

A NUMERICAL STUDY OF FOREST FIRE INITIATION AND SPREAD

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Abstract. *The most dangerous form of the forest fire is crown fire which causes the largest damage. Considering that, natural investigations of these problems are merely impossible, methods of mathematical modeling are urgent. Mathematical model of forest fire was based on an analysis of known experimental data and using concept and methods from reactive media mechanics. The paper suggested in the context of the general mathematical model of forest fires give a new mathematical setting and method of numerical solution of a problem of a forest fire modeling. In this paper the assignment and theoretical investigations of the problems of forest fire initiation and spread were carried out.*

1 INTRODUCTION

One of the objectives of these studies is the improvement of knowledge on the fundamental physical mechanisms that control forest fire initiation and spread. A great deal of work has been done on the theoretical problem of how forest fire initiation. Crown fires are initiated by convective and radiative heat transfer from surface fires. However, convection is the main heat transfer mechanism. Almost all this work however has been devoted to deduced simple functions dealing with the theory of the crown fire initiation and spread. For example the first explanation of this process was given by Van Wagner¹. The theory proposed there depends on three simple crown properties: crown base height, bulk density and moisture content of forest fuel. Also crown fire initiation and hazard have been studied and modeled in detail (eg: Alexander^{2,3}; Van Wagner⁴, Xanthopoulos⁵, Xanthopoulos and Wakimoto⁶, Rothermel^{7,8}, Van Wagner⁹; Cruz¹⁰, Albini¹¹, Scott, J. H. and Reinhardt, E. D.¹²). Nearly all of them invoke radiation from the fire to the fuel bed as the principal mechanism for heating the fuel and hence causing the fire to propagate. For the most part they omit wind effects. Of the various factors which affect the propagation speed of fire, the most significant is observed to be the wind speed. The more complete discussion of the problem of modeling forest fires is provided by a cycle of works produced by a group of co-workers at Tomsk University (Grishin¹³, Grishin and Perminov¹⁴, Perminov^{15,16}). In particular, a mathematical model of forest fires was obtained by Grishin¹³ based on an analysis of known and original

experimental data and using concepts and methods from reactive media mechanics. The physical two-phase models used in D. Morvan, J.L. Dupuy^{18,19} and T. Marcelli and coauthors²⁰ may be considered as a continuation and extension of the formulation proposed by Grishin and Perminov¹⁴⁻¹⁶. However, the investigation of crown fires has been limited mainly to cases studied of forest fires initiation without take into account the mutual interaction of the forest fires and three dimensional atmosphere flows.

2 PHYSICAL AND MATHEMATICAL FORMULATION

The basic assumptions adopted during the deduction of equations, and boundary and initial conditions: 1) the forest represents a multi-phase, multistoried, spatially heterogeneous medium; 2) in the fire zone the forest is a porous-dispersed, multi-phase, two-temperature, single-velocity, reactive medium; 3) the forest canopy is supposed to be non - deformed medium (trunks, large branches, small twigs and needles), affects only the magnitude of the force of resistance in the equation of conservation of momentum in the gas phase, i.e., the medium is assumed to be quasi-solid (almost non-deformable during wind gusts); 4) let there be a so-called “ventilated” forest massif, in which the volume of fractions of condensed forest fuel phases, consisting of dry organic matter, water in liquid state, solid pyrolysis products, and ash, can be neglected compared to the volume fraction of gas phase (components of air and gaseous pyrolysis products); 5) the flow has a developed turbulent nature and molecular transfer is neglected; 6) gaseous phase density doesn't depend on the pressure because of the low velocities of the flow in comparison with the velocity of the sound; 7) diffusion approximation is applied to describe energy transfer by radiation. Let the coordinate reference point $x_1, x_2, x_3 = 0$ be situated at the centre of the surface forest fire source at the height of the roughness level, axis $0x_1$ directed parallel to the Earth's surface to the right in the direction of the unperturbed wind speed, axis $0x_2$ directed perpendicular to $0x_1$ and axis $0x_3$ directed upward (Fig. 1).

