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TRANSITION OF THE FOREST GROUND FIRE TO CROWN FIRE

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At certain conditions, the forest ground fire, which is propagating through near-ground foliage, changes into top fire moving through the tree crowns at a considerably higher speed than the ground fire, making it ecologically more dangerous [1]. This lends importance to an investigation of the conditions for the transition from the ground to the crown forest fire. The results of some experiments have been reported in [2], where, in particular, minimum values were obtained for the ignition pulse (radiation and convection) required for the flame transition to the crown. In [3] temperatures and overall heat fluxes from the location of the forest ground fire to the lower forest canopy were experimentally determined. It was found that for the experimentally given source parameters, the maximum distance to the tree crown, where ignition occurred, did not exceed 0.5 m [3].

Attempts at mathematical modeling of the transition were undertaken in [4] and [5]. In [4] jet theory equations were employed to describe the transition, and the time and ignition conditions for the tree crowns were calculated on that basis. The deficiency of this work lies in the postulation of an instantaneous formation of a jet above the ground fire location. This assumption was removed in [5], while at the same time introducing the assumption that the process is isobaric.

In the present work we report the results of an experimental and theoretical investigation of the transition on the basis of a numerical solution of the complete system of the Reynolds equations. An estimate is made of the degree of reliability of the assumptions incorporated into [4] and [5]. Two regimes are obtained for the transition from the forest ground fire to the crown fire. A comparison is made of the numerical and experimental results for the conditions and characteristics of the tree crown ignition from a ground fire source. It is found that the presence of wind does not have a significant effect on the transition of the forest ground fire to the crown fire in young pine wood. It follows from an analysis of the calculations and experimental data that for the cases considered, that the minimum overall ignition pulse amounts to 4,000 kJ/m^2, with the critical distance being 0.5 m.

Experimental Investigation of the Transition of the Forest Ground Fire to the Crown Fire, and the Physical Model of the Process

The transition of the forest ground fire to the crown fire one understands to be the ignition of the tree crowns by the flame tongue of the forest ground fire. Of principal practical interest are the determination of the minimum distance from the subjacent surface to the forest canopy, over which an ignition is possible, and the limiting energy required for the ignition of the combustible forest materials (CFM) in the tree crowns. Belonging to the CFM are the needles and thin twigs up to $7 \cdot 10^{-3}$ m in diameter. To perform the experiments, a level area was selected, on whose surface four young small pines with a height of up to 3 m were set up. The distance between trees ℓ_t was 0.5 m. The surface of a square

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TABLE 1. Results of the Experimental Investigations

Test number	h_e, m	h_0, m	h_1, m	h_2, m	$Q_\Sigma \cdot 10^{-3}$, kJ/m^2	q_Σ, kW/m^2	t_b, sec	t_i, sec
1	2,1	0,06	0,3	0,3	—	—	80	—
2	2,1	0,06	0,4	0,4	6	144	137	—
3	2,1	0,06	0,5	0,5	7,6	91	122	—
4	2,1	0,06	0,5	0,5	3,6	87,5	220	—
5	2,6	0,07	0,3	0,22	11	122	120	—
6	2,6	0,07	0,4	0,22	6	66	270	—
7	2,5	0,06	0,2	0,27	13,5	121,8	124	—
8	2,4	0.07	0,3	0,27	—	—	63	—
9	2,5	0,06	0,3	0,27	13	140	151	5,6
10	2,5	0,06	0,3	0,27	—	—	115	5,0
11	2,5	0,07	0,4	0,3	—	—	80	9,0
12	3,0	0,07	0,5	0,5	—	—	120	—
13	3,0	0,07	0,6	0,6	—	—	—	—

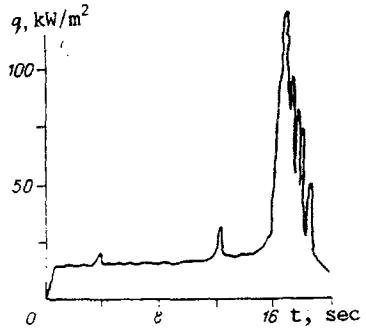

Fig. 1

area with a side h = 1.2 m was lined with a 0.06 to 0.07 m thick layer of the Cladonia lichen.

