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HEAT AND MASS TRANSFER IN COMBUSTION PROCESSES

IGNITION OF FOREST COMBUSTIBLE MATERIALS IN A HIGH-TEMPERATURE MEDIUM

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The ignition of typical forest combustible materials (birch leaves) at temperatures characteristic of a crown forest fire was investigated. The dependence of the delay time of ignition of a birch-leaf sheet on the temperature of the surrounding medium was determined, and the mechanism of ignition of leaves in a high-temperature medium was revealed. A mathematical model of classification of forest combustible materials on the basis of experimental data on their properties has been developed.

Keywords: *ignition, forest combustible material, crown forest fire, ignition delay time, experiment, high-temperature medium, mathematical model.*

Introduction. Of the forest fires, the crown fire is more dangerous. Crown fires happen predominantly in coniferous forests and mixed forests in which the coniferous trees are prevailing. However, as experiments with birch leaves have shown, even though these leaves have a low heat conductivity, they ignite easily and, therefore, represent a very fire-hazardous material. In a crown forest fire, a combustible is formed by needles, leaves, and thin twigs of trees [2], and their trunks and branches of large diameter do not burn in this fire. Because of this, the front of such a fire, representing a high-temperature medium, moves over the crowns of trees. Individual deciduous trees in a coniferous forest can increase the rate of propagation of a crown fire in it. The problem on the propagation of a crown fire in a mixed forest remains to be solved. Therefore, of importance is the study of the ignition of deciduous trees in a high-temperature medium [3].

In [4], the ignition of dead cluster-pine needles and oak leaves by an external heat source was investigated. Such ignition of forest combustible materials (FCM) is realized most frequently in the case where they are heated by a radiant heat flow or a convective heat flow. Sources of ignition of FCMs can be firebrands and heated particles. In [5], the ignition of bush leaves was investigated depending on their thickness and moisture content. Data on the ignition of living elements of plants are necessary for the simulation of the propagation of a fire from the ground of a forest to the branches of trees or brushwoods in it. The pyrolysis of 23 kinds of FCMs was investigated on [6]. It was established that the leaves of different species differ insignificantly in their combustion properties, and marked differences were detected between the FCMs of different types. The influence of the shape, thickness, and orientation of leaves on the delay time and temperature of their inflammation was determined in [7]. In [8], the ignition of branches of coniferous trees by a fixed heat source was experimentally investigated, and, in [9], an experiment on the ignition of vegetable combustibles under identical conditions has been performed. The main goal of these investigations was to determine the moisture content of a FCM at which it is ignited for a definite exposure time. In [10], the ignition of pine needles and oak leaves by a heat flow was investigated depending on the density of their packing. In [11], the heat flows necessary for the ignition of different FCMs were determined without regard for their moisture content. In [12], the ignition of different forest combustible materials by a heat flow was investigated, and, in [13], experiments on the ignition of such materials by a particle heated to a high temperature have been performed.

The aim of the present work is to investigate, by the example of a birch leaf, the ignition of FCMs in a high-temperature medium formed under the conditions of a crown forest fire. It should be noted that this investigation is of importance for control of forest fires in the Russian Federation because the habitat of the birch covers almost the whole of its territory.

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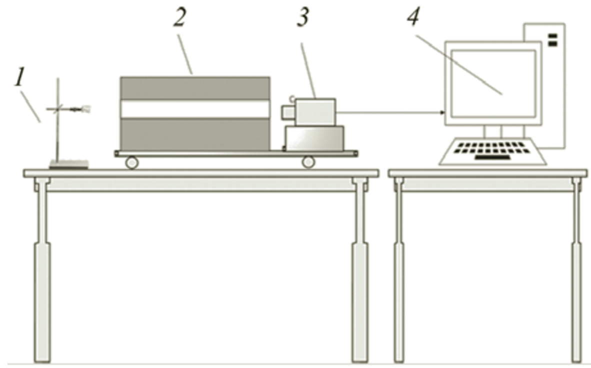

Fig. 1. Diagram of the experimental setup: 1) holder on a moving base; 2) tube furnace; 3) high-speed video camera; 4) personal computer.

Investigation Method. We investigated birch leaves from the Timiryazevskoe forestry of the Tomsk region, belonging in forest-vegetation division into districts, to the Southern-taiga zone with a moderately humid climate in which the vegetation period lasts 120 days. In this forestry, the prevailing species are the pine (39.6%), the aspen (26.6%), and the birch (21.2%), and the cedar, the larch, the spruce, and the fir comprise 13% [14]. Therefore, the choice of the birch as a typical FCM of a broad-leaved tree is justified.