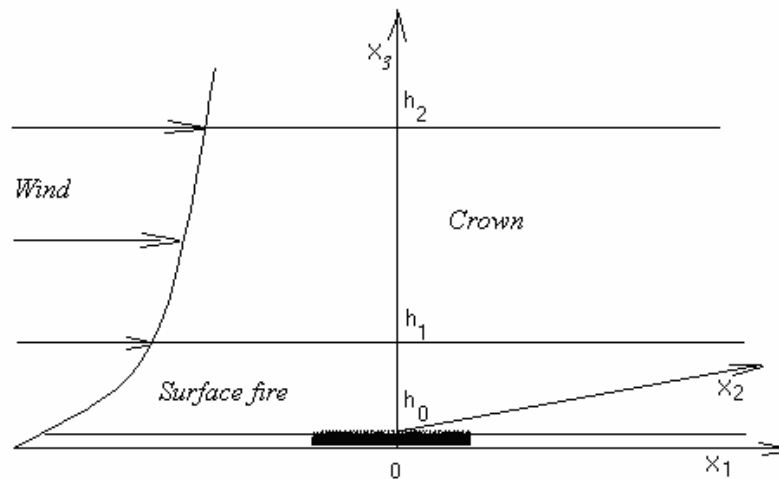


Figure 1: Schematics of the problem in the model computation

Using the results of papers¹³⁻¹⁶ and known experimental data¹⁷ we have the following sufficiently general equations, which define the state of the medium in the forest fire zone, written using tensor notation.

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j} (\rho v_j) = \dot{m}, \quad j=1,2,3, \quad i=1,2,3; \quad (1)$$

$$\rho \frac{dv_i}{dt} = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} (-\rho \overline{v_i' v_j'}) - \rho s c_d v_i |\vec{v}| - \rho g_i - \dot{m} v_i; \quad (2)$$

$$\rho c_p \frac{dT}{dt} = \frac{\partial}{\partial x_j} (-\rho c_p \overline{v_j' T'}) + q_5 R_5 - \alpha_v (T - T_s) + k_g (c U_R - 4\sigma T^4); \quad (3)$$

$$\rho \frac{dc_\alpha}{dt} = \frac{\partial}{\partial x_j} (-\rho \overline{v_j' c'_\alpha}) + R_{s\alpha} - \dot{m} c_\alpha, \quad \alpha=1,5; \quad (4)$$

$$\frac{\partial}{\partial x_j} \left(\frac{c}{3k} \frac{\partial U_R}{\partial x_j} \right) - k c U_R + 4k_s \sigma T_s^4 + 4k_g \sigma T^4 = 0, \quad k = k_g + k_s; \quad (5)$$

$$\sum_{i=1}^4 \rho_i c_{pi} \varphi_i \frac{\partial T_s}{\partial t} = q_3 R_3 - q_2 R_2 - k_s (c U_R - 4\sigma T_s^4) + \alpha_v (T - T_s); \quad (6)$$

$$\rho_1 \frac{\partial \varphi_1}{\partial t} = -R_1, \quad \rho_2 \frac{\partial \varphi_2}{\partial t} = -R_2, \quad \rho_3 \frac{\partial \varphi_3}{\partial t} = \alpha_c R_1 - \frac{M_c}{M_1} R_3, \quad \rho_4 \frac{\partial \varphi_4}{\partial t} = \frac{M_c}{M_1} R_3 - R_{ss}, \quad (7)$$

$$\sum_{\alpha=1}^5 c_\alpha = 1, \quad P_e = \rho R T \sum_{\alpha=1}^5 \frac{c_\alpha}{M_\alpha}, \quad \vec{v} = (v_1, v_2, v_3), \quad \vec{g} = (0, 0, g).$$

Here and above $\frac{d}{dt}$ is the symbol of the total (substantial) derivative; α_v is the coefficient of phase exchange; ρ - density of gas – dispersed phase, t is time; v_i - the velocity components; T, T_s - temperatures of gas and solid phases, U_R - density of radiation energy, k - coefficient of radiation attenuation, P - pressure; c_p - constant pressure specific heat of the gas phase, c_{pi} , ρ_i , φ_i - specific heat, density and volume of fraction of condensed phase (1 – dry organic substance, 2 – moisture, 3 – condensed pyrolysis products, 4 – mineral part of forest fuel), R_i – the mass rates of chemical reactions, q_i – thermal effects of chemical reactions; k_g, k_s - radiation absorption coefficients for gas and condensed phases, k_0 - radiation absorption coefficients for forest fuel in the ground cover, h_0 is the forest fuel (FF) thickness layer in the ground cover; T_e - the ambient temperature; c_α - mass concentrations of α - component of gas - dispersed medium, index $\alpha=1,2,\dots,5$, where 1 corresponds to the density of oxygen, 2 - to carbon monoxide CO , 3 - to carbon dioxide and inert components of air, 4 - to particles of

