Numerical Solution of Problem for Forest Fire Initiation and Spread

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VALERIY PERMINOV, TATIANA BELKOVA
Department of Control and Diagnostics, Tomsk Polytechnic University
Tomsk, RUSSIA

Abstract: The theoretical study of the problems of forest fire initiation and spread were carried out in this paper. Mathematical model of forest fire was based on an analysis of experimental data and using concept and methods from reactive media mechanics. The research was based on numerical solution of three-dimensional Reynolds equations for boundary layer of atmosphere and forest vegetation. The boundary-value problem is solved numerically using the method of splitting according to physical processes.

Keywords: forest fire, mathematical model, control volume, discrete analogue, evaporation, pyrolysis, combustion, crown fire

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1. Introduction

In order to study crown fires initiation and spread it is developed a coupled boundary layer atmosphere – crown forest fire behavior model that is based on laws of conservation of mass, momentum and energy. It is useful to apply this approach because the processes of evaporation, pyrolysis and combustion in crown and processes of transfer in atmosphere have different spatial scales. The conjugate formulation of this problem let us to get solution distinctly in different regions and take into account their influence. This approach to solve like problems using conjugate formulation was proposed by A.Grishin [1-4]. A coupled atmosphere fire model, HIGRAD/FIRETEC, developed at the Los Alamos National Laboratory [5,6], was employed to examine the effects of the atmospheric potential temperature profiles on the rate of spread of fire, in addition to the potential temperature and velocity fields in the domain. The physical multiphase model used in [8,9] may be considered as a development and extension of the formulation proposed by Grishin [2]. This paper presents a mathematical model of the conjugate heat and mass transfer at crown forest fire. A mathematical model of forest fires was obtained there based on an analysis of known and original experimental data [2,7], and using concepts and methods from reactive media mechanics.

2. Physical and Mathematical Model

The basic assumptions adopted during the deduction of equations, and boundary and initial conditions: 1) the forest represents a multiphase, multistoried, 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), 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 coordinate reference point x_1, x_2 , x_3= 0 be situated at the center of the crown forest fire source at the height of the roughness level, axis 0x1 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).

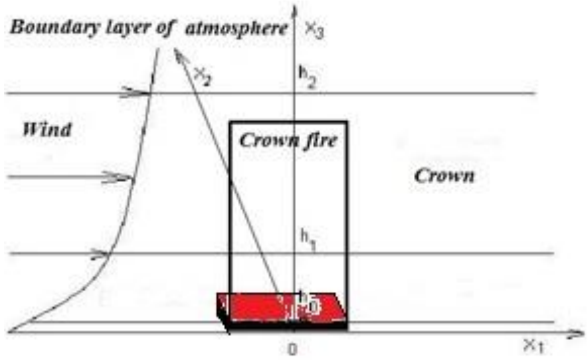

Figure 1.

Using the results of [1-4] and known experimental data [2,7] problem formulated above reduces to the solution of systems of equations (1)-(7):

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

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

$$\rho c_p\frac{dT}{dt}=\frac{\partial}{\partial x_j}(-\rho c_p v_j'\overline{v_i'T'})+q_5R_5-\alpha_v(T-T_s)+ \\ +k_g(cU_R-4\chi\sigma T^4); \tag{3}$$

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

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

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

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

$$\sum_{\alpha=1}^{5} c_\alpha = 1, \ p_e = \rho RT \sum_{\alpha=1}^{5} \frac{c_\alpha}{M_\alpha}, \vec{v} = (v_1, v_2, v_3), \vec{g} = (0,0,g)$$

$$\dot{m} = (1-\alpha_c) R_1 + R_2 + \frac{M_c}{M_1} R_3 + R_{54} + R_{55},$$

$$R_{51} = -R_3 - \frac{M_1}{2M_2} R_5, R_{52} = \nu_g (1-\alpha_c) R_1 - R_5,$$
$$R_{53} = 0, R_{54} = \alpha_4 R_1, R_{55} = \frac{\alpha_5 v_3}{v_3 + v_{3*}} R_3.$$

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 models [2-4].