All principal dimensions of the experimental items are presented in the table. Placed at a height of h_2 inside the tree crown were a chromel–alumel thermocouple and a sensor for the measurement of the overall heat flux. The construction of this sensor has been described in [3]. The sensing elements of the probes were oriented toward the subjacent surface. Prior to the experiment, the moisture contents of the lichen and the pine needles were 47.6 and 66%, respectively. The edge of the lichen layer was ignited simultaneously along the perimeter. The signals from the overall heat flux probe q_Σ were recorded with a K-12-22 oscillograph. A typical oscillogram is presented in Fig. 1. Also measured were ρ_0, the density of the lichen layer which in all experiments was kept at 2 kg/m^2, the tree height h_t, the lichen layer height on the subjacent surface h_0, the distance from the subjacent surface to the lower tree crown boundary h_1, the distance from the subjacent surface to the probe h_2, the moisture content of the CFM W_0, the maximum overall heat flux at a given point of the forest canopy q_Σ, the time of the CFM burnup of the subjacent surface t_b, and the forest canopy ignition time from the instant of initiating the ground fire action t_i. The error in measuring the temperatures did not exceed ±5%, for the overall heat flux it was no more than ±8%, for the moisture content ±10%, and for the various distances, the measurement error was less than ±5%.

The method followed in performing the experiments has been described in greater detail in [3]. The experiments were performed in the absence of wind.

In each test the value of q_Σ was recorded on the oscillograph. then, by integration, we determined the ignition heat pulse

$$Q_\Sigma = \int_0^{t_b} q_\Sigma dt$$

which is the total amount of energy entering the forest canopy up to the instant of ignition and during the entire burning time of the experimental stand.

After the creation of the ground fire source, a convective column is formed, and heating, drying and the pyrolysis of the CFM begin in the tree crowns. The energy from the ground fire source is transferred as a result of free convection and the radiation from the ground fire flame tongue. After the completion of the heating stage, the drying and pyrolysis of the CFM, an ignition of the gaseous combustible pyrolysis products occurs, i.e.,

the mechanism of the tree crown ignition takes place in the gas phase. The ignition occurs at the lower tree crown boundary; afterwards the flame spreads upwards through the tree crown.

The level of the maximum temperatures at the lower forest canopy boundary reached between 600 and 800 K. The height of the flame tongue did not exceed 0.4 m. The experimental investigation data are presented in the Table 1. No CFM ignition was observed in tests 4 and 13; ignition did occur in the remaining cases. It as established that under the indicated conditions, the tree crowns get ignited if the distance to them from the subjacent surface is between 0.2 and 0.5 m. In the tests 2 to 6 the total amount of energy arriving at the forest canopy did not exceed 6000 kJ/m^2 (see Table 1). This quantity agrees with the data in [2], where it was found that the minimum magnitude of the igniting pulse was 4500 kJ/m^2.

The Mathematical Formulation of the Problem

We consider the plane problem of radiation/convective heat- and mass-exchange of combustible forest materials at all forest strata with gaseous combustion products and the radiation of the flame tongue of the forest ground fire. The ground fire source is modeled by a surface source of mass of heated combustion products, which radiate like a black body with an effective blackness index. It is assumed that during the forest fire, the forest can be modeled by a two-temperature, multiphase, porous and reacting medium [1]. Let us suppose that we have a so-called blow-through forest massif [1], where the volume portion of the CFM condensed phase, consisting of the dry organic material, water in the liquid droplet state, the condensed pyrolysis products and sol, can be neglected in comparison with the volume portion of the gas phase (components of air and of the gaseous products of pyrolysis). To describe the energy transport by radiation, we use the diffusion approximation [1], while for the convective transport, caused by the gravity forces, the Reynolds equations are employed.

