Numerical study of propagation of forest fires in the presence of fire breaks using an averaged setting

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Abstract. The forest fires spread in the pine forests have been numerically simulated using a three-dimensional mathematical model. The model was integrated with respect to the vertical coordinate because horizontal sizes of forest are much greater than the heights of trees. In this paper, the assignment and theoretical investigations of the problems of crown forest fires spread pass the firebreaks were carried out. In this context, a study (mathematical modeling) of the conditions of forest fire spreading that would make it possible to obtain a detailed picture of the change in the temperature and component concentration fields with time, and determine as well as the limiting condition of fire propagation in forest with these fire breaks.

1. Introduction

The forest fires are very complicated phenomena. At present, fire services can forecast the danger rating of, or the specific weather elements relating to, forest fire. There is need to understand and predict forest fire initiation, behaviour and spread. This paper's purposes are the improvement of knowledge on the fundamental physical mechanisms that control forest fire spread. A great deal of work has been done on the theoretical problem of how forest fire spread. Crown fires are initiated by convective and radiative heat transfer from surface fires. However, convection is the main heat transfer mechanism. Crown fires a more difficult to control than surface. The first accepted method for prediction of crown fires was given by Rothermal [1] and Van Wagner [2]. The semi-empirical models [1, 2] allow to obtain a quite good data of the forest fire rate of spread as a function of fuel bulk and moisture, wind velocity and the terrain slope. But these models use data for particular cases and do not give results for general fire conditions. Also crown fires initiation and hazard have been studied and modeled in detail [3–9].The discussion of the problem of modeling forest fires is provided by a group of co-workers at Tomsk University (Grishin [10], Grishin and Perminov [11–13], A mathematical model of forest fires was obtained by Grishin [10] based on an analysis of known and original experimental data [9, 14], and using concepts and methods from reactive media mechanics. Using this approach, a number of problems of mathematical modeling of forest fires were solved for the first time [9–13]. The physical two-phase models used in [15] may be considered as a development and extension of the formulation proposed by Grishin [10]. However, the investigation of crown fires initiation has been limited mainly to cases studied of forest fires propagation without take into account the mutual interaction of crown forest fires with different obstacles (roads, glades and etc.). This paper's purpose is to demonstrate the influence of these firebreaks on crown forest fires spread.

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2. Physical and mathematical model of crown forest fire

It is assumed that the forest during a forest fire can be modelled as 1) a multi-phase, multi-storeyed, spatially heterogeneous medium; 2) in the fire zone the forest is a porous-dispersed, two-temperature, single-velocity, reactive medium; 3) the forest canopy is supposed to be non - deformed medium (trunks, large branches, small twigs and needles), which 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.

Let the point x_1, x_2 , x_3= 0 is 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 (Figure 1).

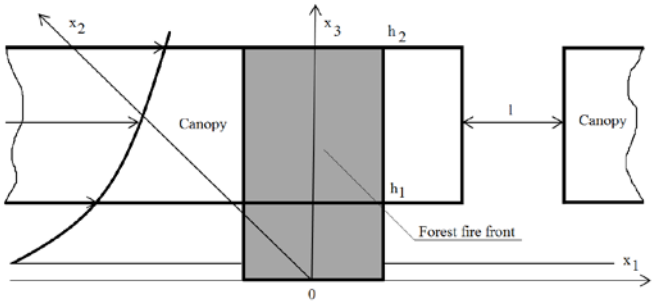


Figure 1. Computational domain.