black, 5 - to particles of smoke; R – universal gas constant; M_α , M_C , and M molecular mass of α -components of the gas phase, carbon and air mixture; g is the gravity acceleration; c_d is an empirical coefficient of the resistance of the vegetation, s is the specific surface of the forest fuel in the given forest stratum. The source of ignition is defined as a function of time at $|x_1| \leq \Delta_{x_1}, |x_2| \leq \Delta_{x_2}$ and turned off after the forest fire initiation (t is the time of the fire source formation, characteristic time of setting the maximum temperature in the source).

$$\rho v_3 = h_0 \dot{m}, T = T_s = \begin{cases} T_e + \frac{t}{t_0} (T_0 - T_e), t \leq t_0 \\ T_e + (T_0 - T_e) \exp \left[-k \left(\frac{t}{t_0} - 1 \right) \right], t > t_0 \end{cases}$$

The initial values for volume of fractions of condensed phases are determined using the expressions:

$$\varphi_{1e} = \frac{d(1-\nu_z)}{\rho_1}, \varphi_{2e} = \frac{Wd}{\rho_2}, \varphi_{3e} = \frac{\alpha_c \varphi_{1e} \rho_1}{\rho_3}$$

where d -bulk density for surface layer, ν_z – coefficient of ashes of forest fuel, W – FF moisture content, α_c – coke number. To define source terms which characterize inflow (outflow of mass) in a volume unit of the gas-dispersed phase, the following formulae were used for the rate of formulation of the gas-dispersed mixture $\dot{m}$, outflow of oxygen R_{51} , changing carbon monoxide R_{52} , generation of black R_{54} and smoke particles R_{55} .

$$\begin{aligned} \dot{m} &= (1-\alpha_c)R_1 + R_2 + \frac{M_c}{M_1} R_3 + R_{54} + R_{55}, \\ R_{51} &= -R_3 - \frac{M_1}{2M_2} R_5, R_{52} = \nu_g (1-\alpha_c) R_1 - R_5, R_{53} = 0, R_{54} = \alpha_4 R_1, R_{55} = \frac{\alpha_5 \nu_3}{\nu_3 + \nu_{3*}} R_3. \end{aligned}$$

Here ν_g – mass fraction of gas combustible products of pyrolysis, α_4 and α_5 – empirical constants. Reaction rates of these various contributions (pyrolysis, evaporation, combustion of coke and volatile combustible products of pyrolysis) are approximated by Arrhenius laws whose parameters (pre-exponential constant k_i and activation energy E_i) are evaluated using data for mathematical model^{13,15}.

$$R_1 = k_1 \rho_1 \varphi_1 \exp \left(-\frac{E_1}{RT_s} \right), R_2 = k_2 \rho_2 \varphi_2 T_s^{-0.5} \exp \left(-\frac{E_2}{RT_s} \right), R_3 = k_3 \rho \varphi_3 s_\sigma c_1 \exp \left(-\frac{E_3}{RT_s} \right), R_5 = k_5 M_2 \left(\frac{c_1 M}{M_1} \right)^{0.25} \frac{c_2 M}{M_2} T^{-2.25} \exp \left(-\frac{E_5}{RT} \right).$$

It is supposed that the optical properties of a medium are independent of radiation

wavelength (the assumption that the medium is “grey”), and the so-called diffusion approximation for radiation flux density were used for a mathematical description of radiation transport during forest fires. To close the system of equations (1)–(7), the components of the tensor of turbulent stresses, and the turbulent heat and mass fluxes are determined using the local-equilibrium model of turbulence or k - ε model of turbulence. The system of equations (1)–(7) contains terms associated with turbulent diffusion, thermal conduction, and convection, and needs to be closed. The components of the tensor of turbulent stresses, as well as the turbulent fluxes of heat and mass are written in terms of the gradients of the average flow properties using the formulas

$$-\overline{\rho v_i v_j} = \mu_t \left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right) - \frac{2}{3} K \delta_{ij}, \quad -\overline{\rho v_j c_p T'} = \lambda_t \frac{\partial T}{\partial x_j}, \quad -\overline{\rho v_j c'_a} = \rho D_t \frac{\partial c_a}{\partial x_j},$$

