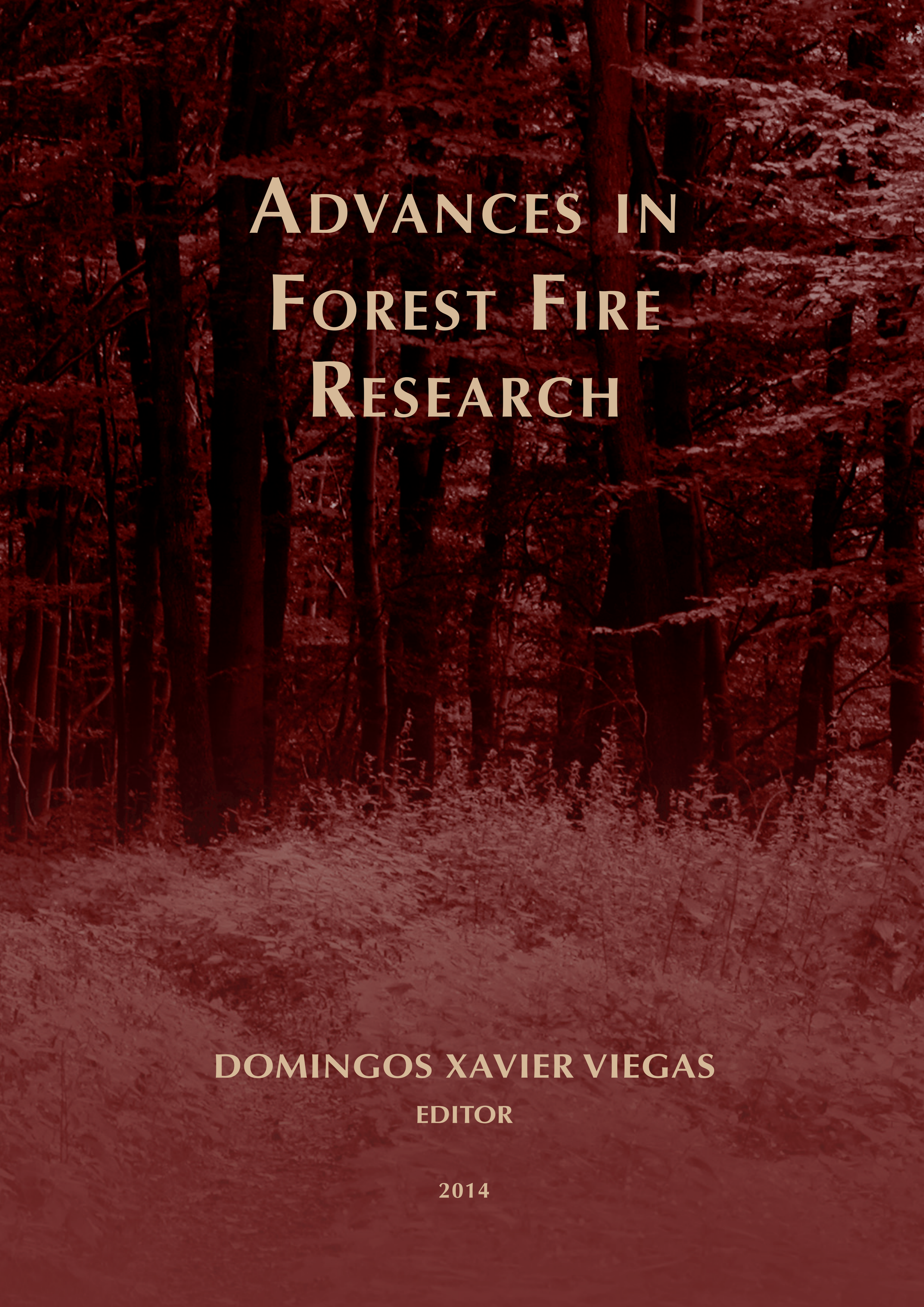

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The velocity and structure flame front at spread of fire across the pine needle bed. Experiment