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

The system of equations (1)–(7) must be solved taking into account the initial and boundary conditions:

$$t = 0 \ : v_1 = 0, v_2 = 0, v_3 = 0, T = T_e, \ c_\alpha = c_{\alpha e}, \quad (8)$$
$$T_S = T_e, \ \varphi_i = \varphi_{ie};$$

$$x_1 = x_{1e} : \frac{\partial v_1}{\partial x_1} = 0, \ \frac{\partial v_2}{\partial x_1} = 0, \frac{\partial v_3}{\partial x_1} = 0, \ \frac{\partial c_\alpha}{\partial x_1} = 0, \quad (9)$$
$$\frac{\partial T}{\partial x_1} = 0, \frac{c}{3k}\frac{\partial U_R}{\partial x_1} + \frac{c}{2} U_R = 0 \ ;$$

$$x_2 = x_{20} : \frac{\partial v_1}{\partial x_2} = 0, \ \frac{\partial v_2}{\partial x_2} = 0, \ \frac{\partial v_3}{\partial x_2} = 0, \frac{\partial c_\alpha}{\partial x_2} = 0, \quad (10)$$
$$\frac{\partial T}{\partial x_2} = 0, -\frac{c}{3k}\frac{\partial U_R}{\partial x_2} + \frac{c}{2} U_R = 0 \ ;$$

$$x_2 = x_{2e} : \frac{\partial v_1}{\partial x_2} = 0, \ \frac{\partial v_2}{\partial x_2} = 0, \frac{\partial v_3}{\partial x_2} = 0, \frac{\partial c_\alpha}{\partial x_2} = 0, \quad (11)$$
$$\frac{\partial T}{\partial x_2} = 0, \frac{c}{3k}\frac{\partial U_R}{\partial x_2} + \frac{c}{2} U_R = 0 \ .$$

$$x_3 = 0 : v_1 = 0, \ v_2 = 0, \frac{\partial c_\alpha}{\partial x_3} = 0, -\frac{c}{3k}\frac{\partial U_R}{\partial x_3} + \frac{c}{2} U_R = 0 \ , \quad (12)$$
$$v_3 = v_{30}, T = T_g \ , |x_1| \le \Delta, |x_2| \le \Delta$$
$$v_3 = 0, \ \ T = T_e \ , |x_1| > \Delta, |x_2| > \Delta;$$

$$x_3 = x_{3e} : \frac{\partial v_1}{\partial x_3} = 0, \ \frac{\partial v_2}{\partial x_3} = 0, \frac{\partial v_3}{\partial x_3} = 0, \frac{\partial c_\alpha}{\partial x_3} = 0, \quad (13)$$
$$\frac{\partial T}{\partial x_3} = 0, \frac{c}{3k}\frac{\partial U_R}{\partial x_3} + \frac{c}{2} U_R = 0 \ .$$

Here and above $\frac{\mathrm{d}}{\mathrm{d}t}$ 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; T_e - the ambient temperature; c_α - mass concentrations of α - component of gas - dispersed medium, index α=1,2,...,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, $_g$ – mass fraction of gas combustible products of pyrolysis, α_4 and α_5 – empirical constants. To define source terms which characterize inflow (outflow of mass) in a volume unit of the gas-dispersed phase were used the following formulae 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}. Coefficients of multiphase (gas and solid phase) heat and mass exchange are defined $\alpha_V = \alpha S - \gamma C_P \dot{m}, S = 4\varphi_S / d_S$. Here $\alpha = Nu\lambda/d_S$ – coefficient of heat exchange for sample of forest combustible material (for example needle), Nu – Nusselt number for cylinder, λ – coefficient of heat conductivity for pine needle; γ –

parameter, which characterize relation between molecular masses of ambient and inflow gases.

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. 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 [2]. 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 pine forest [2]) type of forest. The conditions of symmetry are used because of the patterns of flow and distributions of all scalar functions are symmetrical relatively to the plates Ox_1. Ox_3.

3. Numerical Method and Results

The boundary-value problem (1)–(7) we solve numerically using the method of splitting according to physical processes [2]. 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 splitting [2] was then integrated. A discrete analog was obtained by means of the control volume method using the SIMPLE like algorithm [10]. The accuracy of the program was checked by the method of inserted analytical solutions. The time step was selected automatically. Fields of temperature, velocity, component mass fractions, and volume fractions of phases were obtained numerically.