The investigations were performed in a NevaTerm tube furnace, the temperature in whose channel reached 1100^{o}C. This temperature can be realized at the front of a crown forest fire. Samples of birch leaves in the form of a sheet were investigated. Such a sheet was preliminarily dried in a drying cabinet for removal of moisture from it. With the use of a holder mounted on a moving base, a birch-leaf sheet was positioned in the furnace channel where it was ignited. A high-speed video camera was installed on the opposite side of the furnace channel. A video tape of the inflammation of a birch-leaf sheet, obtained with this camera, was transmitted to a personal computer. Six experiments were performed with birch-leaf sheets identical in shape, size, and thickness at one and the same temperature in the furnace channel. A diagram of the experimental setup is shown in Fig. 1.

Results and Discussion. Figure 2 shows frames of a videogram of the ignition of a birch leaf in the high-temperature medium formed in the channel of a NevaTerm tube furnace. The frames obtained allow us to propose the following physiochemical mechanism of combustion of a leaf in a high-temperature medium. The first stage of this combustion is the inertial heating of the leaf sheet. At the second stage of the combustion process, the material of the leaf experiences thermal decomposition with a high-temperature evaporation of terpene-like substances from it. Then the gaseous products of pyrolysis of the leaf material and the terpene-like substances are injected into the near-wall region of the leaf sheet where they are mixed with the air oxygen. As a result, the leaf is ignited in the gas phase, and its flame combustion proceeds with the after-burning of the carbon residue in it.

A FASTCAM SA 1.1 high-speed video camera of model 675K-M1 was used in the experiments. The high resolution (1024 × 1024 points) and the high recording rate (of the order of 500 frame/s), provided by this camera, made it possible to reveal the main and secondary mechanisms of the combustion of a leaf. Initially, at the edge of a leaf sheet there appear individual rounded glowing microregions in which the gaseous products of pyrolysis of the dry organic substance of the leaf burn. Then the sizes and the number of these regions increase, several of them unite into one region of large size, and the leaf ignites in the gas phase. Finally the gaseous pyrolysis products and terpene-like substances are intensively injected into the leaf sheet, which leads to its explosion-like combustion.

Figure 3 presents the dependence of the delay time of ignition of a birch leaf on the temperature of the surrounded medium, obtained as a result of the statistical treatment of experimental data on the ignition of such leaves with confidence intervals calculated with a confidence probability $P = 0.95$ [15]. The curve shown in this figure represents an approximation of the experimental data by the second-degree polynomial. It is seen that the experimental data can be adequately represented in the zero approximation by a straight line. It should be noted that this straight line is characteristic of the inflammation of FCMs by a single metal particle or a nonmetal one heated to a high temperature.

As noted in [16], the combustion of a FCM under the conditions of a forest fire can be defined in terms of its preignition, ignition, and burning, which is not in conflict with the mechanism of a forest fire proposed in [2]. At the first

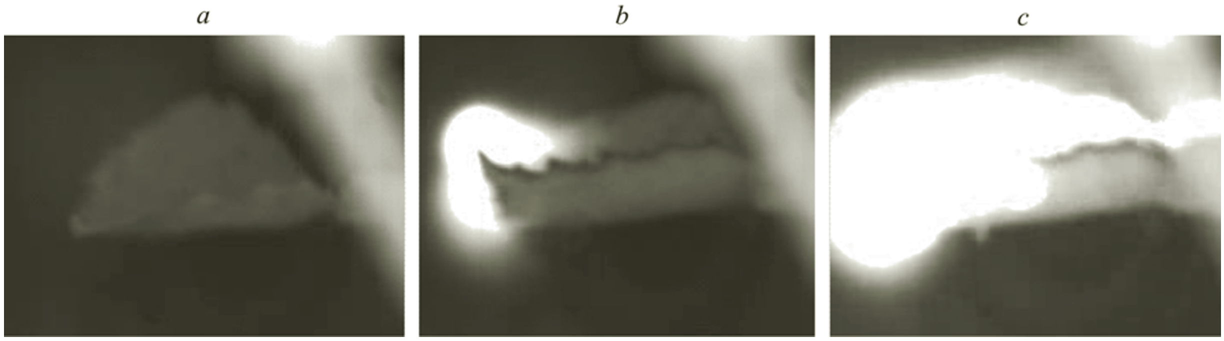

Fig. 2. Video frames of the ignition of a birch leaf in a high-temperature medium: a) inertial heating of the leaf; b) inflammation of the leaf (appearance of microflames); c) combustion of the leaf in the gas phase.