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Abstract
The paper addresses an experimental study of the flame speed and of spatial temperature distribution at various depths of the bed of pine needles of Siberian boreal forests, a study of the composition of gaseous species and distribution of their concentrations across the bed during fire spread and the study of the impact of the wind velocity on these characteristics. It has been found that, as the wind velocity rises in the range of 0.12 - 0.2 m/s, the burning regime changes dramatically, as well as the temperature and concentration profiles of gaseous species inside the bed. At low wind velocities, flame penetrates the bed, while at high ones it does not. At wind velocities 0.15 m/s and higher, as the wind velocity grows, together with the dramatic growth of the flame velocity the maximum temperature in the flame front in the middle of the bed decreases from 1200 °C to 600 °C , the width of the combustion zone increases, in accordance with the temperature and O_2 и CO_2 concentration measurements. The flame front in the middle of the bed is biased relative to the flame front on the bed surface The data obtained in the study may be used in developing a ground fire spread model.

***Keywords**: pine needles;; fire spread across fuel bed; flame structure; forest fire*

1. Introduction

Propagation of a ground fire across a fuel forest (FF) bed is a frequently used model of a forest fire. Consideration of this model is also of practical importance, as it describes the general features of the mechanism of ground forest and steppe fires. There are many papers devoted to computer simulation of forest fire spread across a FF bed (Balbi 2007, Grishin 1997, Konev 1977, Lyons 1993, Morandini 2005, Morvan 2001, Porterie 2007, Simeoni 2003, Weber 1990). At the same time, there are unfairly few experimental studies of the process, measuring such parameters as the spread velocity, temperature and FF temperature profiles in a FF bed and outside it (Marcelli 2004, Morandini 2005, Santoni 2002, Simeoni 2003, Sukhinin 1975). The compositions of the pyrolysis and combustion products, their concentration and their profiles both in a FF bed and outside it have never been measured elsewhere. All these data, though, are required for verification of the assumptions made in certain models, by comparing the experimental data and the modeling data. Especially noteworthy are the studies of fire spread across a pine needles bed. In (Morandini 2005) temperature distribution was measured both in the gas phase and inside the bed of pine needles in still air and exposed to wind, the minimum velocity of which was 1 m/s. In (Sukhinin 1975) the same measurements were made in still air, while in (Marcelli 2004) temperature distribution was measured only over a bed of pine needles in still air. In (Morandini 2005) it was found that the minimum temperature approximately in the middle of the bed 2.3. cm thick reaches the value of 1,000 – 1,100 ° C. It is interesting that the maximum temperature measured with a thermocouple placed over the FF bed surface at the distance of 4 cm from it was about the same. We can suppose diffusion combustion of each needle in the bed to take place. Similar results under similar conditions were obtained in (Sukhinin 1975). In this study, the temperature profile was measured for a pine needle located on the bed surface with a thermocouple embedded inside a needle. The maximum temperature of a needle reached 800 °C. The flame spread velocity across the needles bed was approximately equal to 3 mm/s. It is to be noted that in the above studies temperature profiles of the needles at different distances from the bed surface inside it were mot measured. We did not find the papers in literature which would be devoted to the composition of gaseous products and their concentration distribution in the FF bed. Therefore one of the objectives of the study was to measure under laboratory conditions the temperature profiles inside of the bed of needles of the Siberian boreal forests (SBF), to study the composition of the gaseous products and distribution of their concentrations inside the bed during flame spread across the bed and to investigate the impact of the wind velocity on these characteristics.

2. Methods

2.1. Materials

The materials were the pine needles from SBF. The pine needles litter was sampled from under trees in a pine forest, then leaves and twigs were removed from it, with only litter needles left. The needles thus obtained were dried at the temperature of 60 °C during 24 hours in a drying cabinet. Weight loss after drying was 7.8-9.4 %. The average length of a pine needle was 5 mm, it was 1 mm wide and 0.6 mm thick. Specific surface area was determined using the BET method. It was 0.18 m^2/g.

2.2. Measuring the flame spread velocity across the pine needles bed depending on the wind velocity

The experiments were conducted in a chamber (Fig.1.) with the dimension of 70 cm/15 cm/30 cm. A photo of setup is presented in Fig.2. Placed inside the chamber a tray with a bed of pine needles 8 cm wide and 34 cm long. A photo of a tray with a bed of pine needles is presented in Fig.3. The amount of the pine needles was 0.07 g/cm^2. The needles were placed on an asbestos board plate 10 mm thick into a space restricted by fire-clay plates, 17 mm high. The layer porosity was 0.928.

