Investigations of ground forest fire spread through fallen leaves and needles

A.M. Grishin, A.A. Dolgov, V.V. Reino, R.Sh. Tsvyk, and M.V. Sherstobitov

*Institute of Atmospheric Optics,
Siberian Branch of the Russian Academy of Sciences, Tomsk*
Received June 22, 1999

The paper describes some results of investigations into the spread and radiation temperature of burning of fallen birch leaves and pine and cedar needles at different moisture content using the IR imaging technique. The paper presents the exponential functions of the fire front spread speed depending on the moisture content in the fallen leaves and needles. The radiation temperature of the condensed phase burning in the range of 3–12 μm is 800–900 K provided that the radiation coefficient ε equals unity.

Introduction

General mathematical models of forest fires are widely used for predicting the occurrence, evolution and spread of ground forest fires (GFF) and their ecological consequences. The most general, in our opinion, mathematical model of forest fires, in which the grouped diffusion approximation of radiation transfer is used, takes into account all the main physical-chemical burning processes of forest combustible materials (FCM) and energy transfer.[1,2] With the use of this model the techniques have been developed, which enable us to detect the contaminating emissions to the atmosphere.[3,4] In the model development a large body of data from the semi-field and laboratory investigations were used.

It should be noted that in a given model we use the static parameters of burning process and FCM characteristics. In reality, the burning processes and the environmental characteristics are random fields with their own statistical parameters. Therefore, we believe that the development of the statistical mathematical model of forest fires is a logic continuation of the earlier performed investigations.

The development of such a model will require both the advancement of theory and a great deal of experimental investigations of statistical characteristics of FCM fields (spatial distribution of stock, density and moisture content of FCM) in various landscape areas, burning processes in the field and laboratory conditions with random fields of FCM parameters distribution, limiting conditions of firing and burning, and so on.

This paper discusses the results of experimental investigations of the FCM fire front spread velocity at different moisture content.

Measurement technique

Experimental investigations were performed using a laboratory setup for physical modeling of ground forest fires. The model setup includes a table-polygon of 1.3×0.75 m^2 in size covered with a 0.1 m thick soil layer, upon which a layer of studied combustible material was placed. In this case the IR imaging measurement technique has been applied.[6–8] As FCM the fallen birch leaves and cedar and pine needles with different moisture content were used. In most cases the moisture content of the first fired half of the above layer was less than 1% and the humidity of the second half of the layer was more than 1%.

In the measurements two types of IR imaging system were utilized, namely, an AGA–780 IR imaging system (operating in the 3–5 μm wavelength range) modernized by the authors and intended for investigating the dynamics of thermal fields and an Igframetric–760 IR imaging system (operating in the 3–12 μm wavelength range) having wider temperature range and high precision, but allowing the recording only separate frames. The application of the dynamic system allows the programmed determination of variation of the fire front spread speed, the relative maximum temperature and its coordinates, flame height and a series of other characteristics. The speed of the fire front spread is determined with the interval of 1–2 s along the path (coordinates) of motion of the maximum temperature point. Such a technique enables us to increase the accuracy of determination of the speed as compared with the thermocouple technique as well as to measure the speed within isolated intervals of motion of the fire front. The second system is a calibrated one and its use allows one to determine absolute temperatures by the law of blackbody radiation at a given blackbody radiation coefficient.

The horizontal and vertical spatial resolutions were determined according to a heated plane of a required size. The distance from the IR imager AGA–780 up to the table-polygon was 7 m, the height of elevation above the floor surface was 1.4 m, the IR imager was located at a distance of 0.7 m from the floor, the resolution by the direction of the fire front spread (coordinate x) was 7.7 mm.