stage of combustion of a FCM in a forest fire other than a catastrophic one, an endothermic evaporation of moisture from the FCM takes place with release of volatile compounds from it at low temperatures. As the temperature of the FCM increases, its pyrolysis begins, and the molecules of the dry organic substance of the FCM break down with the formation of smaller-mass molecules, including the molecules of volatile compounds, a coke breeze, an ash, and a gum. The thermal decomposition of the cellulose of a FCM begins at a temperature of 280–400^{o}C and proceeds by two mechanisms [17, 18]. The first mechanism is the dehydration of the FCM leading to the formation of a coke breeze and gases (CO, CO_2, and H_2O predominantly), and the second mechanism is the depolymerization of the FCM with the formation of a gum and volatile compounds in the phase of formation of levoglucosan. In the case where the FCM is rapidly heated to a high temperature, volatile compounds are formed. These compounds interact chemically with each other, and, in so doing, sustain the combustion of the FCM. In the case where the FCM is heated to a low temperature, a gum and a coke breeze are formed. The hemicellulose of a FCM has a structure similar to the structure of its cellulose, and it comprises a pentose and a hexose. As the temperature of the FCM increases, its hemicellulose is decomposed by mechanisms identical to the mechanisms of decomposition of the FCM cellulose. Lignin is a more complex and thermally stable component of a FCM: its thermal decomposition begins at a temperature of 280–500^{o}C, and it makes the main contribution to the formation of a coke breeze [18, 19]. The next stage of combustion of a FCM can proceed with no flame. A flame combustion of a FCM is provided by a complex of gas-phase reactions in it. This combustion is realized when the temperature of the volatile compounds penetrating through the surface of the FCM reaches a critical value [18]. At the same time, the combustion of a FCM with no flame is due to the heterogeneous oxidation of the coke breeze with release of the heat necessary for the subsequent pyrolysis of the near-wall layers of the FCM. It is shown in [20] that the heterogeneous processes proceed in the three zones of a FCM where the dry organic substance is subjected to thermal decomposition, the coke breeze oxidizers at a maximum temperature, and a residual porous material consisting of a coke breeze and an ash with a gradually decreasing temperature is accumulated. In the general case, the heating of a FCM to a high temperature is favorable to the formation of volatile compounds, while, at a low temperature, gums and a coke breeze are formed, which leads to the combustion of the FCM in the smouldering regime. Such combustion (smouldering) takes place in samples of FCMs with a high packing density [21].

In [11], the indices of ignition of FCMs have been developed. In this work, the ignition index of a FCM was determined by the probability of its ignition, the ignition coefficient of the FCM, and the capacity of its samples to burn under the action of a radiant heat flow. The frequency of ignition of FCM samples was calculated as the percentage of the positive results of this ignition. The delay time of ignition of the FCM and the period of its combustion were determined. The indicated data were then analyzed for the subsequent classification of the FCM.

It is known [2] that all the FCMs have their own thermophysical parameters and thermokinetic characteristics of drying and pyrolysis, which can be used for the physically substantiated prediction of the fire hazard in a forest, including in the case where a crown fire propagates in it. It may be suggested that the integral characteristic of a forest fire, representing the delay time of ignition of the FCMs in it, can be also used for the quantitative estimation of the forest fire hazard. Works on determination of the delay time of ignition of FCMs in combination with the achievements in the simulation of the drying and pyrolysis of FCMs [13, 23, 24] can serve as a base for the development of a physical and mathematical theory of forest fire hazard, including a mathematical model of the ignition of FCMs in which the delay time of ignition of a FCM is defined as

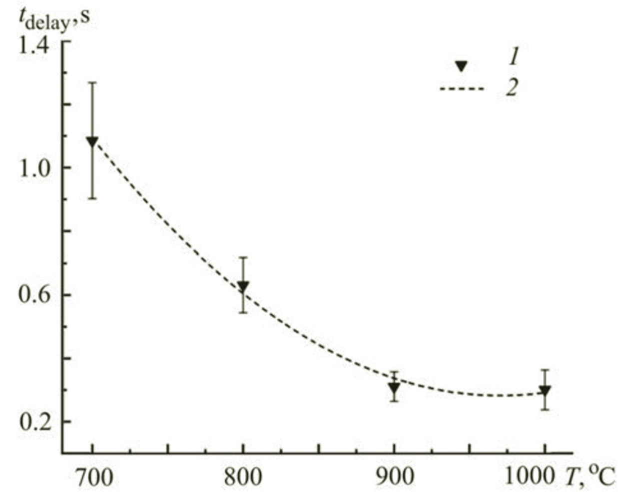

Fig. 3. Dependence of the delay time of ignition of a birch leaf on the temperature of the surrounding medium: 1) experimental data; 2) approximation curve defined by a second-degree polynomial.

$$t_{ign} = K_1\rho_{FCM} + K_2c_{FCM} + K_3\lambda_{FCM} + K_4E_{FCM} + K_5k_{FCM} ,$$

where K_i (i = 1–5) are coefficients of the model, r_{FCM}, c_{FCM}, l_{FCM}, and E_{FCM} are the density, the heat capacity, the heat conductivity, and the activation energy of the pyrolyzing FCM, and k_{FCM} is a pre-exponential factor.