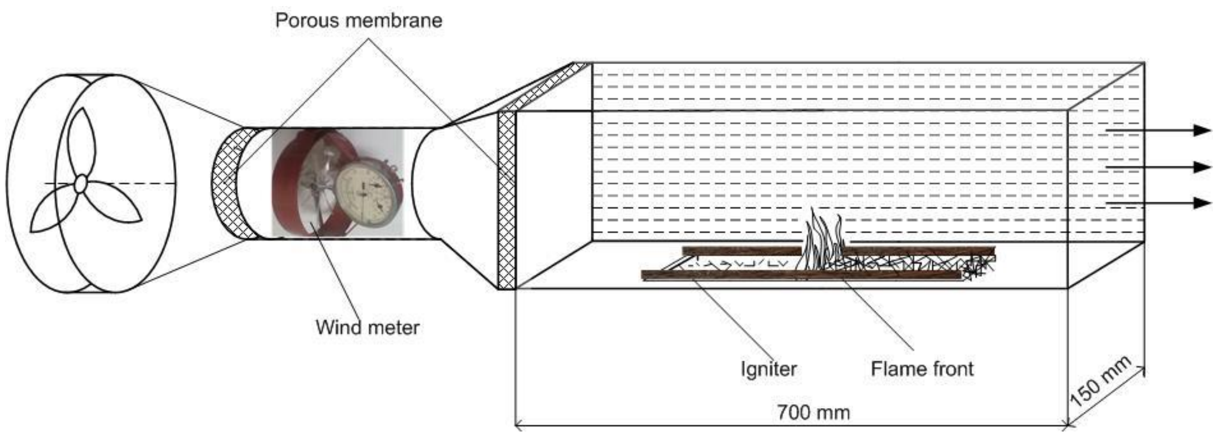


Figure 1- Experimental chamber for measuring the flame spread velocity across pine needles bed

Air was blown into the chamber from an air blower the capacity of 0.11 m^3/s. The wind velocity varied from 0 to 0.5 m/s. The air penetrated a porous filter to generate uniform flow. The air flow velocity was measured with a calibrated anemometer. The error in determining the average wind velocity was ±5%. The pine needles were ignited by a nichrome wire heated by electric current and a nearby glass wool bundle, impregnated with 1 ml ethanol. To avoid wire sagging during heating, it was mounted with a spring. The flame spread velocity was determined by signals from three thermocouples placed along the pine needles bed near its surface and from a video recording of the burning process. Variance in measuring the velocity of flame spread across a pine needles bed is ± 15%.

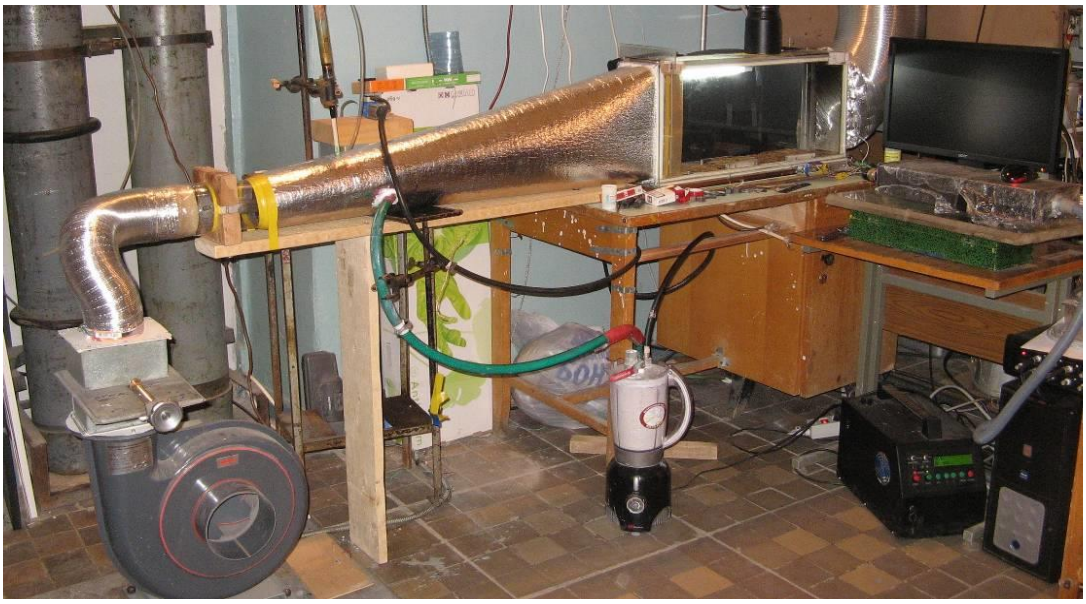


Figure 2. Experimental setup for measuring the flame spread velocity across pine needles bed