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 $a)(1-\bar{T}=T/T_e, 2-\bar{T}_s=T_s/T_e, T_e=300K)$, $b)(1-\bar{C}_1=C_1/C_{1e}, 2-\bar{C}_2=C_2/C_{1e}$, $C_{1e}=0.23)$, $c)(1-\bar{\varphi}_1=\varphi_1/\varphi_{1e}, 2-\bar{\varphi}_2=\varphi_2/\varphi_{2e}, 2-\bar{\varphi}_3=\varphi_3/\varphi_{3e})$.

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, i.e. initially heating of solid and gaseous phases occurs, moisture is evaporated. Then decomposition process into condensed and volatile pyrolysis products starts, the latter being ignited in the forest canopy. 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.

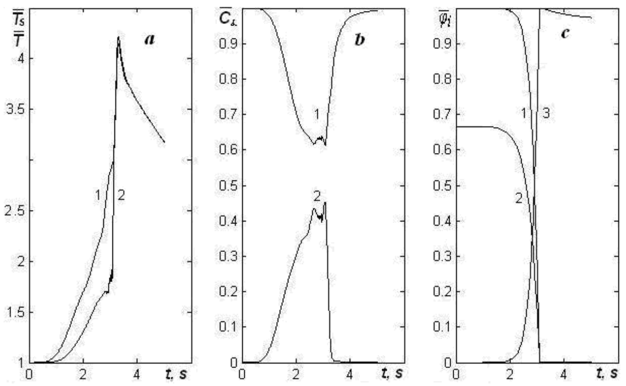

Figure 2.

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 effect of the wind on the zone of forest fire initiation is shown in Figures 3-5 present the space distribution of field of temperature for gas phase for different instants of time (*t=3.3 sec., 3.8 sec.* and *4.8 sec.*) when a wind velocity V_e= 7 m/s. We can note that the isosurfaces are deformed by the action of wind. The isosurfaces of the temperature of gas phase 1, 2, 3 и 4 correspond to the temperatures $\bar{T}$ = 1.2., 2, 3 and 4. In the vicinity of the source of heat and mass release, heated air masses and products of pyrolysis and combustion float up. 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. 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 isosurfaces of the gas phase temperature are deformed in the direction of the wind.

Figures 4 and 5 present the distribution of the velocity and isosurfaces of the temperature at the different instants of time when a wind velocity V_e= 7 m/s.

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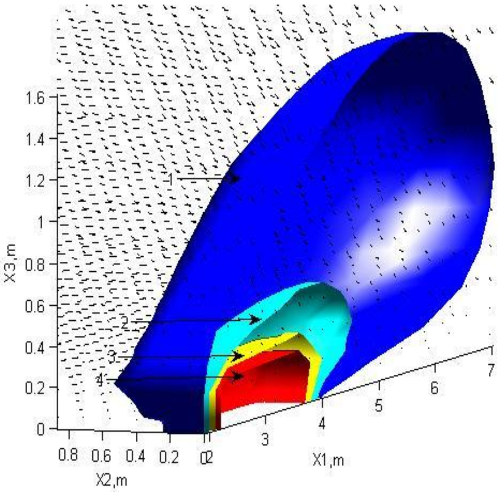

Figure 3.

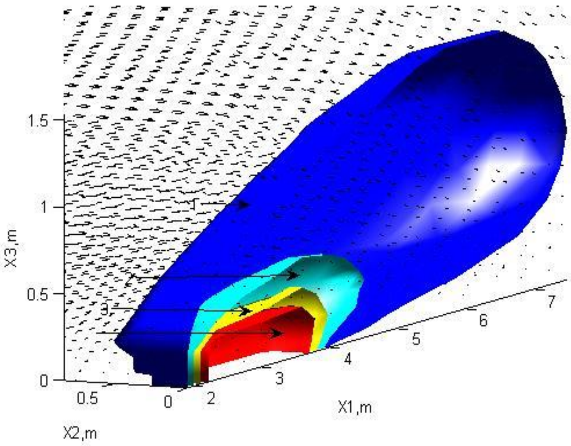

Figure 4.