We assume that the coordinate origin x_1, $x_2 = 0$ is located at the center of the forest ground fire source at a height of the roughness level, that the ox_2 axis is oriented upward, and that the ox_1 is directed to the right, parallel to the ground surface. The problem formulated above reduces to the solution of the following system of equations [5]:

$$\frac{\partial \rho_5}{\partial t} + \frac{\partial}{\partial x_j}(\rho_5 v_j) = \dot{m}, \quad j = 1, 2, \quad i = 1, 2; \tag{1}$$

$$\rho_5 \frac{Dv_i}{Dt} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(-\rho_5 \overline{v_i' v_j'}\right) - \rho_5 S C_d v_i |v| - \rho_5 g_i - \dot{m} v_i; \tag{2}$$

$$\rho_5 c_p \frac{DT}{Dt} = \frac{\partial}{\partial x_j}\left(-\rho_5 C_p \overline{v_j' T'}\right) + q_5 R_5 - A_s (T - T_s); \tag{3}$$

$$\rho_5 \frac{DC_\alpha}{Dt} = \frac{\partial}{\partial x_j}\left(-\rho_5 \overline{v_j' C_\alpha'}\right) + R_{5\alpha} - \dot{m} C_\alpha, \quad \alpha = 1, 2; \tag{4}$$

$$\frac{\partial}{\partial x_j}\left(\frac{c}{3\varkappa}\frac{\partial U_R}{\partial x_j}\right) - \varkappa\left(cU_R - 4\sigma T_s^4\right) = 0; \tag{5}$$

$$\sum_{i=1}^{4} \rho_i C_{pi} \varphi_i \frac{\partial T_s}{\partial t} = q_3 R_3 - q_2 R_2 + \varkappa\left(cU_R - 4\sigma T_s^4\right) + A_s (T - T_s); \tag{6}$$

$$\rho_1 \frac{\partial \varphi_1}{\partial t} = -R_1, \quad \rho_2 \frac{\partial \varphi_2}{\partial t} = -R_2, \quad \rho_3 \frac{\partial \varphi_3}{\partial t} = \alpha_c R_1 - \frac{M_C}{M_1} R_3, \quad \rho_4 \frac{\partial \varphi_4}{\partial t} = 0; \tag{7}$$

$$R_1 = k_1 \rho_1 \varphi_1 \exp(-E/RT_s), \quad R_2 = k_2 \rho_2 \varphi_2 T_s^{-1'2} \exp(-E_2/RT_s); \tag{8}$$

$$R_3 = k_3 \rho_5 \varphi_3 C_1 S_\sigma \exp(-E_3/RT_s), \tag{9}$$

$$R_5 = M_2 k_5 \left(\frac{C_1 M}{M_1}\right)^{1/4} \left(\frac{C_2 M}{M_2}\right) T^{-2,25} \exp(-E_5/RT); \tag{10}$$

$$R_{51} = R_3 - \frac{M_1}{2M_2} R_5, \quad R_{52} = \nu_C (1 - \alpha_c) R_1 - R_5,$$

$$\dot{m} = (1 - \alpha_c) R_1 + R_2 + \frac{M_C}{M_1} R_3;$$

$$\sum_{\alpha=1}^{3} C_\alpha = 1, \quad P_e = \rho_5 RT \sum_{\alpha=1}^{3} \frac{C_\alpha}{M_\alpha}, \quad v = (v_1, v_2), \quad g = (0, g); \tag{11}$$

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + v_j \frac{\partial}{\partial x_j}. \tag{12}$$

The initial and boundary conditions are:

$$t = 0: \; v_1 = 0, \; v_2 = 0, \; T = T_e, \; C_\alpha = C_{\alpha e}, \; T_s = T_e, \; \varphi_i = \varphi_{ie}, \tag{13}$$

$$x_1 = 0: \; v_1 = 0, \quad \frac{\partial v_2}{\partial x_1} = 0, \quad \frac{\partial T}{\partial x_1} = 0, \quad \frac{\partial C_\alpha}{\partial x_1} = 0, \quad \frac{\partial U_R}{\partial x_1} = 0, \tag{14}$$