Figure 3. A photo of a tray with a bed of pine needles

2.3. Measuring the temperature profiles and the composition of the gaseous products on the bed surface and inside the bed exposed to flame spread

The temperature profiles and the composition of the gaseous products on the bed surface and inside the bed were measured with two П-shaped Pt-Pt 10% Rh thermocouples 50μm in diameter. The junction of one thermocouple (T1) was in the middle of the bed at the 13.2 cm distance from the igniter, the junction of the other one (T2) was on the bed surface at the 12 cm distance from the igniter. The photo of the thermocouples location is shown in Figure 4.

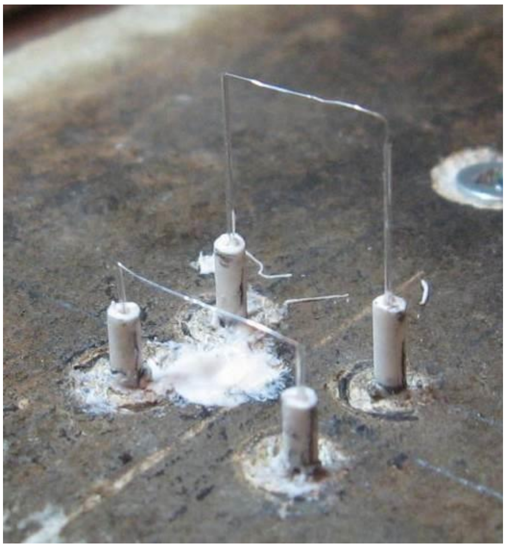


Figure 4. A photo of thermocouples location

To measure the temperature, a multichannel AD converter E14-140-M (“L-Card”) was used. The measurement error of thermal EMF was ±0.5%. The temperature measurements were conducted at the frequency of 1 kHz. The thermocouples’ signals were shown on the computer.

The composition of the pine needles pyrolysis products was measured by the probe mass spectrometry method. As a sampling probe, a pyrex tube was used with an internal diameter of 1.5 mm, embedded in the middle of the bed at a 18.8 cm distance from the igniter. The sample taken from the flame was cleaned from fine aerosol particles and tar and was delivered to the molecular beam system of the Hiden HPR-60 mass spectrometer. The response time of the sampling system was 2-2.5 sec, which is comparable with the time of recording one mass spectrum. Concentrations of O_2, CO_2, N_2, C_2H_5OH (ethanol), C_3H_6O (acetone), C_4H_4O (furan) in the sample studied were determined by the mass peak intensities with m/e 32, 44, 28, 31, 15 and 43, 68, accordingly. Sensitivity of the mass-spectrometer was determined by the calibration mixtures of the known composition. The ignition time and the starting time of the mass spectrometric measurements were synchronized. The dependences of mass peak intensities were measured, corresponding to the compounds chosen, as a function of time. Considering the measured average flame spread velocity across the pine needles bed, the dependences of temperature and species concentrations on time were recalculated into the respective dependences of temperature and species concentrations on the horizontal coordinate relative to the flame front.

3. Results

3.1. Dependence of the flame spread velocity across the bed of pine needles on the wind velocity

It can be seen from Figure 5, showing the results of measuring the dependence of the flame spread velocity on the wind velocity, that, as the wind velocity grows from 0 to 0.12 m/s, the flame spread velocity varies little, while with the change in the wind velocity from 0.12 m/s to 0.2 m/s, it almost triples. With the wind velocity of 0.15 - 0.2 m/s and higher, the regime of flame spread changes critically. As the wind velocity increases from 0.15 to 0.2 m/s the flame speed dramatically increases to 6 mm/s. Simultaneously, as seen from Fig.5, the temperature in the middle of the bed dramatically drops from 1200 до 600°C. With the wind velocity higher than 0.2 m/s, probably comparable with the velocity of the pyrolysis products rise, the angle of flame slope to the horizon dramatically decreases (with the wind velocity of 0.1 m/s, it would be close to 90 degrees), the flame seems to lie down on the pine needles layer (Figure 6).