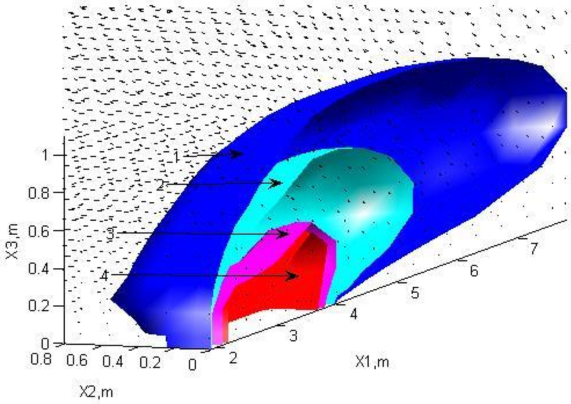

Figure 5.

The effect of the wind on the forest fire spread is shown in Figures 6(a, b, c) present the horizontal distribution of field of temperature for gas phase in plane $0x_1\ x_2$ for different instants of time (a - t=4.3 sec., b - 6 sec., c - 8 sec.); when a wind velocity *Ve*= 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.

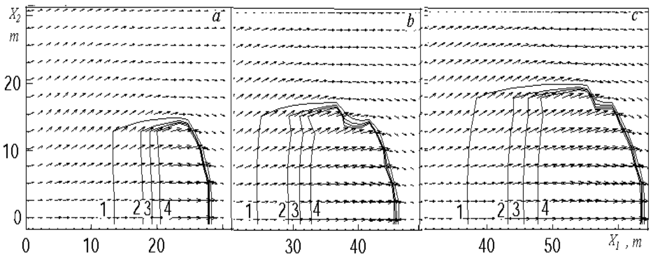

Figure 6. Fields of velocity and isotherms for:
$1-\bar{T}=2,\ 2-\bar{T}=2.5,\ 3-\bar{T}=3.,4-\bar{T}=4.;\bar{T}=T/T_e,T_e=300K.$

Figures 7 and 8 (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 (*a - t=4.3 sec.*, *b - 6 sec.*, *c - 8 sec.)*, 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

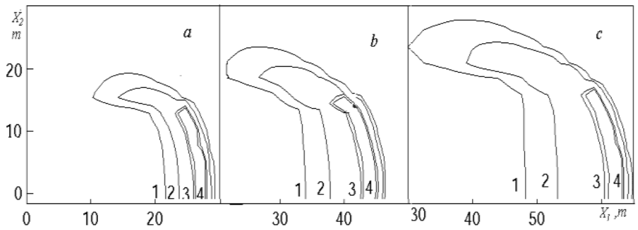

Figure 7. The distribution of oxygen $\bar{c}_1$;
$1-\bar{c}_1=0.9,\ 2-\ \bar{c}_1=0.8,\ 3-\bar{c}_1=0.5, 4-\bar{c}_1=0.4;$

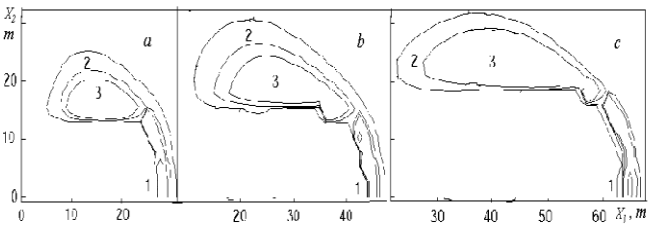

Figure 8. The distribution of $\bar{c}_2$ for *t=4.3 sec (a), 6 sec (b), 8 sec (c)* and V_e = 5 m/sec;
$1-\bar{c}_2=0.1,\ 1-\bar{c}_2=0.5, 1-\bar{c}_2=1.$

Mathematical model and the result of the calculation give an opportunity to evaluate critical height of the forest canopy and carry out preventive measures, which allows preventing initiation of crown fires.

4. Conclusion

Mathematical model and the result of the calculation give an opportunity to evaluate critical condition of the forest fire initiation and spread which allows applying 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 [2,7]. This paper represents the attempt for application of three dimensional models for description of crown forest fires initiation and spread.

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