Forest combustible materials can be classified by their coordinates K_i in a model five-dimensional hyperspace. With the use of experimental data on the five points in this space, corresponding to definite temperatures of a high-temperature medium represented by it, five linear algebraic equations for the delay time of a FCM can be written. It should be noted that four such points have been obtained in our experiments. The fifth point was determined by extrapolation of the experimental data obtained on the assumption that the dependence of the delay time of ignition of a FCM on its temperature can be defined in the zero approximation by a straight line. In the final analysis we have obtained the following system of five linear algebraic equations:

$$t_{ign,1} = K_1\rho_{FCM} + K_2c_{FCM} + K_3\lambda_{FCM} + K_4E_{FCM} + K_5k_{FCM} ,$$
$$t_{ign,2} = K_1\rho_{FCM} + K_2c_{FCM} + K_3\lambda_{FCM} + K_4E_{FCM} + K_5k_{FCM} ,$$
$$t_{ign,3} = K_1\rho_{FCM} + K_2c_{FCM} + K_3\lambda_{FCM} + K_4E_{FCM} + K_5k_{FCM} ,$$
$$t_{ign,4} = K_1\rho_{FCM} + K_2c_{FCM} + K_3\lambda_{FCM} + K_4E_{FCM} + K_5k_{FCM} ,$$
$$t_{ign,5} = K_1\rho_{FCM} + K_2c_{FCM} + K_3\lambda_{FCM} + K_4E_{FCM} + K_5k_{FCM} .$$

Numerical solution of this system of linear algebraic equations gives a vector of the quantities K_1, K_2, K_3, K_4, and K_5. In this way, a point, representing the properties of a FCM, is definitely determined in a five-dimensional hyperspace. To test the mathematical model described, it is necessary to perform experimental investigations on the ignition of other FCMs in the high-temperature medium represented by this hyperspace.

We propose an algorithm for classifying FCMs, including

1) the performance of experimental investigations on the ignition of FCMs of definite kind in a high-temperature medium;
2) the calculation of the average values of the parameters of these FCMs and the confidence intervals of their determination with a confidence probability for six or seven experiments performed at one and the same temperature;
3) the identification of the thermophysical and thermokinetic constants of the indicated FCMs;
4) the construction of a system of five linear algebraic equations for the delay time of ignition of these FCMs, from which their coefficients K_i are determined;
5) the solution of this system of linear algebraic equations;

6) the determination of the position of the points, representing the properties of the FCMs in a five-dimensional hyperspace;
7) the analysis of a set of data on the positions of the representative points of FCMs of different kinds in a five-dimensional hyperspace for determining their cluster or regular distribution in this space with the aim to select a reasonable number of classes of FCMs (the necessary information can be obtained with the use of the Dbscan, Kmeans, and Fris-Tax clusterization algorithms [26]);
8) the formation of a predicable data base in a geoinformation system for monitoring, estimating, and predicting a fire hazard in a forest, including information on the coefficients K_i of the combustible materials in this forest and its inventory concerns;
9) the mapping (layer by layer) of the classes of FCMs with the use of tabular data on their attributes.

The above-described computerized method of classification of FCMs can be used for estimating the probability of a crown fire in a forest and the change of this fire to a large forest fire or a spotted one. This method can also be used for determining the scenarios of propagation of a crown forest fire.

Conclusions. A methodology for investigating experimentally the ignition of a FCM in a high-temperature medium has been developed. The data obtained on the delay time of ignition of a FCM (a birch leaf) can be used for estimating the fire hazard in a forest as well as for classification of complex forest and building materials in urbanized areas by their physical properties [2, 28]. A computerized method of classifying FCMs was proposed. This method can be used for estimating a fire hazard in a forest and determining scenarios of propagating a crown fire in it on the basis of data on the thermokinetic parameters of the forest combustible materials and on the relay development of a forest fire with the use of geoinformation technology [29, 30]. In the present work, the ignition of a single FCM was investigated; of interest is the ignition of a group of FCMs in a high-temperature medium, which will be a subject of our further investigations.

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