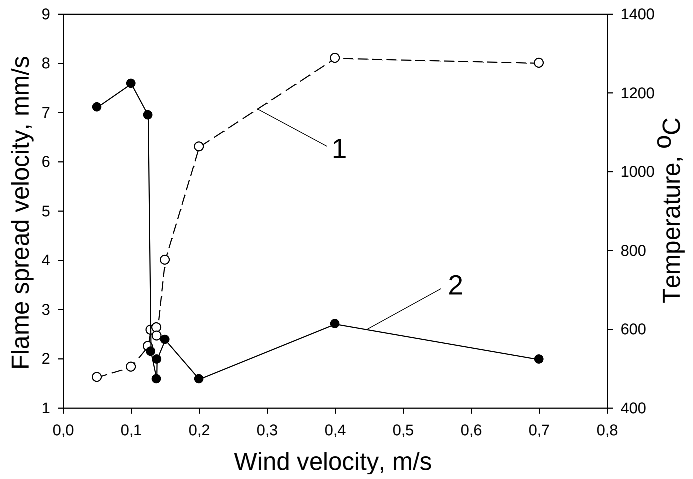
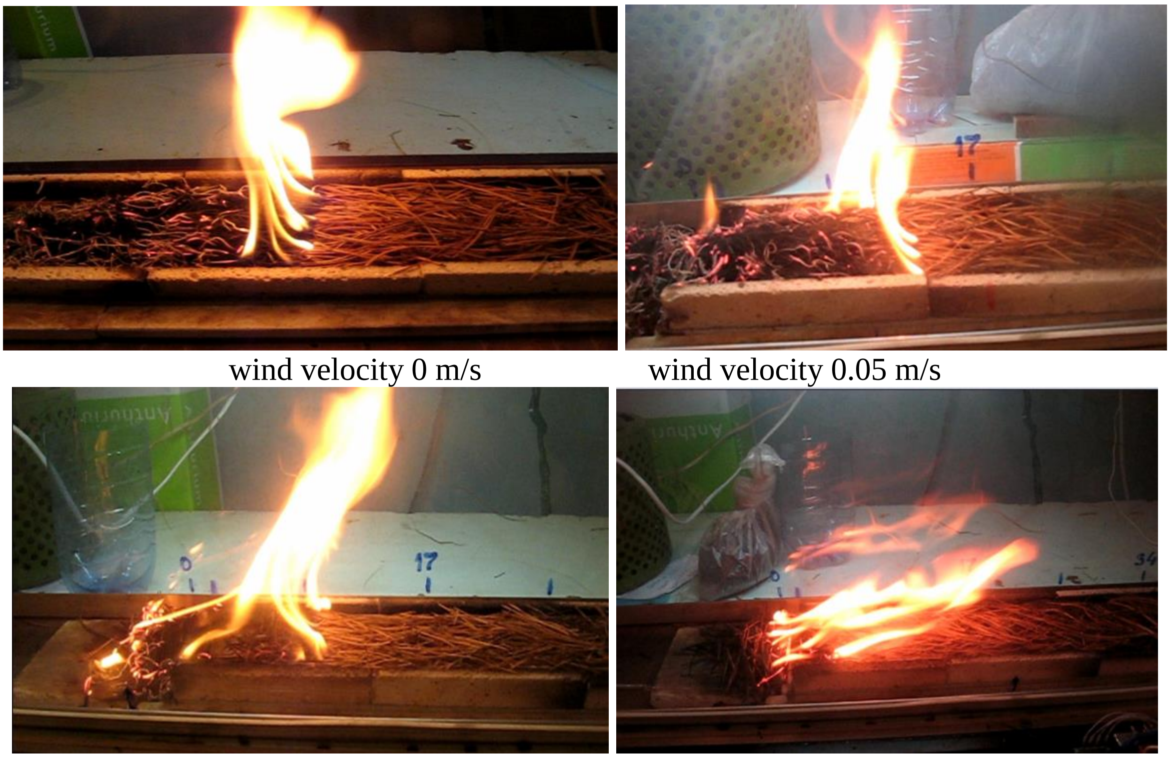


Figure 5. Dependences of the velocity of flame spread across the pine needles bed (1) and temperature in the middle of the bed (2) on the wind velocity



wind velocity 0 m/s   wind velocity 0.05 m/s

wind velocity 0.1 m/s   wind velocity 0.2 m/s

Figure 6. The photos of flame spread across a bed of pine needles depending on the wind velocity in the range from 0 to 0.2 m/s.