$$x_1 = x_{1e}: \; \frac{\partial v_1}{\partial x_1} = 0, \quad \frac{\partial v_2}{\partial x_1} = 0, \quad \frac{\partial T}{\partial x_1} = 0, \quad \frac{\partial C_\alpha}{\partial x_1} = 0, \quad \frac{c}{3\varkappa} \frac{\partial U_R}{\partial x_1} + \frac{c}{2} U_R = 0, \tag{15}$$

$$x_2 = 0: \; v_1 = 0, \; v_2 = v_{2c}, \; T = T_c, \; C_\alpha = C_{\alpha c}, \; U_R = \varepsilon\sigma T_c^4, \; x_1 \leqslant x_{1c} \tag{16}$$

$$v = 0, \; v_2 = 0, \; T = T_e, \; C_\alpha = C_{\alpha e}, \; U_R = \varepsilon\sigma T_e^4, \; x_1 > x_{1c};$$

$$x_2 = x_{2c}: \; \frac{\partial v_1}{\partial x_2} = 0, \quad \frac{\partial v_2}{\partial x_2} = 0, \quad \frac{\partial T}{\partial x_2} = 0, \quad \frac{\partial C_\alpha}{\partial x_2} = 0, \quad \frac{c}{3\varkappa} \frac{\partial U_R}{\partial x_2} + \frac{c}{2} U_R = 0. \tag{17}$$

In the above equations R_1 to R_5, and $R_{5\alpha}$ are the mass rates of the CFM pyrolysis, moisture evaporation, combustion of the condensed and volatile pyrolysis products, and of the formation of the α-components of the gas phase, C_{pi}, ρ_i and φ_i are the specific heats, true densities and volume portion of the i-th phase (1 for the dry organic material, 2 for water and 3 for the condensed products of pyrolysis, 4 for the mineral part, and 5 for the gas phase). T and T_s are the temperatures of the gas and condensed phases, C_α is the mass concentration (α = 1 for oxygen, 2 for CO, and 3 for the inert air components). P_e is the pressure in the unperturbed medium, U_R is the radiation energy density, σ is the Stefan-Boltzmann constant, κ is the radiation attenuation coefficient, ε is the degree of blackness, A_s is the phase exchange coefficient, q_i, E_i and k_i (i = 1-4) are the thermal effects, the activation energies, the reaction pre-exponents for the pyrolysis, evaporation, and the combustion of coke and the volatile products of pyrolysis, respectively, S_σ is the specific surface of a CFM element, M_α, M_c and M are the molecular masses of the individual components of the gas phase, carbon, and of the air mixture, S and C_d are the specific surface of the phytomass and the empirical coefficient of the forest canopy resistance, t is time, x_i and v_i (i = 1, 2) are the Cartesian coordinates and the velocity components, C is the speed of light, R is the universal gas constant, ν_c is the mass fraction of the combustible gas and the volatile products of pyrolysis, and α_c is the coke number.

The thermodynamic, thermophysical and structural characteristics corresponding to the CFM of a pine forest canopy [1, 6, 7] are: E_1/R = 9400 K, $k_1 = 3.36 \cdot 10^4$ sec^{-1}, $q_1 = 0$, E_2/R = 6000 K, $k_2 = 3 \cdot 10^6$ K$^{1/2}\cdot$sec^{-1}, $q_2 = 6 \cdot 10^7$ J/kg, $E_3/R = 10^4$ K, $k_3 = 10^3$ sec^{-1}, $q_3 = 1.2 \cdot 10^7$ J/kg, E_5/R = 11,500 K, $k_5 = 3 \cdot 10^{13}$, $q_5 - 10^7$ J/kg, C_{p1} = 2000, C_{p2} = 4180, C_{p3} = 900, $C_{p4} = 10^3$, $C_{p5} = 10^3$ J/(kg·K), $S_\sigma = 10^3$ m^{-1}, SC_d = 0.1 m^{-1}, α_c = 0.06, $\rho_4\varphi_4$ = 0.08 kg/m^3, ρ_1 = 500, $\rho_2 = 10^3$, ρ_3 = 200, ρ_5 = 1.16 kg/m^3, $P_e = 10^5$ N/m^2, T_e = 300°K, C_{1e} = 0.23, C_{2e} = 0, φ_{3e} = 0, κ = 0.8 m^{-1}, ε = 0.9, and A_s = 100 W/(m^3·K).