Problem formulated above reduces to the solution of systems of equations (1)-(8):

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

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

$$\rho c_p \frac{dT}{dt} = \frac{\partial}{\partial x_j}(-\rho c_p \overline{v_j' T'}) + q_5 R_5 - \alpha_v (T - T_s) + k_g (cU_R - 4\sigma T^4)[0,1] \tag{3}$$

$$\rho \frac{dc_\alpha}{dt} = \frac{\partial}{\partial x_j}(-\rho \overline{v_j' c_\alpha'}) + R_{5\alpha} - \dot{m} c_\alpha\ ,\ \alpha = \overline{1,3}; \tag{4}$$

$$\frac{\partial}{\partial x_j}\left(\frac{c}{3k}\frac{\partial U_R}{\partial x_j}\right) - kcU_R + 4k_S \sigma T_S^4 + 4k_g \sigma T^4 = 0, k = k_g + k_S; \tag{5}$$

$$\sum_{i=1}^{4}\rho_i c_{pi}\varphi_i\frac{\partial T_S}{\partial t}=q_{3w}R_{3w}-q_{2R_{2s}}-k(cU_R-4\sigma T_S^4)+\alpha_V(T-T_S);\tag{6}$$

$$\rho_1\frac{\partial\varphi_1}{\partial t}=-R_{1s},\rho_2\frac{\partial\varphi_2}{\partial t}=-R_{2s},\rho_3\frac{\partial\varphi_3}{\partial t}=\alpha_C R_{1s}-\frac{M_C}{M_1}R_{3w},\rho_4\frac{\partial\varphi_4}{\partial t}=0;\tag{7}$$

$$\sum_{\alpha=1}^{5}c_\alpha=1,P_e=\rho_5 RT\sum_{\alpha=1}^{5}\frac{c_\alpha}{M_\alpha},\vec{v}=(v_1,v_2),\vec{g}=(0,g)\ ;$$

$$\dot{m}=(1-\alpha_c)R_1+R_2+\frac{M_c}{M_1}R_3;\tag{8}$$

$$R_{51}=-R_5-\frac{M_1}{2M_2}'R_{52}=\nu_g(1-\alpha_c)R_1-R_5,R_{53}=0,$$

where the symbol $\frac{\mathrm{d}}{\mathrm{d}t}$ marked complete derivative: $\frac{d}{dt}=\frac{\partial}{\partial t}+v_1\frac{\partial}{\partial x_1}+v_2\frac{\partial}{\partial x_2}+v_3\frac{\partial}{\partial x_3}$. To determine the rates of reaction of pyrolysis, evaporation, combustion of coke, and volatile products of pyrolysis used formula:

$$R_1=k_1\rho_1\varphi_1\exp\left(-\frac{E_1}{RT_s}\right),R_2=k_2\rho_2\varphi_2T_s^{-0.5}\exp\left(-\frac{E_2}{RT_s}\right),R_3=k_3\rho\varphi_3 s_\sigma c_1\exp\left(-\frac{E_3}{RT_s}\right);$$

$$R_5=k_5M_2\left(\frac{c_1M}{M_1}\right)^{0.25}\frac{c_2M}{M_2}T^{-2.25}\exp\left(-\frac{E_5}{RT}\right),$$

where $R_1 \div R_5$, $R_{5\alpha}$ are mass rates pyrolysis forest combustible materials, evaporation, combustion of condensed and volatile products of pyrolysis and α – components gas and dispersion phase; c_{pi}, ρ_i, φ_i are specific heat, density and volume fraction of i – phase (1 is dry organic substance, 2 is water in liquid-water-drip condition, 3 are condensed products of pyrolysis, 4 is a mineral part, 5 is a gas phase); T,T_S are temperature of gas and condensed phases, c_α are mass concentrations (α = 1 for oxygen, 2 is CO, 3 are inert components of air); p is pressure; U_R is radiation energy density; σ is Stefan-Boltzmann constant; k is coefficient attenuation of radiation; k_g, k_S are absorption coefficients for gas and condensed phases; α_V is exchange ratio, phase q_i, E_i, k_i are thermal effects, activation energy and constants for pyrolysis, evaporation, combustion of coke and volatile products of pyrolysis reactions; s_σ are specific surface element forest combustible materials; M_α, M_c, M are molecular weight of individual components in the gas phase, carbon and air mixture; S, C_d are specific surface phytomass forest canopy and an empirical factor; c is light speed; v_i is projection velocity on an axis x_i; α_C, ν are coke number and fraction of combustible gases in the mass of volatile products of pyrolysis; $\dot{m}$ is mass rate of gas and dispersion phase formation; g is acceleration of gravity.