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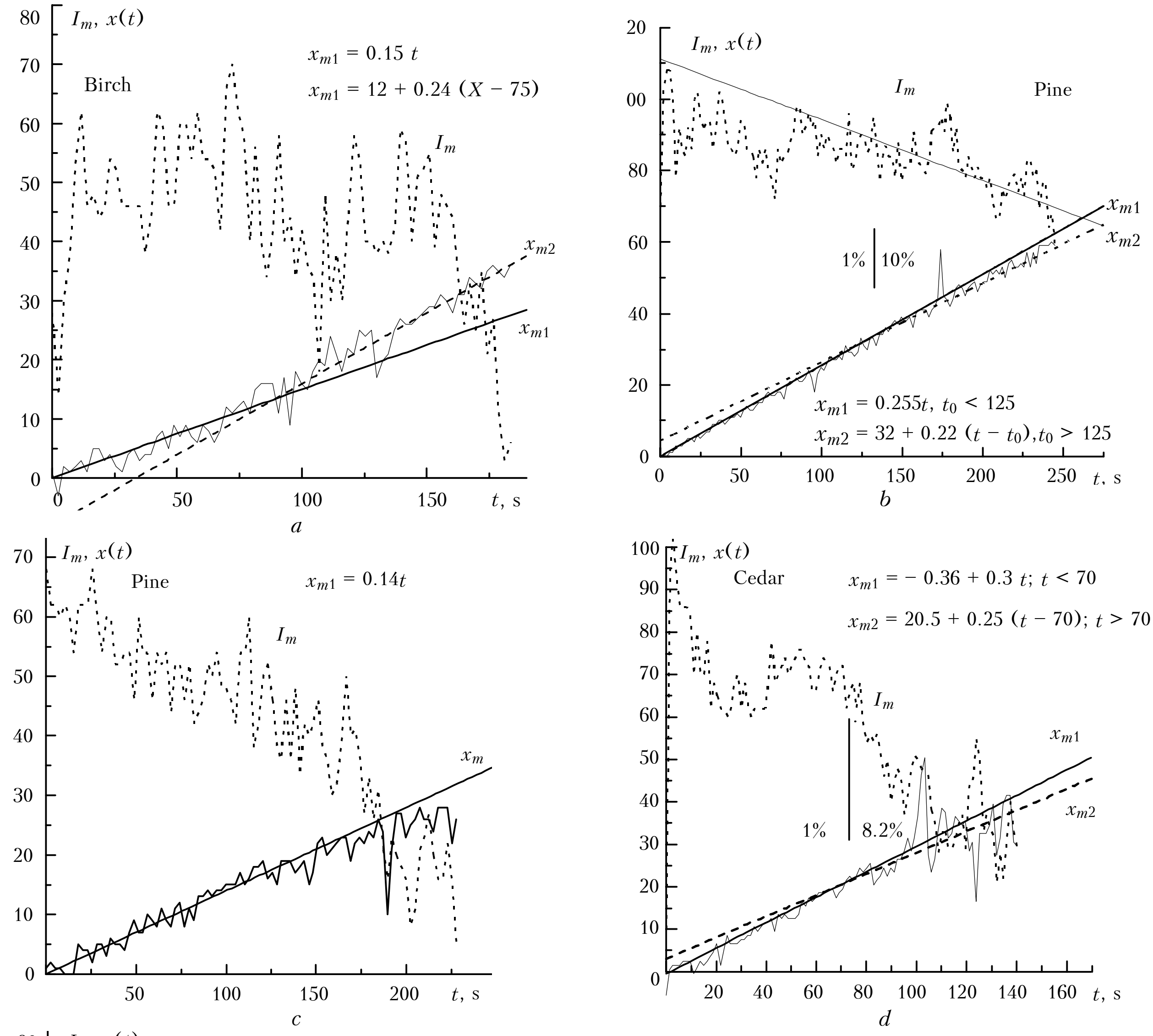