The volumetric heat exchange coefficient was evaluated from the formula

$$A_* = \alpha S,$$

where α is the heat transfer coefficient for a CFM element having a cylindrical shape, which is determined using the data from [6]. The initial φ_1 and φ_2 values were computed from the equations

$$\varphi_{1e} = \frac{(1 - \nu_a)}{\rho_1} \rho_{10}, \quad \varphi_{2e} = \frac{\rho_{10} W_0}{\rho_2}$$

(W_0 is the moisture content of the CFM, ρ_{10} and ν_a are the inventory and the ash content of the CFM). It was assumed that W_0 = 0.666, ρ_{10} = 0.5 kg/m^3, and that ν_a = 0.04. For the closure of the system (1)-(12), the components of the turbulent stress tensor and the turbulent fluxes of heat and mass were determined with the aid of the local-equilibrium turbulence model [7].

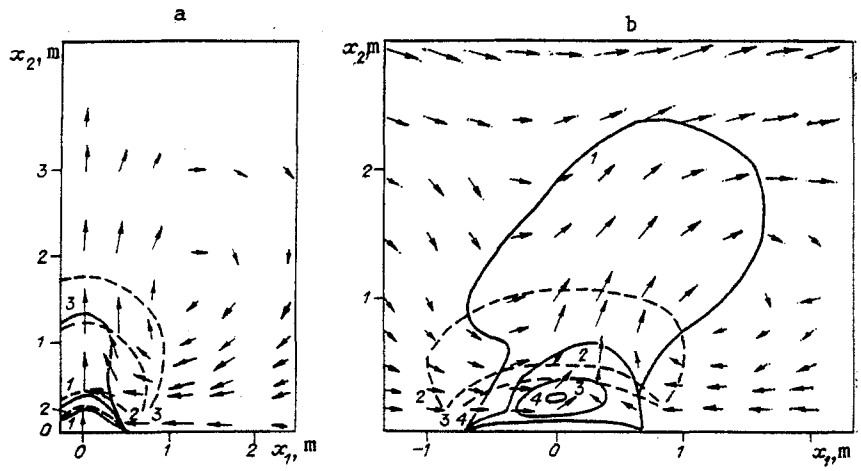

Fig. 2

Method of Solution, and the Validation Tests of the Program

The boundary value problem (1)-(7) was solved numerically by the method of separation into physical processes [8]. In the first stage, the hydrodynamic flow pattern and the distributions of the scalar functions were calculated. Then, the system of ordinary differential equations of the chemical kinetics, obtained as the result of the separation, was integrated. A digital analog for the system (1)-(7) was obtained by the control volume method using the SIMPLE algorithm [9].

The correctness of the program operation was verified by the method of preliminarily determined analytical solutions. Analytical expressions of the sought functions were substituted into the system (1)-(7) and an inviscid equation was evaluated, which later was considered to be the starting point of each equation. Using the above described algorithm, values of the employed functions were regenerated with an accuracy of no less than 1%. We investigated the effect of the control volume dimensions on the solution by reducing them. The time step was selected automatically.

Results of the Computations and Their Analysis

The fields of the temperature, velocity, the concentration of components and of the volumetric phase fractions were calculated numerically. Presented in Fig. 2 are the vector fields of the velocity and the isotherms in the vicinity of the ground fire location (T_c = 1300 K, U_{20} = 0.1 m/sec) in the absence (see Fig. 2a: 1 = $\bar{T}$, $\bar{T}_S$ = 2, 6, 2 − $\bar{T}$, $\bar{T}_S$ = 1, 5, 3 = $\bar{T}$, $\bar{T}_S$ = 1, 2; $\bar{T} = T/T_e$, $\bar{T}_S = T_S/T_e$) and in the presence of wind (see Fig. 2b: 1 − $\bar{T}$ = 1.1, 2 − $\bar{T}$, $\bar{T}_S$ = 1, 5, 3 − $\bar{T}$, $\bar{T}_S$ = 2, 4 − $\bar{T}$, $\bar{T}_S$ = 2.6) in the forest canopy at the time instant t = 4.8 s. In the latter case, the open country wind velocity v_0 = 8 m/sec is specified at a fixed height above the forest canopy (6 m). In the presence of wind, the process pattern is not symmetrical with respect to the ox_2 axis, and therefore, the region from $-x_{1e}$ to x_{1e} is considered. In place of (14) one specifies the boundary conditions