System of equations (1)–(8) describes the flow in the area of forest, which includes the space between underlying surface and the bottom edge of the forest canopy, canopy, and the space above the forest canopy. Thermodynamic, thermophysical and structural characteristics of forest combustible materials matches (FCM) of pine forest and can be found in [10–13]. Equations (2)–(4) contain the members of turbulent convection and needed closure. Turbulent stress tensor components and turbulent heat fluxes and mass are recorded via the gradients middle according to [5]. Coefficient of turbulent dynamic viscosity is defined using locally-equilibrium model of turbulence [10].

It is believed that at the beginning of time parameters of environment be considered to coincide with the values. To set up a low ground cover of grass-roots forest fire and massive speed blowing out

of it. On the left edge of the wind speed is parallel to the surface of the earth and fire hearth bottom positioned at the start of the coordinate system. Then the process will be symmetrical about the coordinate plane Ox_1x_3, i.e. $x_{20}= 0$. The primary assumptions and boundary conditions for the system of equations (1)-(8) are specified as follows:

$$t = 0: v_i = 0,\ T = T_e,\ c_\alpha = c_{\alpha e},\ T_s = T_e,\ \varphi_k = \varphi_{ke},\ i = 1,2,3; k = 1,2,3; \alpha = \overline{1,3}. \tag{9}$$

$$x_1 = -x_{1e} : v_1 = V_e,\ v_2 = 0, \frac{\partial v_3}{\partial x_1} = 0, T = T_e,\ c_\alpha = c_{\alpha e},\ -\frac{c}{3k}\frac{\partial U_R}{\partial x_1} + cU_R/2 = 0; \tag{10}$$

$$x_1 = x_{1e}: \frac{\partial v_1}{\partial x_1} = 0,\ \frac{\partial v_2}{\partial x_1} = 0, \frac{\partial v_3}{\partial x_1} = 0,\ \frac{\partial c_\alpha}{\partial x_1} = 0,\ \frac{\partial T}{\partial x_1} = 0, \frac{c}{3k}\frac{\partial U_R}{\partial x_1} + \frac{c}{2}U_R = 0; \tag{11}$$

$$x_2 = x_{20}: \frac{\partial v_1}{\partial x_2} = 0,\ v_2 = 0,\ \frac{\partial v_3}{\partial x_2} = 0, \frac{\partial c_\alpha}{\partial x_2} = 0, \frac{\partial T}{\partial x_2} = 0,\ \frac{\partial U_R}{\partial x_2} = 0; \tag{12}$$

$$x_2 = x_{2e}: \frac{\partial v_1}{\partial x_2} = 0,\ \frac{\partial v_2}{\partial x_2} = 0, \frac{\partial v_3}{\partial x_2} = 0, \frac{\partial c_\alpha}{\partial x_2} = 0, \frac{\partial T}{\partial x_2} = 0, \frac{c}{3k}\frac{\partial U_R}{\partial x_2} + \frac{c}{2}U_R = 0; \frac{1}{2} \tag{13}$$

$$\begin{aligned} x_3 = 0 : v_1 = 0,\ v_2 = 0, \frac{\partial c_\alpha}{\partial x_3} = 0, -\frac{c}{3k}\frac{\partial U_R}{\partial x_3} + \frac{c}{2}U_R = 0,\ v_3 = v_{30}, T = T_g,\ |x_1| \le \Delta, |x_2| \le \Delta, \\ v_3 = 0,\ \ T = T_e,\ |x_1| > \Delta, |x_2| > \Delta; \end{aligned} \tag{14}$$

$$x_3 = x_{3e}: \frac{\partial v_1}{\partial x_3} = 0,\ \frac{\partial v_2}{\partial x_3} = 0, \frac{\partial v_3}{\partial x_3} = 0, \frac{\partial c_\alpha}{\partial x_3} = 0, \frac{\partial T}{\partial x_3} = 0, \frac{c}{3k}\frac{\partial U_R}{\partial x_3} + \frac{c}{2}U_R = 0. \tag{15}$$