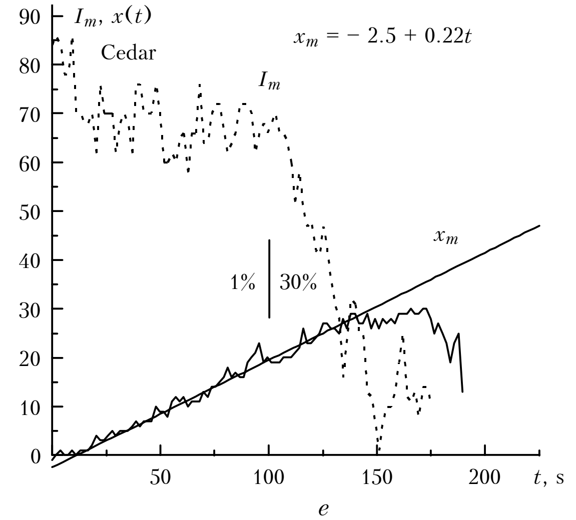


Fig. 1. Burning of the fallen leaves and needles: (*a*) birch leaves at the moisture content W = 6% (W_1 = 6.4%); (*b*) pine needles (C1) at W = 1 + 10% (W_1 − 1 + 11%); (*c*) pine needles (C2) at W = 12% (W_1 = 13.6%); (*d*) cedar needles at W = 1 + 8.2% (W_1 − 1 + 8.9%); (*e*) cedar needles at W = 1 + 30% (W_1 = 1 + 43%).

Measurement results

Figures 1*a* to *d* show the measured results on the dynamics of relative temperature and the coordinate x of the maximum temperature point in time when burning FCM.

Figure 1*a* shows data obtained during one of the experiments on burning of birch leaves at the moisture content $W = 100(m - m_0)/m \approx 6\%$ or $W_1 = 100W/(1 - W) = (m - m_0)/m_0 = 6.4\%$, where m and m_0 are the masses of damp and dry FCM, respectively, the mass $m = 53$ g (the FCM stock is 0.59 kg/m^2), the layer is 1 cm thick over a 30×30 cm^2 area. From these data it follows that the speed of fire front spread grows with time. The entire fire front spread path $x_m(t)$ can be subdivided into two regions and for each region an approximation equation of the first order can be derived. These equations are of the form: $x_{m1}(t) = 0.15t$ at $t < 75$ s, $x_{m2}(t) = 12 + 0.24(t - 75)$ at $t > 75$ s, i.e., the speed of the fire front spread increases from 1.5 to 2.4 mm/s. The relative maximum temperature I_m

fluctuates. However, its mean value is constant (~ 45 units). Under similar conditions, but with the layer less compact the speed of the front spread is higher. In the initial area the speed was 2 mm/s, then it increased to 3 mm/s, and the mean maximum temperature increased up to 55 units.

The increase of the front spread speed can be explained by the radiation and convective drying of FCM as well as by a possible decrease of FCM due to deformation in the course of drying. It should be mentioned that in a given experiment the drying process velocity did not reach maximum, because of a limited fire front length. Note that at the moisture content of 12.5% after passing to the second area the burning process ceased.

Figure 1 shows the measured results on the burning process of pine needles of two types C1 and C2 (Fig. 1*b* and *c*) and cedar needles (Fig. 1*d* and *e*) of different moisture content. The mass of the FCM layer being studied at each moisture content was 27 g. This layer was located at two equal areas of 23×23 cm size in the form of 1 cm layer. In the first area the dry FCM was located for all time (the moisture content was less than 1%), while in the second area the layer of different moisture content was placed. The boundary separating the areas is shown by the vertical line. Figure 1*c* shows the burning process only in the second area (the fallen pine needles with the moisture content of 12%), and it is seen that at $t = 170°$ the fire front reaches the FCM outer limit and the front motion stopped. From the above data it follows that the speed of the fire front spread and the relative maximum temperature I_m in the area with an enhanced moisture content tend to decrease. In this case at cedar needles moisture content of 30% (see Fig. 1*d*) the relative maximum temperature during ~ 40 s decreased and the burning process stopped after traversing a path of 10–15 cm length. This clearly demonstrates that the radiative and convective drying is of a considerable importance in overcoming the bands of an enhanced moisture content at inhomogeneous spatial distribution of the FCM moisture content. The speed of the fire front spread at the FCM edge in the second area was found visually to be less than in the center. This is due to the smaller radiation flow and, accordingly, slowing down of FCM drying process. We would like to point out the fact that we failed to set on fire the fallen dry fir-tree needles. After burning up the fir-tree needles in the region of firing coil the burning process stopped.