$$x_1 = -x_{1e}: \; v_1 = v_e(x_2), \quad \frac{\partial v_2}{\partial x_1} = 0, \quad \frac{\partial T}{\partial x_1} = 0, \quad \frac{\partial C_\alpha}{\partial x_1} = 0,$$
$$\frac{c}{3\varkappa}\frac{\partial U_R}{\partial x_1} + \frac{c}{2}U_R = 0. \tag{18}$$

In the vicinity of the location of heat- and mass-release, heated masses of air and the products of pyrolysis and combustion are raised. For $v_e(x_2) = 0$, the patterns of flow and of the distribution of all scalar functions are symmetrical with respect to the ox_2 axis.

As the result of the influx of air on the periphery along both sides of the source, regions of recirculating flow are formed (see Fig. 2a). The isotherms for the gas (continuous lines) and the solid phase (dashed lines) are presented in Fig. 2a for T_c = 1300 K, v_{2c} = 0.1 m/sec and x_{1c} = 1.5 m. In the case when $v_e(x_2) \neq 0$, the wind fields in the forest canopy interact with the gas jet impediments produced by the ground forest fire source and set on fire by the lower forest canopy boundary. Beyond the zone of heat- and mass-release, recirculating flow is formed, while on the windward side, there occurs an acceleration in the movement of air which flows past the ignition region (see Fig. 2b). Here the gas phase isotherms are deformed in the wind direction. The wind forces the heated flow towards the

tree crowns (see isotherms in Fig. 2b). The picture of the presented flow qualitatively agrees with the results of [7], where the problem of wind transformation was considered in the vicinity of the front of a ground forest fire, modeled by surface mass and energy sources.

The analysis of the ignition of the forest canopy by the forest ground fire source shows that the presence of an external wind field does not significantly influence the given process. In as much as it occurs at the lower boundary, the determinant factor is the effect of the ground fire source. The outer stream flows around the region of the most important chemical transformations, mainly affecting the outer boundary. In the performed calculations the v_0 values were varied from 0 to 10 m/sec. For v_0 = 0, 5, 6, 8, and 10 m/sec, the t_i values were 4.0, 4.6, 4.7, 4.8 and 4.85 sec (h_1 = 0,19 m). The t_i time increases with rising v_0. This is explained by noting that during the time of the CFM pyrolysis, greater quantities of heat energy and of volatile products of pyrolysis are carried away from the forest canopy above the combustion source.

The condition used as the ignition criterion in the calculation of t_i was

$$\frac{\partial^2 T}{\partial t^2_{t=t_i} x_1=0, x_2=h_1} = 0.$$

The distributions of the basic functions in this region at $x_1 = 0$ in the presence of wind, and during its absence, show that in both cases the process goes through the same stages (Fig. 3). As the result of heating of the CFM elements, the moisture evaporates, the pyrolysis proceeds with a release of gaseous products which are then ignited. Plotted in Fig. 3a (continuous lines for the gas phase temperature, dashed for the solid phase) are the processes of heating and CFM ignition at $x_1 = 0$ in the forest canopy at various time instants (time in sec; 1 – 2.2, 2 – 3.2, 3 – 4.8). Figure 3b (continuous lines for the oxygen concentration, dashed for the carbon oxides) shows the distribution of the gas phase components on the $x_1 = 0$ axis. At the instant of ignition, one observes the burnup of CO and a rapid decrease in the oxygen concentration. The temperatures of both phases also reach their maximum values at the ignition point. The ignition process proceeds in a similar manner also in the cases when the wind velocity is different from zero.

