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The Study of Flame Spread along a Single Pine Needle and of its Structure

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Abstract

The thermal and chemical structure of flame spreading along a single pine needle (SPN) in air was studied with microthermocouples, by the pyrometric method and by the method of molecular beam mass spectrometry. The structure of the flame was studied when spread along a SPN and in the perpendicular direction to the SPN. Based on the mass spectrometric and temperature measurements during flame front spread along a SPN, 3 zones of chemical reactions were identified for the condensed phase: (1) SPN pyrolysis, forming char, tar and volatile products; (2) pyrolysis of tar, forming char and volatile products; (3) a heterogeneous reaction of char oxidation by air oxygen. The burning rate and the structure of upward flame spread along the char of a SPN were measured experimentally and calculated by numerical modeling.

Introduction

Pine needles are one of the most combustible components of forest fuels (FF). Combustion of SPN was the subject of a few papers [1, 2]. Studying the combustion mechanism of a SPN may help in understanding and the mechanism of ground fire spread and in developing its model.

Fig. 1. Photo of flame spread across a single pine needle, the probe is to the left of the flame.

Experimental

The materials were pine needles from Siberian Boreal Forest (SBF). The pine needles litter was sampled from under trees in a pine forest. The needles were dried at the temperature of 60 °C during 24 hours in a drying cabinet. Mass loss after drying was 7.8-9.4 %. The results of the element analysis of the pine needle were as follows: - C- 51.78%, H- 6.96%, N-1.78%, O – 34.5%. The average length of a pine needle was 50 mm, it was 1 mm wide and 0.6 mm thick. The velocity of flame spread across the needle was measured by analyzing the video recording made with a Panasonic M3000 camera. The flame temperature was measured during combustion of the single pine needle with a Pt/Pt-Rh thermocouple (d= 30 micron) and a pyrometric method (spectrometer LR1-T ASEQ). In measuring the condensed phase temperature profile, the thermocouple was shaped as V, with its junction contacting the SPN. Measurements were also carried out with a thermocouple wound around the pine needle. The flame structure of SPN was studied at a setup

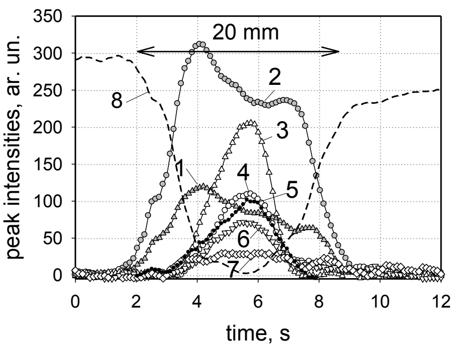


Fig. 2. Dependences of peak intensities on time, measured by a probe at the 0.6 mm distance from the pine needle 1- $I_{18}/10$ (H_2O), 2 –$I_{44}/10$ (CO_2), 3- I_{31}(ethanol, butanol), 4, 6 – I_{60}, I_{73} (levoglucosan), 5 - I_{68} (furan), 7 – I_{58} (acetone), 8 – $I_{32}/15$ (O_2).

with molecular beam sampling into the ion source of the time-of-flight mass-spectrometer TOFMS [3]. In measuring the temperature profile in the flame spread along a SPN, the thermocouple junction was placed at different distances from the SPN surface.