where $\lambda_t = \mu_t c_p / Pr_t$, $\rho D_t = \mu_t / Sc_t$, $\mu_t = c_\mu \rho K^2 / \varepsilon$, μ_t , λ_t , D_t are the coefficients of turbulent viscosity, thermal conductivity, and diffusion, respectively; K – turbulent kinetic energy, ε – turbulent kinetic energy dissipation rate, Pr_t , Sc_t are the turbulent Prandtl and Schmidt numbers, which were assumed to be equal to 1. Note that flow turbulence can affect the rate of chemical reactions. The direct effect of turbulence on the rate of chemical reactions is not taken into account, i.e., the method of quasi-laminarization of reactive turbulent flow is used. It should be noted that this system of equations describes processes of transfer within the entire region of the forest massif, which includes the space between the underlying surface and the base of the forest canopy, the forest canopy and the space above it, while the appropriate components of the data base are used to calculate the specific properties of the various forest strata and the near-ground layer of atmosphere. This approach substantially simplifies the technology of solving problems of predicting the state of the medium in the fire zone numerically. The thermodynamic, thermophysical and structural characteristics correspond to the forest fuels in the canopy of a different (for example pine¹³) type of forest. The system of equations (1)–(7) must be solved taking into account the following initial and boundary conditions^{14–16}.

3 CALCULATION METHOD AND RESULTS

The boundary-value problem Eq. (1)–(7) we solve numerically using the method of splitting according to physical processes¹⁵. In the first stage, the hydrodynamic pattern of flow and distribution of scalar functions was calculated. The system of ordinary differential equations of chemical kinetics obtained as a result of splitting¹⁵ was then integrated. A discrete analog was obtained by means of the control volume method using the SIMPLE like algorithm^{15,21}. The accuracy of the program was checked by the method of inserted analytical solutions. The time interval was selected automatically. Fields of temperature, velocity, component mass fractions, and volume fractions of phases were obtained numerically. These computations have been carried out using a non-uniform grid covering a space domain of

200m×100m×20m and comprising 200×100×40 control volumes in the correspondences directions.

The distribution of basic functions in the vicinity of the source of heat and mass release shows that the process goes through the next stages. The first stage is related to increasing maximum temperature in the ground cover at $t < t_0$ with the result that a surface fire source appears. At this process stage over the fire source a thermal wind is formed a zone of heated forest fire pyrolysis products which are mixed with air, float up and penetrate into the crowns of trees. As a result, forest fuels in the tree crowns are heated and gaseous and dispersed pyrolysis products are generated. Ignition of gaseous pyrolysis products of the ground cover occurs at the next stage, and that of gaseous pyrolysis products in the forest canopy occurs at the last stage. Figures 2 a, b and c illustrate the time dependence of dimensionless temperatures of gas and condensed phases (a), concentrations of components (b) and relative volume fractions of solid phases (c) at crown base of the forest. At the moment of ignition the gas combustible products of pyrolysis burns away, and the concentration of oxygen is rapidly reduced. The temperatures of both phases reach a maximum value at the point of ignition. The ignition processes is of a gas - phase nature, i.e. initially heating of solid and gaseous phases occurs, moisture is evaporated. Then decomposition process into condensed and volatile pyrolysis products starts, the later being ignited in the forest canopy.