It is of interest to understand the ignition of the forest canopy from the ground fire source for various blowing velocities v_{2b}, which are dependent on the propagation velocity of the forest ground fire, the supply of the CFM and other parameters. Thus, for v_{2b} = 0.1 m/sec, the temperature of the solid phase on the lower canopy boundary is higher than the gas temperature during the entire heating period (Fig. 4a, curves 2). In this case, the energy transfer by radiation predominates over that by convection. For v_{2b} = 1 m/sec (see Fig. 4b, curves 1) the gas phase temperature is above that of the solid practically up to the instant of ignition. Also presented in Fig. 4b are the concentration variations with time of oxygen C_1 and of the volatile pyrolysis products C_2 at $x_1 = 0$ on the lower forest canopy boundary. It is evident from the curves that a burnup of the volatile pyrolysis products occurs at the ignition instant. At the same time, oxygen is also used up.

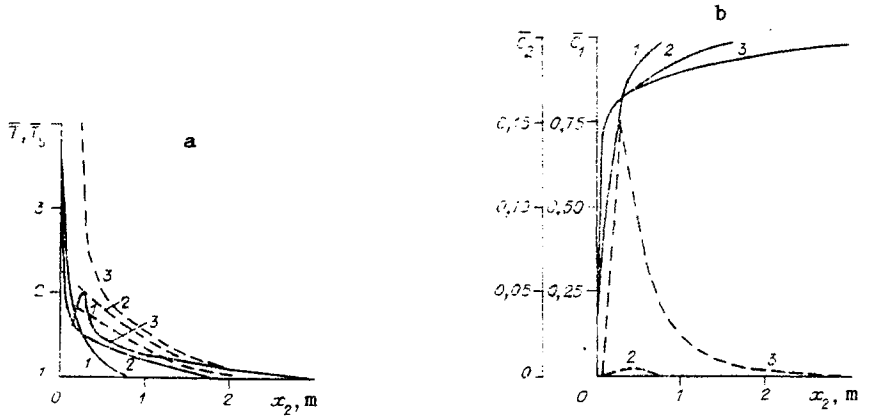

Fig. 3

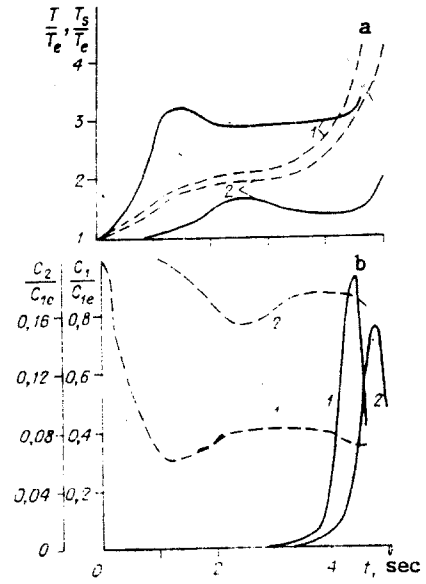

Fig. 4

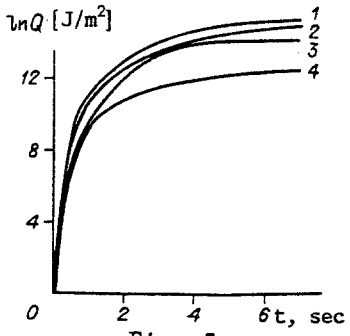

Fig. 5

It follows from an analysis of the curves in Fig. 4a that there are three stages in the process of transition of the forest ground fire to the crown fire: radiation-convective heating and drying of the CFM, a period of induction and ignition and the combustion of the gas phase combustible products of pyrolysis. The first stage lasts from 0 to $t = t_{max}$, where t_{max} is the time at which the maximum temperature is reached in the gas phase. The second lasts over the time period $t_{max} < t < t_i$, and the third during $t > t_i$.