Results and discussion

The diffusion flame structure of a single pine needle

The flame spread velocity along the horizontally placed SPN was 3 mm/s, and that along the vertically placed SPN in downward flame spread was 1.5 mm/s. They were close to those measured in [1, 2]. Dependences of peak intensities on time measured with the probe placed at the 0.6 mm distance from the needle during passage of flame across the horizontally placed SPN in air and a photo of the flame are shown in Fig. 1 and Fig. 2. The width of the luminous combustion zone across the needle was 20 mm. By these data, the following composition of the pyrolysis products was determined for the moment of maximum peak intensity of the volatile pyrolysis products (in mole fractions) at the 0.6 mm distance from the needle: $(0.016C_2H_6O + 0.023C_3H_6O + 0.038C_4H_{10}O) + (0.59\ H_2O + 0.33\ CO_2 + 0\ O_2)$. Fig. 3 shows the temperature profile during combustion of a horizontally placed SPN measured by a thermocouple wound around the needle. Based on the mass spectrometric and temperature measurements during flame front spread along a SPN, 3 zones of chemical reactions were identified for the condensed phase: (1) SPN pyrolysis, forming char, tar and volatile products; (2) pyrolysis of tar, forming char and volatile products; (3) a heterogeneous reaction of char oxidation by air oxygen. The structure of the flame in the perpendicular direction to the SPN was studied, too. Shown in Fig. 4 is the dependence of the intensity of mass peak 31 (ethanol, butanol) on the distance from the upper surface of the burning SPN. This allowed the diffusion flame width in the perpendicular direction to the SPN to be determined, which was equal to about 2.5 mm. Shown in Fig. 5 is a photo of the flame when spread down a vertically positioned SPN and of a thermocouple. Fig. 6 presents a temperature profile of the flame perpendicular to the SPN in the location of the maximum temperature of the SPN, obtained from the results of measuring the temperature profiles along a vertical SPN with thermocouples placed at different distances from the pine needle surface.

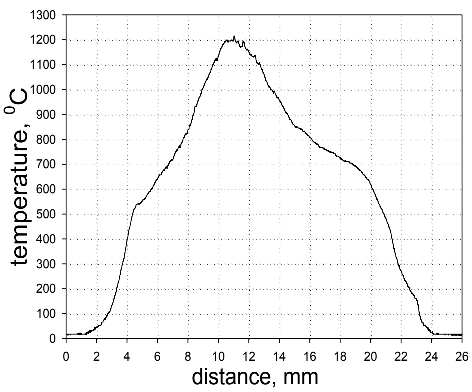


Fig. 3. Dependence of temperature on time during combustion of a pine needle by a thermocouple wound around the needle

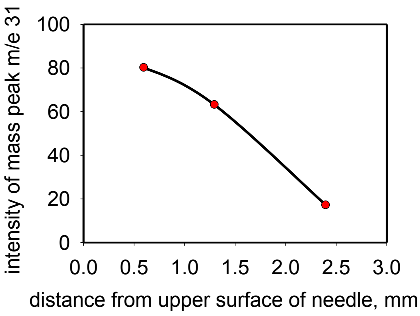


Fig. 4. Dependence of the intensity of mass peak 31 on the distance from the upper surface of the burning SPN

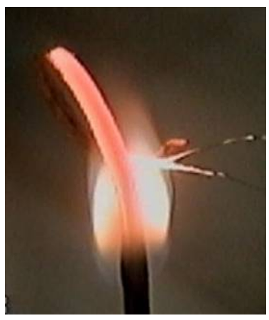


Fig. 5. A photo of the flame when spread down a vertically positioned SPN and of a thermocouple

The temperature is seen to grow as the distance from the pine needle surface grows, reaching its maximum at the distance of approximately 0.5-1.0 mm and then falling.

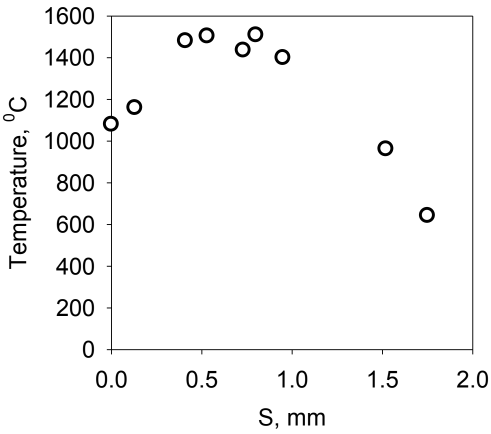
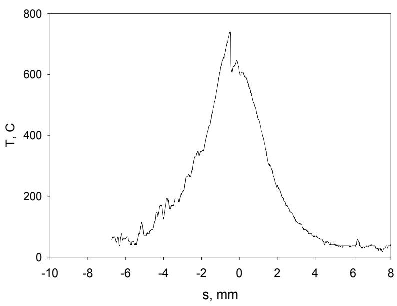