Figure 2 shows the measurement results on the speed of the fire front spread depending on the moisture content W for all types of FCM of fallen leaves. Curve *1* in Fig. 2 shows the semiempirical dependence of the fire front spread speed on the moisture content:

$$V_p = V_0 W_1/(1 + 14.8 W_1), \qquad (1)$$

which is widely used in mathematical models of fires,[1,5] when the value of the fire front spread speed of dry FCM $V_0 = 3$ mm/s and $W_1 = W/(1 - W)$. Curves *2* and *3* fit the experimental data with the use of the exponential dependence of the speed on moisture content:

$$V = V_0 \exp[- W^2/W_0^2] \qquad (2)$$

and

$$V = V_0 \exp[- W^2/(W - W_0)^2]. \qquad (3)$$

These functions show a weak dependence at small moisture content observed in the experiment, because the FCM moistening decreases rapidly due to intensive radiation and convective drying of the FCM. At the same time the first function (2) exhibits fast decrease of the speed at $W \geq W_0$, when, even with due regard for drying the FCM, moistening exceeds the limiting values sufficient for the maintenance of burning process. The second function (3) tends to zero at $W \to W_0$ and is applicable only at $W < W_0$. It would appear natural that, as the V_0, the value of W_0 will depend on the type of FCM fallen leaves and needles, its density, stock, degree of destruction, and the rate of radiation and convective drying by the fire front. Preliminarily, the mean, over all measurements, values of W_0 for Eq. (2) are: $W_0 = 14\%$, for Eq. (3) $W_0 = 25\%$. It should be noted that in many cases the exponential dependence is conveniently expressed in mathematical models, since it enables one to solve a wide range of equations.

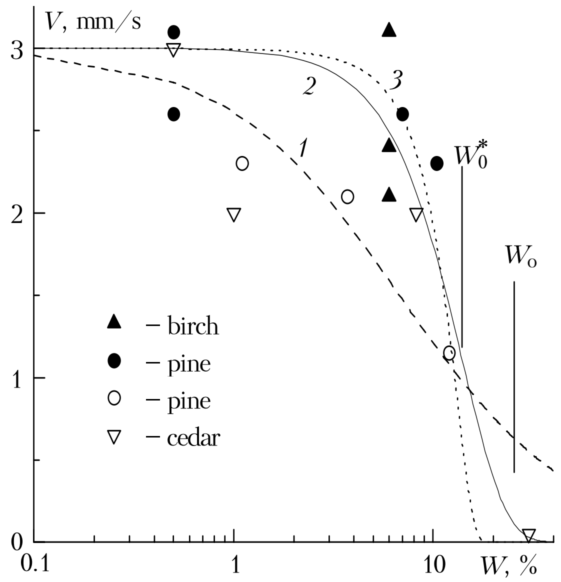
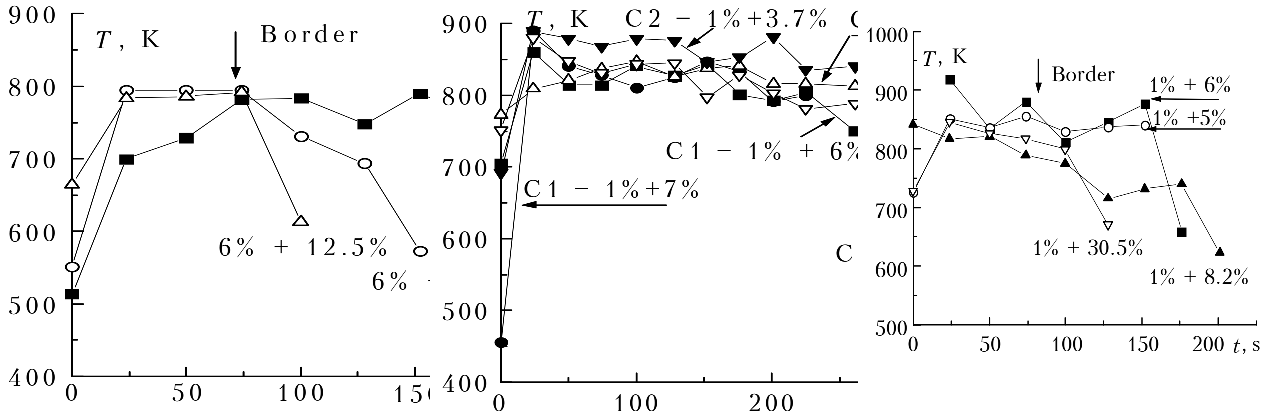


Fig. 2. Dependence of the fire front spread speed V on the moisture content W.