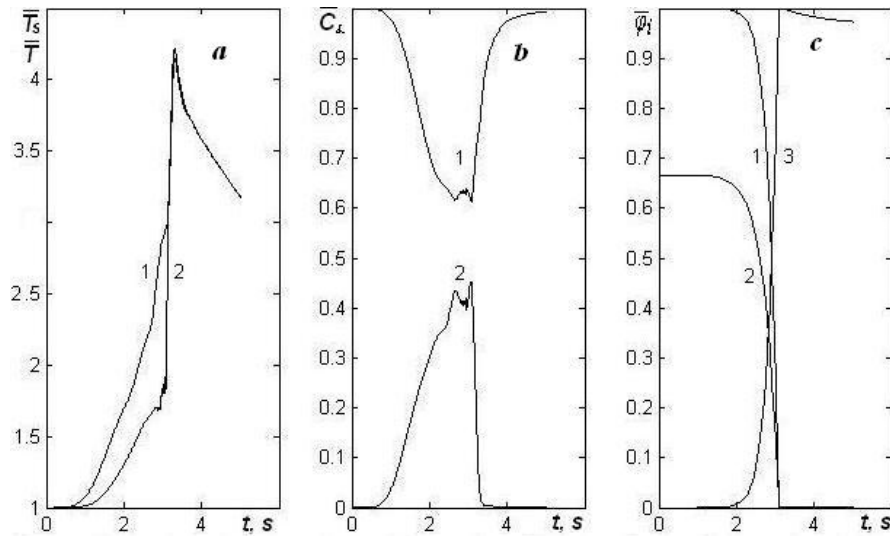


Figure 2: Relationships of dimensionless temperatures, concentrations and volume fractions in the lower boundary of the forest canopy:

$$a(1 - \bar{T} = T / T_e, 2 - \bar{T}_s = T_s / T_e, T_e = 300K), b(1 - \bar{C}_1, 2 - \bar{C}_2, \bar{C}_\alpha = C_\alpha / C_{1e}),$$

$$c(1 - \bar{\phi}_1 = \phi_1 / \phi_{1e}, 2 - \bar{\phi}_2 = \rho_2 \phi_2 / \rho_c, 3 - \bar{\phi}_3 = \rho_3 \phi_3 / \alpha_c \rho_1 \phi_{1e}).$$

Note also that the transfer of energy from the fire source takes place due to radiation; the value of radiation heat flux density is small compared to that of the convective heat flux.

The distribution of basic functions in the presence of wind shows that the process goes through the next stages (Fig. 3). As a result of heating of forest fuel elements, moisture evaporates, and pyrolysis occurs accompanied by the release of gaseous products, which then ignite. The vector field of velocities and isotherms of gas phase (Fig. 3): 1,2,3 correspond to the isotherms $\bar{T} = 2, 3$ and 5.

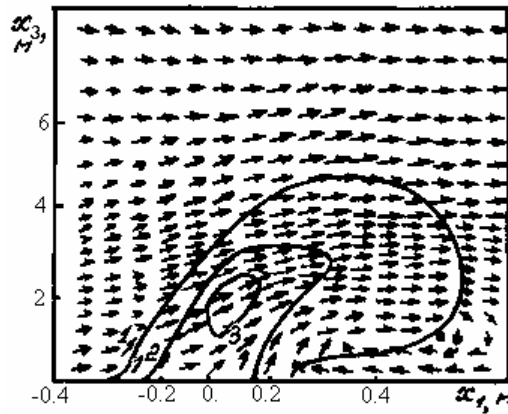


Figure 3: The distribution of temperatures and velocities

In this case, the wind field in the forest canopy interacts with the gas-jet obstacle that forms from the surface forest fire source and from the ignited forest canopy base. Recirculating flow forms beyond the zone of heat and mass release, while on the windward side the movement of the air flowing past the ignition region accelerates (Fig. 3). Under the influence of the wind the tilt angle of the flame is increased. As a result this part of the forest canopy, which is shifted in the direction of the wind from the center of the surface forest fire source, is subjected to a more intensive warming up. The isotherms of the gas and condensed phases are deformed in the direction of the wind.

The effect of the wind on the forest fire spread is shown in Figures 4(a, b, c) present the horizontal distribution of field of temperature for gas phase in plane $Ox_1 x_2$ for different instants of time when a wind velocity $V_e = 5$ m/s and moisture of forest combustible materials – 0.6. We can note that the isotherms is moved in the forest canopy and deformed by the action of wind. Also the fields of component concentrations are deformed. It is concluded that the forest fire begins to spread and the fire front is extent.