Because of the horizontal sizes of forest massif more than height of forest – *h*, system of equations of general mathematical model of forest fire (1)-(7) was integrated between the limits from height of the roughness level from 0 to *h*. Besides, suppose that

$$\int_0^h \phi\, dx_3 = \overline{\phi}\, h,$$

where $\overline{\phi}$ is average value of φ. The problem formulated above is reduced to a solution of the two-dimensional system of equations. It is assumed that heat and mass exchange of fire front and boundary layer of atmosphere are governed by Newton law [10].

3. Numerical solution and results

The boundary-value problem is solved numerically. In order to efficiently solve this problem in a reactive flow the method of splitting according to physical processes [11–13] was used. A discrete analogue was obtained by means of the control volume method using the SIMPLE like algorithm [16].

Fields of temperature, velocity, component mass fractions, and volume fractions of phases were obtained numerically. As a result of heating of forest fuel elements of crown, moisture evaporates, and pyrolysis occurs accompanied by the release of gaseous products, which then ignite and burn away in the forest canopy. At the moment of ignition, the gas combustible products of pyrolysis burn 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.

Figures 2 present the distribution for different instants of time for temperature *a)* $\overline{T}$ ($\overline{T} = T/T_e, T_e = 300K$) (1 – 1.5; 2- 2; 3 – 2.6; 4 – 3; 5 – 3.5; 6 – 4) for gas phase, *b)* oxygen $\overline{c}_1$

(1 – 0.1; 2 – 0.5; 3 – 0.6; 4 – 0.7; 5 – 0.8; 6 – 0.9), *c)* volatile combustible products of pyrolysis $\bar{c}_2$ concentrations (1 – 1; 2- 0.1; 3 – 0.05; 4 – 0.01) ($\bar{c}_\alpha = c_\alpha / c_{1e}, c_{1e} = 0.23$) for different instants of time.

The isotherms are moved in the forest canopy and deformed by the action of wind (Figure 2*a*). Similarly, the fields of component concentrations oxygen (Figure 2*b*) are deformed. It is concluded that the forest fire begins to spread. The results of calculation give an opportunity to evaluate critical condition of the forest fire spread, which allows applying the given model for preventing fires. It overestimates the rate of crown forest fire spread that depends on crown properties: bulk density, moisture content of forest fuel and etc.

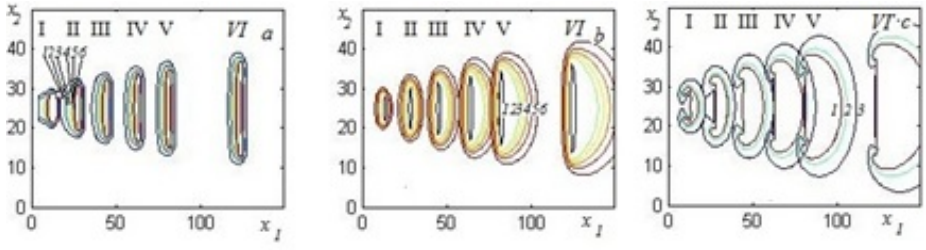


Figure 2. The distribution of temperature (*a*), concentration of oxygen (*b*) and gas product of pyrolysis (c), where I is at t=3 s, II is at 7 s, III is at 12 s, IV is at 18 s, V is at 24 s, VI is at 38 s; *V*=5m/s.

The model proposed there give a detailed picture of the change in the velocity, temperature and component concentration fields with time, and determine as well as the influence of different conditions on the crown forest fire initiation. It is important to study the interaction of forest fire front with firebreak of finite size (glade) (Figure 3*a)* temperature *T* for gas phase, *b)* oxygen $\bar{c}_1$, *c)* volatile combustible products of pyrolysis $\bar{c}_2$ concentrations).