Fig. 6. A temperature profile of the flame perpendicular to the SPN in the location of the maximum temperature of the SPN

Combustion of char of SPN. Experiment and modeling

The velocity of flame spread along the char of SPN (CSPN), as opposed to that along the SPN, was insignificantly dependent on the spatial position of the SPN and on the direction of the flame spread and was equal to 0.33 mm/s when flame was spread upwards. Fig. 7 (left) shows the temperature profile of CSPN when flame is spread along it, measured with a thermocouple, the junction of which contacted it. The width of the burning zone was about 6 mm. The maximum char temperature measured with the pyrometric method T^pmax was 1000 °C, while that measured with a thermocouple was T^Tmax=750 °C. Disagreement between the pyrometric data and the results of the thermocouple measurements is attributed to heat loss in the cold ends of the thermocouple. Combustion of CSPN is the simplest model of SPN combustion, as chemical reactions in the gas phase can be neglected in this process. The model of flame spread along CSPN based on the following assumptions was developed: CSPN has the shape of a cylinder with radius $r_{0;}$ combustion takes place along the cylinder axis; the temperature and oxygen concentration do not depend in the radius in the cross section of CSPN; the chemical reaction of char oxidation is of the first order for oxygen; oxygen diffusion towards the CSPN surface is rather high compared to the flame spread rate; oxygen concentration near the CSPN surface n_0 was found by solving the diffusion equation in cylindrical coordinates. To find the flame spread rate along CSPN, the non-stationary thermal conductivity equation derived from these assumptions was solved. Shown in Fig. 7 (right) is the calculated temperature profile. Considering the pyrometric data, agreement between experiment and modeling can be considered satisfactory. The calculated burning rate of CSPN (0.3 mm/s) and burning zone width (5 mm) were close to the measured ones.



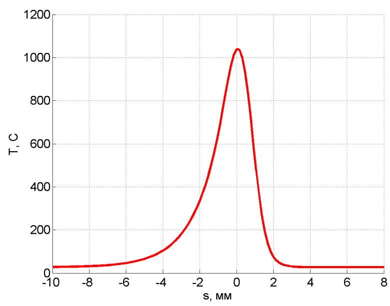


Fig.7. Temperature profiles: measured with a thermocouple (left) and calculated (right).

Conclusion

The thermal and chemical structure of flame spreading along a single pine needle (SPN) in air was studied with microthermocouples, by the pyrometric method and by the method of molecular beam mass spectrometry. The structure of the flame was studied along SPN, as well in the perpendicular direction to the SPN. Based on the mass spectrometric and temperature measurements during flame front spread along a SPN, 3 zones of chemical reactions were identified for the condensed phase: (1) SPN pyrolysis, forming char, tar and volatile products; (2) pyrolysis of tar, forming char and volatile products; (3) a heterogeneous reaction of char oxidation by air oxygen. The burning rate and the structure of upward flame spread along the char of a SPN were measured experimentally and calculated by numerical modeling. The calculated and measured temperature profile, the burning zone width and the burning rate are in agreement. The data obtained can be used for ground fire modeling.

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Reference

1. R. O. Weber, N. J. De Mestre, Combust. Sci. Tech. 70 (1) (1990) 17 —32.
2. P.R.A. Lyons, R.O. Weber, Combust. Sci. Tech. 89 (1) (1993) 153 — 165.
3. O.P. Korobeinichev, L.V.Kuibida, A.A.Paletsky, A.G. Shmakov, Jour. Prop. Power. 1998. Vol. 14. No. 6. P. 991.