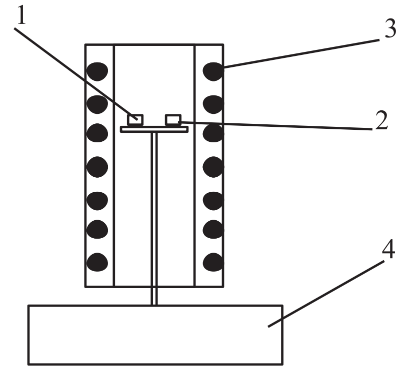

Fig. 1. Experimental setup: 1 is the sample, 2 is the reference element, 3 is the furnace, 4 is the balance.

The following parameters were recorded during the experiment: the mass change of the sample (TG signal, Thermogravimetry), the reference element temperature, and the difference in the heat flows for the sample and the reference element (DSC signal, Differential Scanning Calorimetry). The mass of the reference element was not changed. The maximum permissible relative error of the temperature and enthalpy measurements was ± 1.5% and ± 3.0%, respectively.

Before conducting the experiments temperature and heat flow sensitivity calibration of the instrument was performed. For this purpose, metals with the known reference values of the temperature and heat of phase transition were used: indium, tin, bismuth, zinc, aluminum, silver, gold and nickel.

As previously noted, the balance is very sensitive. When the blow-down gas is heated in the furnace, its density changes and, consequently, the buoyancy force that acts on the holder with the sample and the reference element is also changed. Because the balance registers this, it is necessary to exclude this effect on the TG signal indications. In addition, the holder is located in the furnace in such a way that the distribution of heat flows into the sample and the reference element is unique which also has an effect on the DSC signal too. To compensate for these two factors, the experimental procedure involved the construction of the so-called baseline and was carried in the following way: the instrument parameters, namely, the temperature program, the gaseous medium with a certain flow rate, the sampling rate for the sensors in the digital recording system, etc. were set in the same way as in a real experiment. An empty crucible of the same material as in the real experiment serving as a reference element was used instead of the sample.

The experiment is conducted in the "correction" mode, and the TG and DSC signals are recorded. They constitute the content of the baseline according to the conditions which are supposed to be used for studying the materials. To study the materials, the instrument is switched to the mode "sample + correction", the test material is placed in the crucible, and the TG and DSC signals are recorded. When processing the experimental result, the instrument software automatically subtracts the baseline from the signals received in the experiment, which leads to the compensation of the change in the buoyancy force and the individual arrangement of the holder in a furnace.

Wood and bark of pine were used as the test materials. The cylinders 5 mm in diameter were cut from the material using a tube cutter and a sample 2–4 mm in height was then cut from the cylinders with a sharpened knife. The mass of the samples ranged from 6 to 17 mg ((6–$17)\times10^{-6}$ kg) depending on the material and its size.

2.3. Experimental setup of firebrands smouldering

To measure the temperature and mass loss in the air flow during smouldering, the following procedure has been developed. The experiment setup is shown in Fig. 2.