The distance between forest fire source and glade equals 84 m. Figures 3*a, b, c* show the results of numerical simulation of a forest fire spreading around the glade under the action of wind blowing through it at a speed 5 m/s in the direction of the Ox_1-axis. Initially, the source of the fire has the shape of a rectangular. Then isotherms are deformed under the action of wind and the contour of forest fire is look as crescent. When the fire (isotherms II in Figure 3*a*) moves around the forest glade it is divided in two parts. But after that two fire fronts were joined in united fire (isotherms VI in Figure 3*a*).

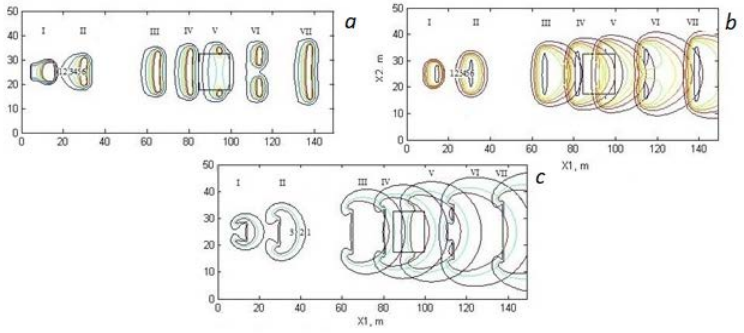


Figure 3. The distribution of temperature (*a*), concentration of oxygen (*b*) and gas product of pyrolysis (c), where I is at t=3 s, II is at 7 s, III is at 12 s, IV is at 18 s, V is at 24 s, VI is at 32 s, VII is at 38 s; *V*=5m/s.

Figures 3*b, c* present the distribution of concentration of oxygen and volatile combustible products of pyrolysis $\bar{c}_2$ for this case. If in our case the distance between the initial forest fire source and glade is increased to 74 m the crown forest fire does not spread around the glade and the forest fire dies before this clearing (Figure 4*a)* temperature $\bar{T}$ for gas phase, concentrations for *b)* oxygen $\bar{c}_1$, *c)*

volatile combustible products of pyrolysis $\bar{c}_2$ concentrations). The results of calculation give an opportunity to evaluate critical condition of the forest fire spread, which allows applying the given model for preventing fires.

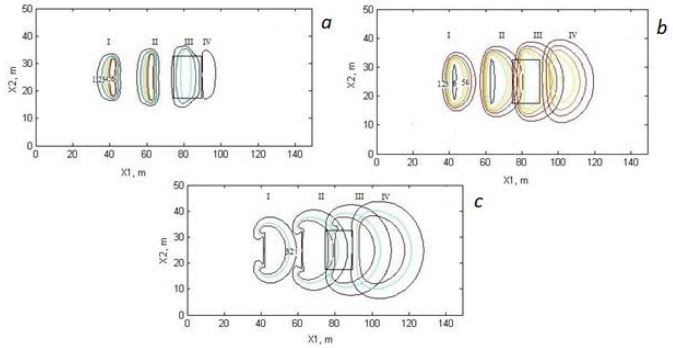


Figure 4. The distribution of temperature (*a*), concentration of oxygen (*b*) and gas product of pyrolysis (c), where I is at t=11 s, II is at 18 s, III is at 24 s, IV is at 28 s; *V*=5m/s.

4. Conclusion

The model proposed here gives a detailed picture of the change in the temperature and component concentration fields with time, and determine as well as the influence of different conditions on the crown forest fire spreading for the case of inhomogeneous of forest combustible materials supply distribution in the area and there being such obstacles to fire spread as roads, fire breaks, glades, water bodies etc. The results of calculation of the rate of crown forest fire spread obtained agree with the laws of physics and experimental data for the cases when the forest fire spread through the crowns of forest under the influence of wind velocity.

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