Figures 3*a–c* give the maximum radiation temperatures determined with the Igframetric–760 IR – imager assuming that the combustion zone of a condensed phase emits according to the Planck law with the emissivity ε being equal to unity. From the obtained data it follows that the area of maximum temperature reconstructed, based on the emission in the IR range, equals 800–900 K and is located in the flaming zone of FCM (the combustion zone of a condensed phase); with the increase of the moisture content the maximum temperature decreases; when reaching the edge of the portion of the FCM studied and at the moisture content higher than critical (curve for the moisture content of 12.5%, Fig. 3*a* and 30.5%, Fig. 3*b*, the fire front spread slows down, the maximum temperature decreases rapidly and burning stops. Lower temperature of burning of birch fallen leaves 700–800 K is conditioned by the fact that within the entire area the birch fallen leaves with 6% moisture content was used. It should be noted that the maximum temperature of burning of a condensed phase measured in different spectral ranges, differs within the limits of 30°. This fact indicates that the condensed phase emits really according to the Planck law, at least as a gray body.



a *b* *c*

Fig. 3. Maximum temperature when burning the birch fallen leaves (*a*), pine (*b*), and cedar (*c*) fallen needles.

Conclusions

The results of experimental investigations of the FCM burning were considered. The authors proposed the relationships of the form $V = V_0 \exp[-(W/W_0)^2]$ and $V = V_0 \exp[-(W^2(W - W_0)^2]$ for describing the dependence of the fire front spread speed on the moisture content W (%) where $V_0 = 3$ mm/s is the fire front spread speed of dry FCM. The preliminary value of the moisture content W_0, at which the spread speed V decreases by a factor of 2.7, equals to 14% for the first relationship and 25% for the second one when $V = 0$. The values of W_0 are proportional to the limiting moisture content, at which the fire front spread occurs.

The maximum fire radiation temperature of the condensed phase of FCM in the 3–12 μm range, reconstructed by the black-body radiation law with the radiation coefficient of 1 for dry pine and cedar fallen needles, is 800–900 K. With the increasing moistening of the FCM the maximum radiation temperature decreases.

Acknowledgment

The present work has been supported by the Russian Foundation for Basic Research (Grant 99–01–0363).

References

1. A.M. Grishin, *Mathematical Simulation of Forest Fires and New Techniques of Fire Control* (Novosibirsk, Nauka, 1992), 408 pp.
2. A.M. Grishin, *Mathematical Simulation of Forest Fire and New Techniques of Fire Fighting*, Frank Albini, ed. (Publishing House of Tomsk State University, 1997), 390 pp.
3. A.M. Grishin, A.A. Dolgov, and A.F. Tsymbalyuk, *Techniques for Determination and Calculation of Contaminant Emissions of Forest Fires* (Moscow, State Committee of Russian Federation for Environmental Protection, 1997), 37 pp.
4. A.M. Grishin, A.A. Dolgov, and A.F. Tsymbalyuk, *The Calculation Technique of Fire Source Emissions in Oil and Oil Products Spread* (Moscow, State Committee of Russian Federation of Environmental Protection, 1997), 37 pp.
5. E.V. Konev, in: *Analysis of Process of Forest Fires and Burns. Thermal Physics of Forest Fires* (Novosibirsk, Institute of Heat Physics SB AS USSR, 1984), pp. 99–125.
6. A.M. Grishin, A.A. Dolgov, V.P. Zima, V.V. Reino, and P.Sh. Tsvyk, Atmos. Oceanic Opt. **10**, No. 10, 712–719 (1997).
7. A.M. Grishin, A.A. Dolgov, V.P. Zima, A.V. Isakov, O.L. Maksimov, V.V. Reino, and R.Sh. Tsvyk, Fiz. Goreniya i Vzryva **32**, No. 6, 1–11 (1996).
8. A.M. Grishin, A.A. Dolgov, V.P. Zima, V.V. Reino, and R.Sh. Tsvyk, Proc. SPIE **3122**, 317–326 (1997).