3.2. Temperature profiles and concentration profiles of O_2, CO_2 and volatile pyrolysis products in flame spread across a pine needles bed

Shown in the Figure 7 are the temperature profiles in the middle of the bed (T1) and on the surface (T2), considering the fact that the distance between the thermocouples was 11.8 mm, and the concentration profiles of CO_2, O_2 and ethanol inside the bed with the wind velocity of 0.1 m/s. The flame spread velocity is 2.05 mm/s. Analysis of the temperature profiles allows the following conclusions to be made:

1. Flame penetrates into the pine needles bed. The maximum temperature in the middle of the bed is 1300 °C. These data are in good agreement with the data of (Morandini 2005, Sukhinin 1975), obtained for conditions close to those of this study.
2. The flame front in the middle of the bed is 1.2 cm shifted relative to the flame front on the bed surface.
3. The width of the flame zone determined by the T2 profile is 7 cm. The width of the glowing (high temperature) zone is 1.2 cm on the bed surface (which agrees with the video recording data) and 0.9 cm in the middle of the bed.
4. Although combustion behind the flame front on the bed surface finishes at the 7 cm distance from the flame front, the temperature in this place in the middle of the bed is higher than on the bed surface, indicating continuing reactions inside the bed.

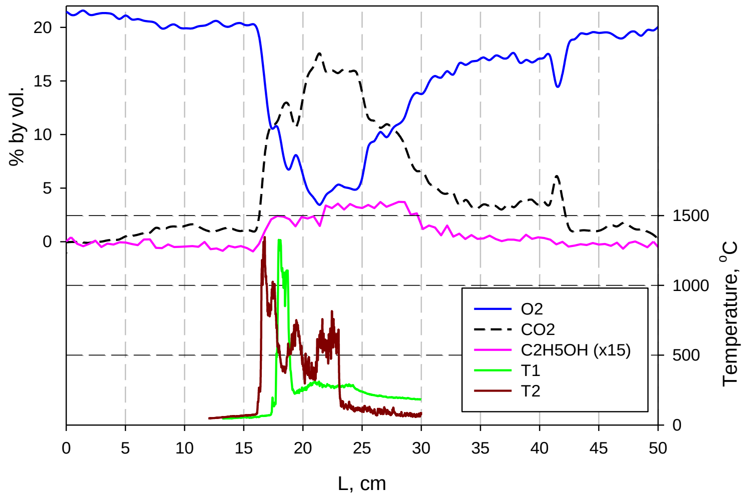


Figure 7. Temperature profiles in the middle of the pine needles bed (T1) and on the surface (T2), as well as CO_2, O2 and ethanol concentrations inside the bed, with the wind velocity of 0.1 m/s.

Thus, it follows from the results of mass spectrometric studies that:

1. As the flame front advances, O_2 concentration in the middle of the pine needles bed decreases to 4-5 %, while the maximum CO_2 concentration is reached at the distances from 6 to 9 cm from the flame front and is equal to 15-17 %. The width of the flame front determined from the O_2 и CO_2 concentration profiles is equal to 6 cm, which is close to the value of 7 cm, obtained from the data of the temperature profiles (T2). Thus, O_2 concentration in the middle of the bed does not decrease to zero. Oxygen may penetrate the bed due to diffusion and gas transfer along the bed. At the distances from the flame front greater than 9 cm, CO_2 concentration gradually decreases, while O_2 concentration goes up.
2. Maximum concentrations of two major volatile products of pine needles pyrolysis ethanol and acetone in the middle of the bed are 0.2 and 0.4-0.9 %, respectively. The width of the yield zone of the main volatile pyrolysis products is 12-13 cm. When the distances from the flame front are greater than this value, char smolders in the middle of the bed.