For a complete representation of the characteristics of heat- and mass-exchange of the forest canopy with the gaseous products of the forest ground fire combustion, isotherms, lines of constant concentration of carbon oxides and of oxygen, as well as vector fields of the velocity were obtained for different blowing velocities v_{2b} at various time instants. After an analysis of the obtained data, it is possible to assert that the heating stage is characterized by the fact that it includes the formation of thermals, volumes of heated gaseous combustion products of the ground fire, which rise in the atmosphere. This stage is completed by the attainment of the maximum gas phase temperature on the lower canopy boundary (see Fig. 4). Afterwards, the inflow of air from the surrounding medium begins to play a significant role in the heat- and mass-transfer (see Fig. 2). The consequence of this is that on the lower boundary the gas phase temperature initially decreases and then remains almost constant (see Fig. 4a). Due to the air inflow, one observes a nonmonotonic variation in $\overline{T}(o, x_2)$ (see Fig. 3) and a mushroom-shaped form of the isotherm (see Fig. 2). In consequence of the mass force action, the velocity vortex is shifted up and to the right. It must also be noted that the injection velocities of the gaseous products of the CFM combustion during ground fire v_{2b} were between 0.1 and 1 m/sec. As shown by the analysis of the results of the mathematical modeling presented in Fig. 2, 4 at small values $v_{2b} = 0.1$, the heat energy from the ground fire front is transferred mainly by radiation, while for $v_{2b} =$ 1 m/sec, the transfer is accomplished by free convection. In both cases, the energy transport by radiation dominates for short times, since for the emergence of thermals, whose vertical dimension exceeds the distance between the subjacent surface and the lower tree crown boundary, a specified time is required.

Presented in Fig. 5 is the heat pulse ($v_{2b} = 0.1$ m/sec) supplied to a unit surface area in the vicinity of the ignition point for various time instants due to all transfer processes (curve 1), by convection (curve 2), radiation (3) and by turbulent induction (4). It is evident that the convective transfer predominates. At $x_1 = 0$ and $x_2 = h_1$ the respective heat impulses are designated by the indices 2 to 4

$$Q_2 = \int_0^{t_i} \rho_5 v_2 C_{p5} T dt, \quad Q_3 = \frac{c}{3\varkappa} \int_0^{t_i} \frac{\partial U_R}{\partial x_2} dt, \quad Q_4 = \int_0^{t_i} \left(-\rho_5 C_{p5} \overline{v_2' T'}\right) dt.$$

It has been pointed out in [2] that the heat pulse, which is required for the ignition of the pine tree crowns should not be less than 4500 kJ/m². In the numerical calculations presented above this quantity reached 3800 kJ/m², which agrees with the experimental data.

Conclusions

The value of the minimum distance from the subject surface to the tree crowns, over which ignition occurs, and the minimum igniting pulse were determined experimentally. With the aid of numerical modeling, distributions were obtained of the temperature, component concentrations and of the velocity in the zone of transition of the forest ground fire to the crown fire. The calculations showed that compared to the radiation, the role of the convective energy transfer mechanism increases with rising blowing velocity from the combustion source and with time. The process pattern is basically preserved even with a rising wind velocity on the outer forest canopy boundary, however, the ignition time increases somewhat. For the calculation conditions, the value of the critical heat pulse amounts to 3800 kJ/m^2, while the critical height of the lower tree crown boundary is 0.5 m. The numerical and experimental results may have practical applications for forest fire-fighting arrangements.

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EFFECT OF THE FOREST CROWN FIRE FRONT ON GLASS-REINFORCED PLASTIC

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Glass-reinforced plastic materials are widely used in industry and in daily life, this includes the fabrication of various transportation equipment subassemblies. The employment of this transportation equipment in forest fire fighting naturally leads to the consideration of the possible effect of the forest fire front on the structural elements.

In the present work, we present the formulation and numerical solution of the combined problem of the interaction of a glass-reinforced plastic disk, situated perpendicularly to the wind velocity and to the propagation velocity of the more dangerous forest crown fire [1]. It is found that as a result of the crown fire front action, there may exist regimes of nonignition, autoignition, and of ignition from the radiation and convective fluxes, as well as regimes of nonextinction and of extinction. It is shown that the persistent forest crown fires, for which the heat pulse is maximized, consitute the greatest fire hazard.

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