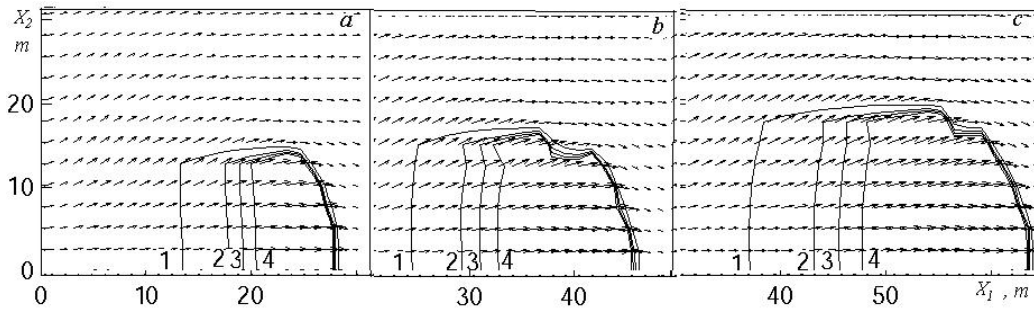


Figure 4: Field of velocity and isotherms of the forest fire for $t=4.3$ sec(a), 6 sec(b), 8 sec(c) and $V_e = 5$ m/sec;
 $1-\bar{T}=2, 2-\bar{T}=2.5, 3-\bar{T}=3, 4-\bar{T}=4; \bar{T}=T/T_e, T_e=300K$.

Figures 5 and 6 (a, b, c) present the distribution of field of concentration of oxygen and volatile combustible products of pyrolysis concentration for the same instants of time when a wind velocity $V_e = 5$ m/s and moisture of forest combustible materials – 0.6 ($\bar{c}_\alpha = c_\alpha / c_{1e}, c_{1e} = 0.23$). The lines of equal levels of component concentrations are deformed. It is confirmed that the forest fire begins to spread.

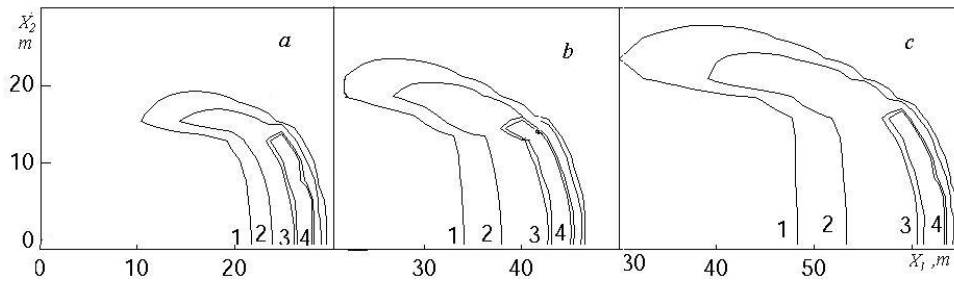


Figure 5: The distribution of oxygen $\bar{c}_1$ for $t=4.3$ sec (a), 6 sec (b), 8 sec (c) and $V_e = 5$ m/sec;

$$1-\bar{c}_1=0.9, 2-\bar{c}_1=0.8, 3-\bar{c}_1=0.5, 4-\bar{c}_1=0.4.$$

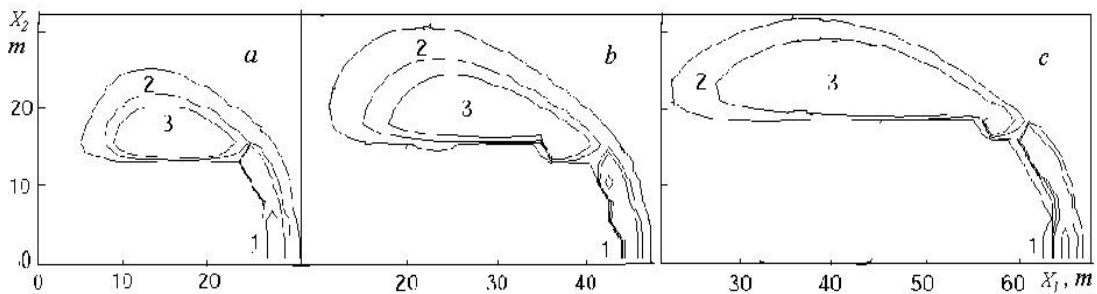


Figure 6: The distribution of $\bar{c}_2$ for $t=4.3$ sec (a), 6 sec (b), 8 sec (c) and $V_e = 5$ m/sec;
 $1-\bar{c}_2=0.1, 2-\bar{c}_2=0.5, 3-\bar{c}_2=1$.

4 CONCLUSIONS

Mathematical model and the result of the calculation give an opportunity to evaluate critical height of the forest canopy, which allows to apply the given model for preventing fires. The model overestimates the rate of the crown forest fires spread. The results obtained agree with the laws of physics and experimental data^{13,15,17}. This work represents the first attempt for application of three dimensional models for description of crown forest fires initiation and spread.

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