Similar facts are observed for the wind velocity of 0.05 m/s and in the absence of wind. However, with the wind velocity of 0.2 m/s and higher, the regime of flame spread changes critically. With the wind velocity higher than 0.2 m/s, probably comparable with the velocity of the pyrolysis products rise, the angle of flame slope to the horizon dramatically decreases. Due to this, the width of the heated zone before the flame front expands and the front zone expands, too, which is confirmed by the temperature profiles and species concentrations in the pine needles bed at the wind velocity of 0.2 m/s shown in Figure 8.

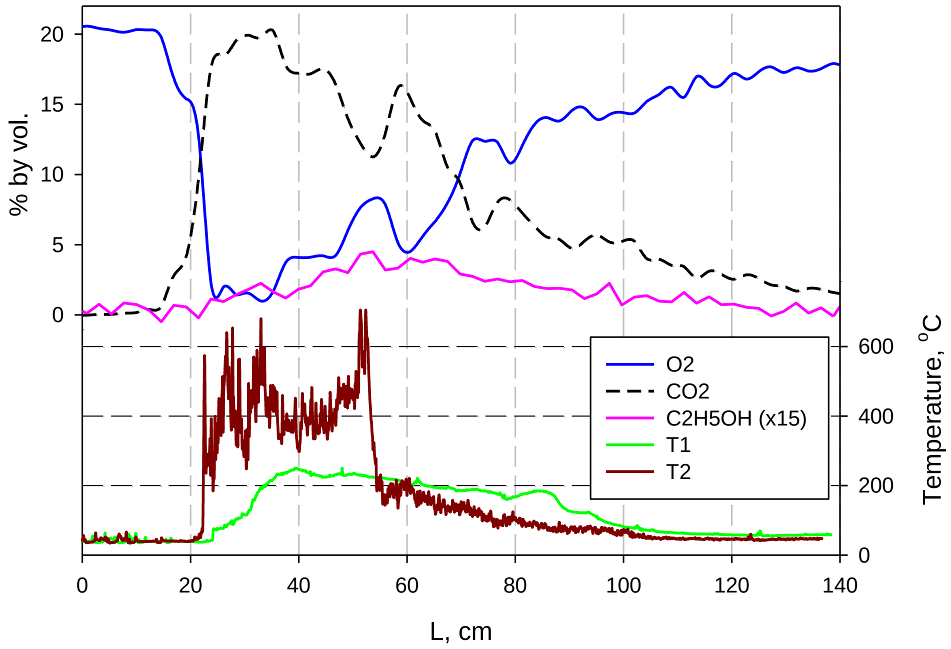


Figure 8. Temperature profiles in the middle of the pine needles bed (T1) and on the surface (T2), as well as CO_2, O_2 and ethanol concentrations inside the bed, with the wind velocity of 0.2 m/s.

It can be seen that the maximum temperature near the bed surface drops to 700 ºC, evidently among other factors due to dilution of the combustion and pyrolysis products with air, while in the middle of the bed it drops to 230ºC. The flame front width near the bed surface with the temperature 600-700ºC increases several times due to the drop of temperature and therefore of the pyrolysis rates to become about 30 cm.

4. Conclusion

1. First changing the regime of flame spread across a bed of pine needles was found for changing wind velocity. It has been observed that in flame spread across a bed of pine needles there emerges a complex spatial distribution of temperatures and species concentrations, which depends on the wind velocity. The character of combustion essentially changes as the wind velocity changes from one range (0-0.12 m/s) to the other one (0.12 - 0.2 m/s). In the first range of wind velocities, the flame spread velocity is only slightly dependent on the wind velocity, while in the second range the dependence significantly increases. At low wind velocities flame penetrates the bed of pine needles, while at high wind velocities this does not occur. At wind velocities 0.12 m/s and higher, at the wind velocity grows, together with the growth of the flame velocity the maximum temperature in the flame front decreases from 1200 °C and 700 °C , the width of the flame zone, in accordance with the temperature and O_2 и CO_2 concentration measurements. The flame front in the middle of the bed is shifted relative to the flame front on the bed surface.
2. The experimental data on the dependence of the flame spread velocity across the bed of pine needles on the wind velocity obtained in the study and on the flame front structure (distribution of temperature and concentrations of gaseous species inside the bed) may be used in developing a model of ground fire spread.

5. Acknowledgment

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